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Canada

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2022

Permanent link: https://doi.org/10.4095/330473
ISBN 978-0-660-44727-8
Catalogue No. M183-7/2-2022E-PDF

This publication is available for free download through GEOSCAN (https://geoscan.nrcan.gc.ca/).

Recommended citation
McClenaghan, M.B., Spirito, W.A., Day, S.J.A., McCurdy, M.W., McNeil, R.J., and Adcock, S.W., 2022. Overview of GEM surficial geochemistry and indicator-mineral surveys and case studies in northern Canada; Geological Survey of Canada, Preprint 2, 1 .zip file. https://doi.org/10.4095/330473

The final version of this manuscript will be released in the following volume:
McMartin, I. (ed.), in press. Surficial geology of northern Canada: a summary of Geo-mapping for Energy and Minerals program contributions; Geological Survey of Canada, Bulletin 611.

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APPENDIX B – GEM_Syn_AppendixB_IndicatorMin.xlsx

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Volume editor's timeline:
Received February 26, 2020
Revised May 6, 2020
Accepted June 1, 2020
Updated July 13, 2022 (figures and in press references)

ABSTRACT

As part of the Geo-mapping for Energy and Minerals (GEM) program, which ran from 2008 to 2020, the Geological Survey of Canada carried out reconnaissance-scale to deposit-scale geochemical and indicator mineral surveys, and case studies across northern Canada. In these studies, geochemical methods were used to determine the concentrations of 65 elements in lake sediment, lake water, stream sediment, stream water, and till samples across approximately 1,000,000 km^2 of northern Canada. State-of-the-art indicator methods were used to examine the indicator mineral signatures identified in regional-scale stream sediment and till surveys. As a result of this research, areas with anomalous concentrations of elements and/or indicator minerals that are indicative of bedrock mineralization were identified, new mineral exploration models and protocols were developed, a new generation of geoscientists was trained, and knowledge was transferred to northern communities. The most immediate impact of the GEM surveys has been the stimulation of mineral exploration in Canada's north, with exploration efforts being focused on high mineral-potential areas identified in GEM regional-scale surveys. Regional- and deposit-scale studies demonstrated how transport data (till geochemistry, indicator minerals) and ice-flow indicator data can be used together to identify and understand complex ice flow and glacial transport. Detailed studies at the Izok Lake, Pine Point, Strange Lake, and Kiggavik deposits and across the Great Bear magmatic zone demonstrate new suites of indicator minerals that can now be used in future reconnaissance- and regional-scale stream sediment and till surveys across Canada.

RÉSUMÉ

Dans le cadre du Programme de géocartographie de l'énergie et des minéraux (GEM), la Commission géologique du Canada a réalisé, entre 2008 et 2020, des levés géochimiques et de minéraux indicateurs à l'échelle des gisements et aux fins de reconnaissance dans le nord du Canada. Au cours de ces études, des méthodes géochimiques ont été utilisées pour déterminer les concentrations de 65 éléments dans les sédiments lacustres, les sédiments des ruisseaux, l'eau des ruisseaux, l'eau des lacs et des échantillons de till dans une aire d'environ 1 000 000 km^2 dans le Nord canadien. Des méthodes de pointe ont été utilisées pour examiner les signatures des minéraux indicateurs dans les sédiments des ruisseaux et les échantillons de till à l'échelle régionale. Ces travaux de recherche ont permis de cerner des secteurs présentant des concentrations anormales d'éléments et/ou de minéraux indicateurs révélateurs d'une minéralisation dans la roche-mère. Les travaux ont également permis d'élaborer de nouveaux protocoles et de nouvelles méthodes d'exploration minérale, de former une nouvelle génération de géoscientifiques et de transférer des connaissances aux collectivités nordiques. Dans l'immédiat, les levés géocartographiques de l'énergie et des minéraux ont stimulé l'exploration minérale dans le nord du Canada et concentré les efforts en matière d'exploration dans les secteurs à fort potentiel minéral cernés dans les levés GEM régionaux. Les études menées à l'échelle régionale et des gisements ont démontré comment les données relatives au transport (géochimie du till, minéraux indicateurs) et les données indicatrices sur l'écoulement des glaces peuvent être utilisées de façon combinée pour identifier et comprendre les écoulements glaciaires complexes et le transport glaciaire. Des études détaillées réalisées aux gisements du lac Izok, de Pine Point, du lac Strange et Kiggavik, ainsi que de part et d'autre de la zone magmatique du Grand lac de l'Ours, indiquent de nouveaux ensembles de minéraux indicateurs qui pourront être utilisés dans le cadre de futurs levés de reconnaissance et de levés régionaux de tills et de sédiments des ruisseaux à l'échelle du Canada.

INTRODUCTION

Reconnaissance to regional-scale and deposit-scale geochemical and indicator mineral surveys and case studies were carried out in targeted areas across northern Canada (Fig. 1) as part of the Geo-mapping for Energy and Minerals (GEM) program to advance geological knowledge, support increased exploration of natural resources, and inform decisions on land use that balance conservation of resources and responsible resource development. Four significant outcomes resulted from these surveys and case studies:

1) Areas were identified that contain considerable concentrations of elements and/or indicator minerals that are indicative of bedrock mineralization for a broad range of commodities including precious, base and rare metals, uranium and diamonds;
2) Exploration models and protocols were developed to improve the search for base, precious and rare metals, and diamonds using surficial methods;
3) A new generation of professional personnel were trained through collaborative research partnerships with research organizations and academia, courses taught at universities, short courses given at conferences, and through publication of journal papers and special volumes; and
4) Knowledge transfer to northern communities was accomplished through consultations, presentations, local field hires and activity wrap-up meetings, summaries and discussions.

This paper provides an overview of GEM surficial geochemical and indicator mineral surveys conducted between 2008 and 2020, including a list of all publications that report GEM geochemical and mineralogical data in appendices A and B and a description of the surficial sample media and analytical methods used. In addition to regional-scale surveys, this paper provides an overview of detailed case studies conducted around known minerals deposits. The GEM geochemical and heavy mineral surveys and case studies listed in appendices A and B are too numerous to be able to describe all of the results achieved, therefore, highlights from selected GEM regional-scale surveys and case studies are reported here. The highlights below include figures reproduced from individual Geological Survey of Canada (GSC) reports. Readers are encouraged to refer to the original GSC reports to fully understand how the data were plotted.

Five main types of surficial media were collected as part of GEM geochemical and mineralogical surveys: lake sediments, lake waters, stream sediments, stream waters, and till. A few esker samples were also collected as part of three till surveys. The various sample media were collected in order to characterize regional elemental and mineralogical concentrations and delineate anomalies for exploration targeting at the broad scale of geological provinces down to individual mineral deposits. Surficial geochemical surveys and case studies conducted as part of the GEM program are listed in Appendix A and indicator mineral surveys and case studies are listed in Appendix B. Note that there is overlap between these two lists because many surveys were conducted for both geochemistry and heavy mineral studies. Each survey listed in the appendices includes a link to its metadata page on the Canadian Database of Geochemical Surveys website. From the site, links to related publications can be accessed.

SURFICIAL SAMPLE MEDIA USED IN GEM SURVEYS

Centre-lake sediments and water

Lake sediments and waters are effective reconnaissance-scale to high density sampling tools for mineral exploration in those parts of the Canadian Shield that have low relief and disorganized

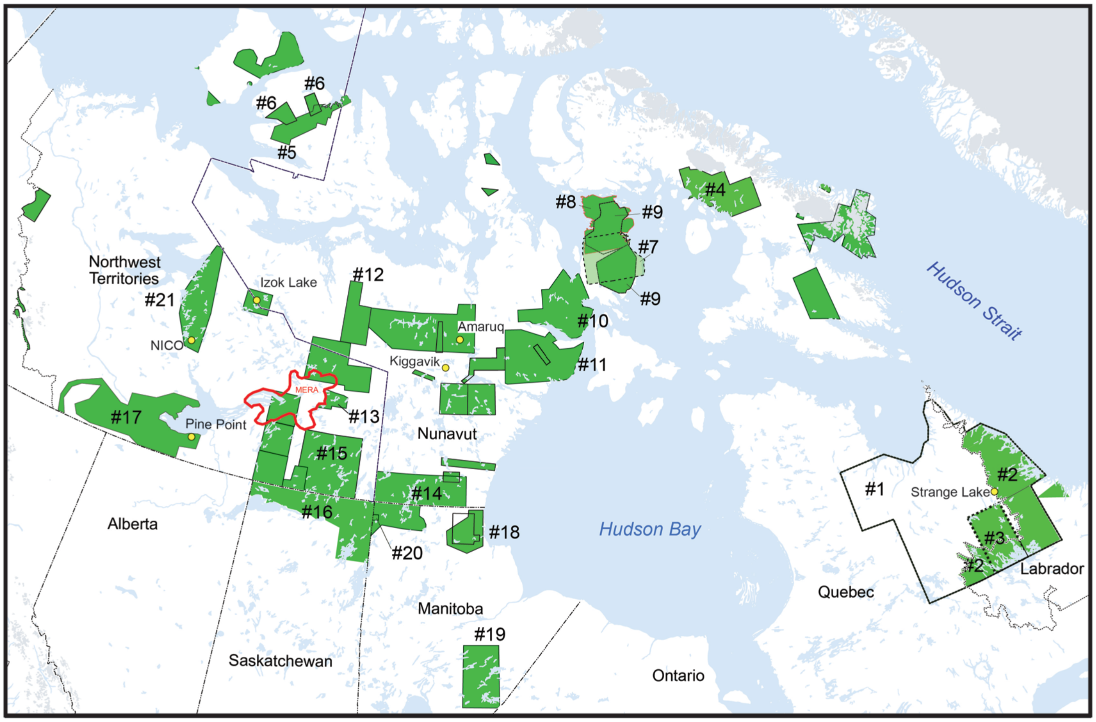

Figure 1. *Locations of the reconnaissance- and regional-scale lake sediment, stream sediment, and till geochemical surveys conducted as part of the Geo-mapping for Energy and Minerals (GEM) program across northern Canada are indicated by green polygons. The large area covered by the joint GSC–Quebec–Newfoundland and Labrador lake-sediment geochemical data compilation is outlined by a thick black line (area 1). Other surveys mentioned in the text are numbered from 2 to 21. The locations of GEM-supported deposit-scale studies are indicated by yellow dots. Mineral and Energy Resources Assessment (MERA) project area is outlined in red.*

drainage systems (Friske, 1991). Samples are collected from the centres of lakes or the centres of bays in large lakes, away from inflows and outflows. Lake sediments consists of varying mixtures of three types of material, as summarized below from Allan et al. (1972), Timperley et al. (1973), Timperley and Allan (1974), Coker and Nichol (1975), Jonassen (1976), Coker et al. (1979, 1980), and Friske (1991):

i) Inorganic sediments: mixtures of sand, silt, clay, and hydrous oxides with minor amounts of organic matter that commonly exist near the shores of lakes, near inflows and outflows, and in lakes where surrounding vegetation is sparse (e.g., north of the treeline).

ii) *Organic gels*: mature organic-rich sediments also referred to as gyttja. They are generally found in deeper, less active parts of lake basins, are thixotropic, and commonly green-brown to grey in colour.

iii) *Organic sediments:* a blend of inorganic sediments, organic gels, and immature organic debris. They usually occur near shore or stream inflows.

GSC reconnaissance lake sediment and water surveys were conducted using protocols established by the GSC in the mid 1970s (Friske, 1991; Friske and Hornbrook, 1991; McCurdy et al., 2014). The protocols have remained the same but analytical techniques and elements determined have progressed with technology. The GSC's use of these protocols over the past 40+ years allows comparison of new GEM datasets with older datasets that may be separated by large distances or time. Each sample is air dried and sieved to recover the -80 mesh (<0.177 mm) fraction. This fraction is geochemically analyzed using an aqua regia digestion combined with ICP-ES and ICP-MS and by using instrumental activation analysis (INAA).

Under the GEM program, archived lake sediment samples from 30 previous GSC surveys were reanalyzed (Fig. 1). The reanalysis allowed for the determination of a broader range of elements (65 in 2018 versus 31 in the 1990s and 12 in the 1970s), benefited from lower analytical detection limits, and increased data precision. One new lake sediment survey was conducted in Abitau Lake area of southeast Northwest Territories and included the collection of surface lake water (McCurdy et al., 2016a). New lake sediment geochemical data for archived and new samples covering about 450,000 km^2 were generated for 26,865 samples. Reports containing the geochemical data for lake sediment samples are listed in Appendix A.

Stream sediment and water

Stream sediment and water sampling are effective reconnaissance-scale to high density tools for mineral exploration in areas that have moderate to high relief and organized drainage systems (Ballantyne, 1991; Friske and Hornbrook, 1991). In mountainous to hilly terrains, stream sediments are derived from erosion of bedrock as well as local glacial and colluvial sediments. In lower relief terrain of the Canadian Shield, stream sediments are derived primarily from the fluvial erosion of glacial sediments. GEM stream sediment and water surveys were conducted using protocols established by the GSC in the mid 1970s (Ballantyne, 1991; Friske and Hornbrook, 1991; McCurdy et al., 2014) and the use of these protocols over the past 40+ years, allows comparison and integration of new GEM datasets with older GSC datasets. The protocols have remained the same but analytical techniques and the number of elements determined have progressed/increased with technology.

Three types of samples are commonly collected from a stream sample site:

i) Stream waters are sampled in mid-channel, from flowing water where possible and prior to or upstream of any sediment sampling. Each sample is filtered on site through a 0.45 μm single-use disposable filter unit. Two water samples are collected at each site: a) filtered and acidified (FA), and b) filtered and unacidified (FU). Samples are preserved by acidifying to 0.4% with ultrapure 8M HNO_3 either in the field or at GSC Ottawa. The FA water samples are analyzed for trace and major elements by inductively coupled plasma mass spectrometry and emission spectrometry (ICP-MS and ICP-ES). The FU samples are analyzed for anions, pH, conductivity, alkalinity and dissolved organic carbon (DOC).

ii) A small (~2 kg) sample of clay to fine sand-sized material is collected by hand from various points in an active stream channel while moving upstream, over a distance of 5 to 15 m. Each sample is air dried and sieved to recover the -80 mesh (<0.177 mm) fraction. This fraction is geochemically analyzed using an aqua regia digestion combined with inductively couple plasma-emission spectrometry (ICP-ES) and inductively couple plasma-mass spectrometry (ICP-MS) and using instrumental activation analysis (INAA).

iii) A large (~8 to 14 kg) sediment sample is collected using a shovel from high-energy gravel-rich stream sediments in large gravel bars, boulder traps, or tiny pools of sediments in rocky narrow streams. Samples are wet sieved onsite to remove the >2 mm fragments. In a commercial lab, this sample is sieved to -10 mesh (<2 mm) and processed using a combination of shaking table and heavy liquids to produce a heavy mineral fraction (>3.2 specific gravity (SG)) for examination of indicator minerals. In some surveys, the <0.25 mm heavy mineral fraction is also geochemically analyzed.

Under the GEM program, 12 new stream sediment + water surveys were conducted. Re-analysis of one batch of archived stream sediment samples from a previous GSC survey was also carried out. New stream sediment geochemical data covering an area of about 120,000 km^2 across northern Canada (Fig. 1) were generated for approximately 1000 samples for 65 elements. Reports containing the geochemical and indicator mineral data are listed in appendices A and B, respectively.

Till

Till is an effective reconnaissance- to regional-scale sampling medium for mineral exploration in glaciated terrain (McClenaghan and Paulen, 2018, and references therein). It is a non-sorted mixture of sediment, ranging from clay to large boulders deposited directly from or by a glacier with little or no sorting by water (Dreimanis, 1989). Till is a product of glacial erosion, entrainment, transportation, and depositional processes and is the first derivative of bedrock; that is, it was eroded, transported and deposited by a single sedimentary process (i.e., glacial ice movement). Till generally has a simpler sedimentary transport history compared to other glacial or post-glacial sediments (secondary or higher derivative) such as glaciofluvial sediments, stream sediments, beach sediments, colluvial sediments that were transported by more than one (ice and water) sedimentary process (Shilts, 1976).

At the start of the GEM program GSC scientists established protocols for the design, sampling, and analysis of till samples (Spirito et al., 2011; McClenaghan et al., 2013a; Plouffe et al., 2013), similar to those already established for lake and stream sediment sampling. The till protocols were updated and expanded in 2020 and it is this new version that should be referred to for future surveys (McClenaghan et al., 2020). Small (3 kg) till samples are air dried, sieved, and the -250 mesh (<0.063 mm) fraction is geochemically analyzed using aqua regia, borate fusion or 4-acid digestions combined with ICP-ES and ICP-MS. In some surveys, the <0.002 mm fraction is also analyzed. In a commercial lab, the large (10-30 kg) till samples are sieved to -10 mesh (<2 mm) and processed using a combination of shaking table and heavy liquid separation to produce a heavy mineral concentrate (HMC) (>3.2 specific gravity) for examination of indicator minerals (McClenaghan, 2011; Plouffe et al., 2013; McClenaghan et al., 2020).

Under GEM, reconnaissance-, regional- and local-scale till surveys covering about 500,000 km^2 and the collection of 3900 till samples were conducted across northern Canada (Fig. 1). These surveys include five detailed till studies around known mineral deposits (Fig. 1- yellow dots) to test methods and to document for the first time the indicator mineral signature of these deposits: Izok Lake volcanogenic massive sulphide (VMS) deposit, Kiggavik U deposit, Pine Point Pb-Zn Mining District, NICO and Sue Dianne iron oxide copper gold (IOCG) deposits, and the Strange Lake rare earth element (REE) deposit. Reports containing the analytical data for regional and detailed studies are listed in Appendix A (geochemical data) and Appendix B (indicator mineral data).

Esker sediments

Esker sediments can provide useful mineralogical information at a reconnaissance scale for mineral exploration in glaciated terrain (Cummings et al., 2011). Esker sediments were sampled in one GEM survey along with till samples, as a continuation of surficial sediment sampling in the Mineral and Energy Resources Assessment (MERA) project area immediately to the west of the GEM survey, known as the Thaidene Nene National Park Reserve in the area of the East Arm of Great Slave Lake (Kjarsgaard et al., 2013a; Wright et al., 2013). A few esker samples were collected and processed as part of a small GEM-funded study on the effectiveness of a field-portable heavy mineral spiral concentrator (Smith and Paulen, 2016).

GEM DIGITAL DATA

All GEM data are freely available as individual reports/data releases via GEOSCAN https://geoscan.nrcan.gc.ca/geoscan-index.html and the Government of Canada's Canadian Database of Geological Surveys (CDoGS) (Adcock et al. 2013). The public interface to CDoGS can be found at http://geochem.nrcan.gc.ca. This web platform provides high-level metadata for each catalogued survey and its associated publications. Data are searchable by querying location maps, the periodic table, or index tables. Links to raw data in their original published format are included where possible and over 300 surveys have data available for download in a standardized format. Currently, there are metadata for over 1400 surveys stored in the database and links to published GEM surficial geochemical and indicator mineral reports are available on the website. Addition of the most recent surveys and standardizing of the raw data for viewing in Google Earth™ is on-going. More detailed information about the CDoGS website is reported in Spirito and Adcock (2010) and Adcock and Spirito (2019).

GEM SAMPLE ARCHIVES

A split of surficial sediment samples collected as part of the GEM program have been archived in the GSC's unconsolidated sediment sample collection for future reference or analysis. Till sample splits that have been archived include: i) a plastic container of 800 g of unprocessed material; ii) vials of at least 60 g of <0.063 mm material; and iii) vials of heavy and mid-density mineral concentrate fractions and picked mineral grains. Stream sediment sample material that was archived includes vials of: i) at least 60 g <0.177 mm material; and ii) heavy mineral concentrate fractions and picked mineral grains. Archived lake sediment sample material consists of vials of at least 60 g of <0.177 mm material. Sample fractions are stored in bar-coded containers within cardboard boxes with lids to prevent sunlight from degrading the plastic sample containers and vials.

RECONNAISSANCE- AND REGIONAL-SCALE SURVEYS

The GEM geochemical and mineralogical surveys were conducted across Canada's north from the high Arctic on Axel Heiberg, Banks, and Victoria islands to as far south as northern Manitoba and Saskatchewan and northeastern Quebec and western Labrador. During GEM, approximately 35,600 new and archived samples (lake sediments, lake water, stream sediments, stream water, till, and esker) were analyzed. Some survey areas had never previously been sampled before, and other areas had not been sampled in more than 40 years. Highlights of selected surveys are described below.

Northeastern Quebec and western Labrador

To assist in evaluating the mineral potential of Archean "Core Zone" rocks between the Torngat Orogen to the east and the New Quebec Orogen to the west (Corrigan et al., 2015, 2016, 2018), new lake sediment geochemical maps for the entire Core Zone were created (area 1 in Fig.1) (McClenaghan et al., 2014b; McCurdy et al., 2018). These new maps are remarkable because of the large area they cover (295,000 km^2) and the obstacles that were overcome to produce them. Challenges included the need to merge geochemical datasets from two government agencies (Quebec and Canada), the long time span the samples were collected over (40 years), and the slight differences in analytical digestions and methods. In order to merge datasets from the two different agencies, approximately 5,000 GSC archived lake sediment samples collected in Labrador (area 2 in Fig. 1) were reanalyzed in 2015 (McCurdy, 2016; McCurdy et al., 2016b) using similar methods that had been used for the Quebec dataset (Maurice and Labbé, 2009).

These new GEM data were then combined with geochemical data for more than 16,000 lake sediment samples from adjacent northeastern Quebec, previously published by the Ministère de l'Énergie et des Ressources naturelles du Québec. Data treatment and merging methods are described in detail in Amor (2015) and Amor et al. (2016, 2019).

The combined lake sediment dataset contributes new information for the geological mapping of this large region as well as indicating new targets for future mineral exploration (Amor et al., 2019). The data revealed a new geochemical province - the Labrador Trough - characterized by elevated concentrations of Sb, As, Bi, Re (Fig. 2) Cd, and Hg along its length and elevated Cu, Fe, Hf, Ni, Pb, and Zn overlying mafic volcanic and intrusive rocks within it (Corrigan et al., 2018; Amor et al., 2019). Other features identified in the data include elevated Au and Ag concentrations over the Ashuanipi Complex and the passive margin sedimentary basin derived from it that may indicate the potential for these rocks to host orogenic Au mineralization. Elevated rare earth element (REE) values outlined some Mesoproterozoic intrusions and may indicate their potential to host REE mineralization.

In addition to new regional lake sediment data and geochemical maps, Core Zone regional surficial activities included regional-scale till sampling for geochemistry (McClenaghan et al., 2016a, 2019; Rice et al., 2017a; Hagedorn et al., 2018) and indicator minerals (McClenaghan et al., 2016b; Rice et al., 2017b, in press) for the Schefferville-Smallwood reservoir region (area 3 in Fig.1). Highlights for these new data include elevated Cu, Zn, Au, Pt, Pd, and Sb concentrations in till overlying the Laporte terrane metasedimentary rocks, Labrador Trough (Knob Lake Group), and Doublet zone mafic volcanic rocks (see figure in Rice et al., in press). Elevated Au and Ag values in till matrix overlying the Doublet zone coincide with the elevated gold grain content in till samples (>6 grains/10 kg) indicating the potential for gold mineralization. The presence of chalcopyrite and platinum group minerals (sperrylite, moncheite) in till overlying the Doublet zone, and ultramafic rocks further east, suggest that there is potential for Cu-Ni-PGE mineralization (McClenaghan et al., 2017a; Rice et al., in press).

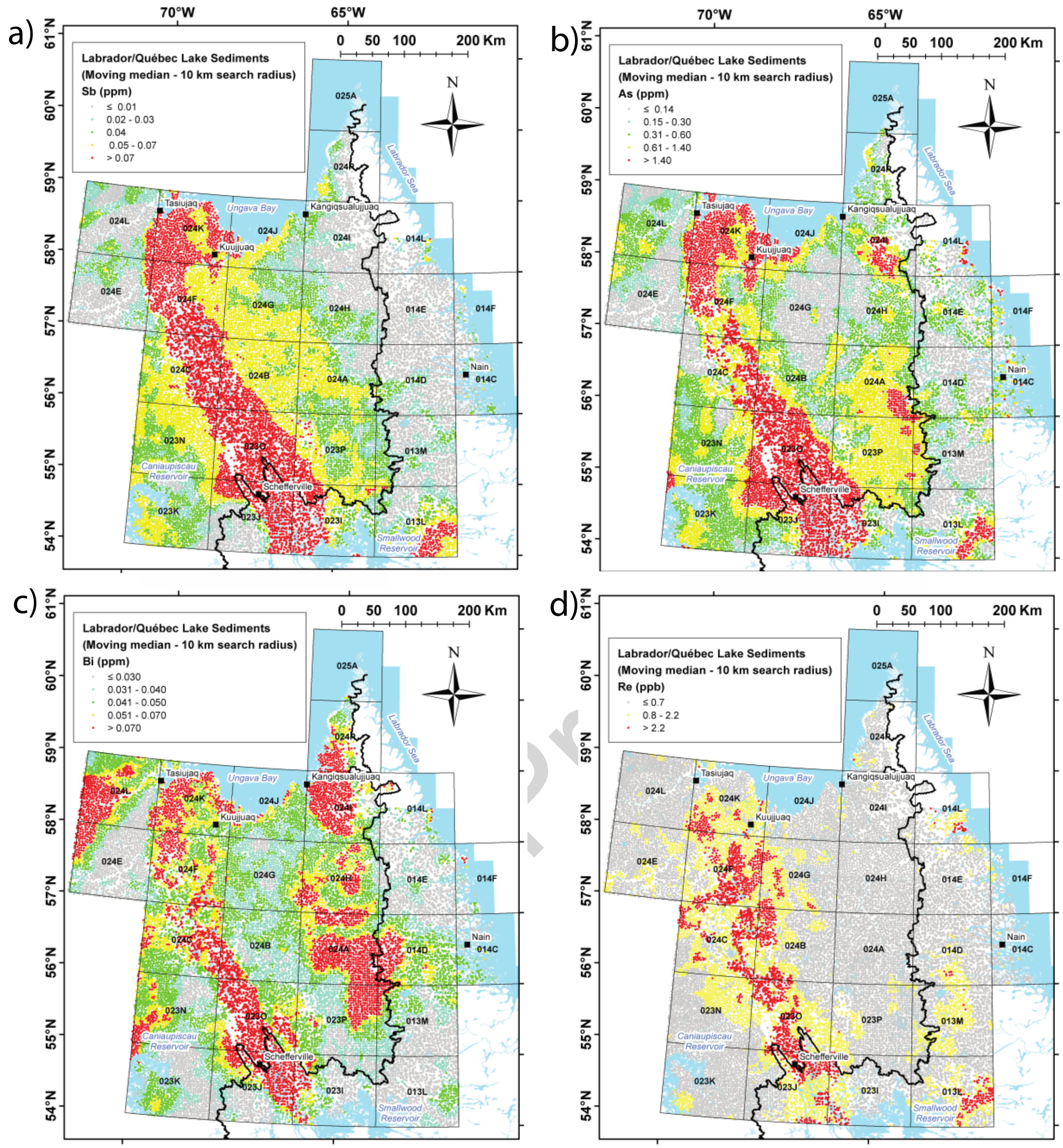

__Figure 2.__ Distribution of trace elements in the fraction smaller than 0.177 mm of lake-sediment samples from Quebec and Labrador determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry: __a)__ antimony (Sb), __b)__ arsenic (As), __c)__ bismuth (Bi), and __d)__ rhenium (Re) (modified from Amor et al., 2019, Fig. 23a–d).

West-central Baffin Island

In 2018, archived GSC lake sediment samples from west-central Baffin Island (see area 4 in Fig. 1) were reanalyzed using funding provided by the Government of Nunavut and GEM (McNeil et al., 2018a, b). Bonham-Carter et al. (2019) provide an interpretation of the new lake sediment dataset and identify and describe multi-element geochemical anomalies using principal component analysis and weighted sum modelling of various types of mineral deposits. Principal component analysis of a large suite of metallic elements shows some clear patterns. The dominant axis, PC1, separates Piling Group sedimentary rock units from igneous Archean and Paleoproterozoic units.

Weighted sum modelling was applied for 16 different mineral deposit types including magmatic Ni-Cu, Au, VMS, carbonate-hosted Pb-Zn (Fig. 3), sediment-hosted Cu, and pegmatites. In most of the models used in the analysis, the anomaly south of Flint Lake is the most obvious. Other highly metalliferous areas of interest include the area east of Flint Lake, further east along the Astarte River and Flint Lake formations at the north edge of the Paleoproterozoic basin, west of Nadluardjuk Lake overlying the Bravo Lake Formation, discrete clusters of samples further east along the Bravo Lake Formation, and a cluster of lake sediment samples overlying the Longstaff Bluff formation. This research provides new insights and a better understanding of this large geochemical dataset in the modern metallogenic framework described by Wodicka et al. (2014).

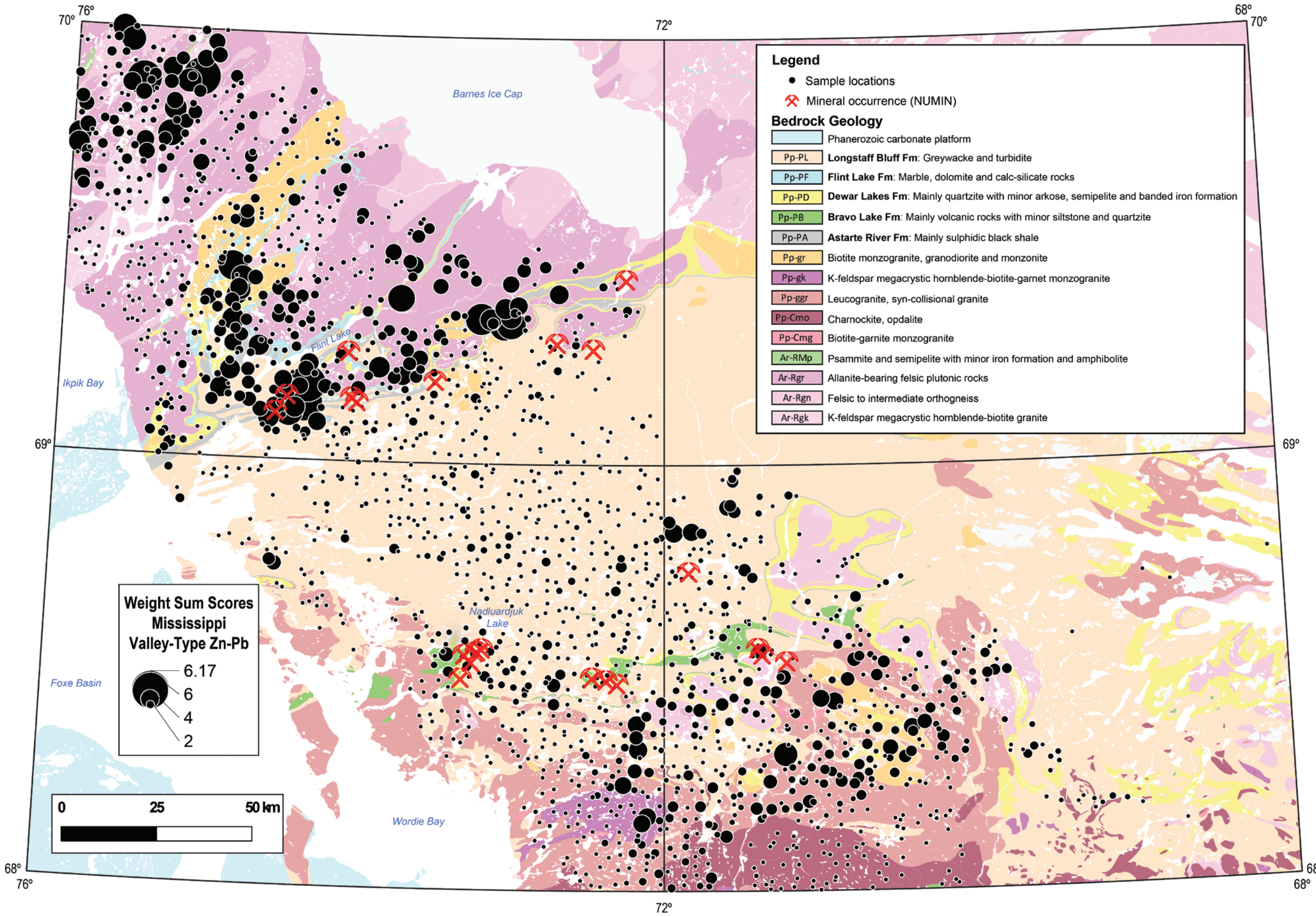

Figure 3. Proportional-dot map of weighted-sum scores for the Mississippi Valley-type Zn-Pb deposit model used to evaluate new lake-sediment geochemical data for west central Baffin Island, Nunavut. Mineral occurrences are from the Nunavut mineral occurrence database (NUMIN). Bedrock geology from Wodicka et al. (2014) and figure from Bonham-Carter et al. (2019).

Victoria Island

Archived GSC stream sediment samples collected from Victoria Island in 1994 were re-analyzed in 2010 to improve the understanding of the Neoproterozoic Shaler Super Group hosting the Franklin/Coronation Sills (base and precious metals) in central Victoria Island (see area 5 in Fig. 1). The analytical data from the reanalysis of 893 stream sediment samples were published in McCurdy et al. (2010a).

New regional stream sediment and water samples were collected overlying Paleozoic strata with potential to host Mississippi Valley-type (MVT) Pb-Zn mineralization further to the north on Victoria Island (see area 6 in Fig. 1) in 2010-2011. The objective was to assess resource potential of this previously unexplored and difficult-to-access region (McCurdy et al., 2011, 2012a). The geochemistry of stream sediment and waters indicates that high concentration of Pb and Zn in stream sediments were likely derived from dolomitized Shaler Supergroup rocks north of Minto Inlet (McCurdy et al., 2013a). Sphalerite, galena, chalcopyrite, pyrite, and barite grains were recovered in the same area as elevated Pb and Zn concentrations in stream sediment and water samples, and indicate the presence of local Pb-Zn mineralization (McCurdy et al., 2010a, 2012a). Regional bedrock geology and the identification of a series of east-northeast-striking faults in the areas where Pb and Zn contents in stream waters (Fig. 4) and sediments are elevated suggest there is potential for MVT-style mineralization in Shaler supergroup rocks north of Minto Inlet (McCurdy et al., 2013a).

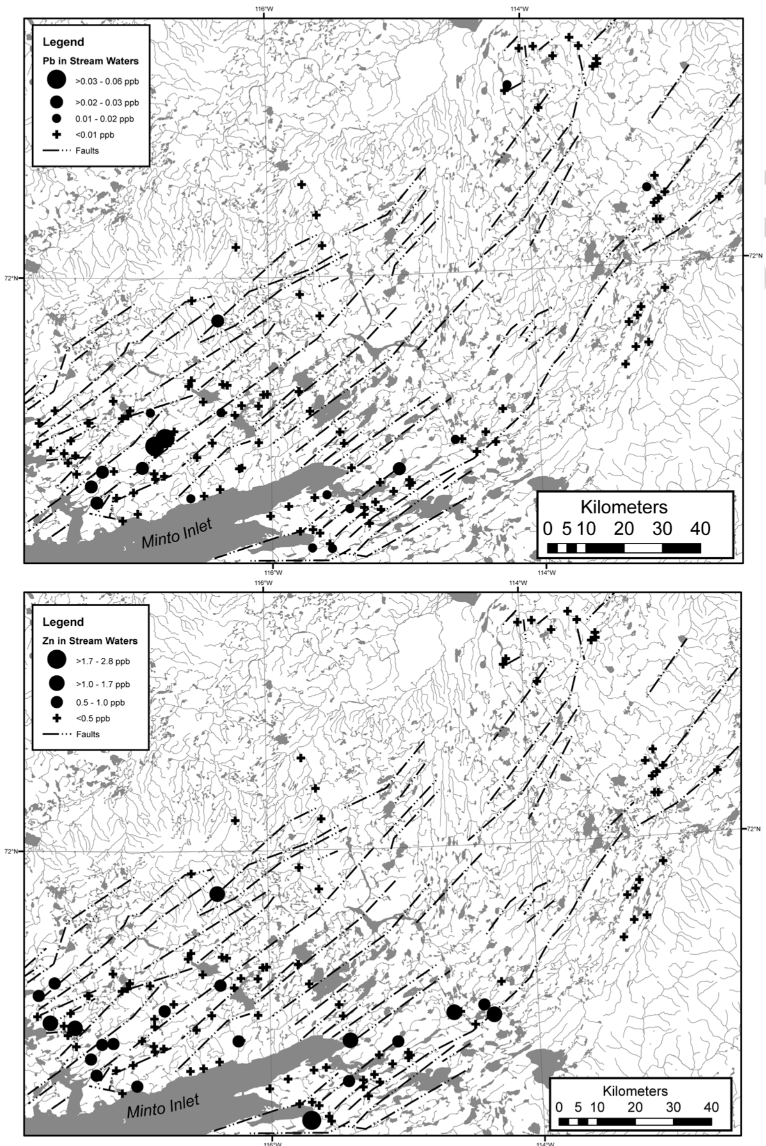

***Figure 4**. Proportional-dot maps of **a)** lead (Pb) and **b)** zinc (Zn) concentrations in stream waters on Victoria Island, Northwest Territories. From McCurdy et al. (2013a).*

Melville Peninsula

Archived GSC lake sediment samples from the central part of the Melville Peninsula (see area 7 in Fig. 1) were re-analyzed under GEM (Day et al., 2009; Corrigan et al., 2013). The new data were used for predictive geological mapping and evaluating mineral resource potential (Grunsky et al., 2014; Mueller and Grunsky, 2016; Grunsky and de Caritat, 2017, 2020). Patterns for Au, Cr, Ni, Cu, and Zn in lake sediments that reflect the underlying bedrock geology were identified. For example high residual Zn values, estimated from a robust linear regression, are associated with the Paleoproterozoic Penrhyn Group supracrustal rocks in southern Melville and appear to be associated, in part, with known Zn mineral occurrences.

Regional till geochemical surveys were carried out in the mid-1980s on northern and central Melville Peninsula to understand the metallogeny and mineral potential of the region. Archived till samples from that study were reanalyzed (Dredge, 2009) and combined with data from new till samples collected by Tremblay and Paulen (2012) and Tremblay et al. (2016a) (see area 8 in Fig.1). This region has carbonate-rich till derived from Paleozoic carbonate rocks in the Foxe Basin (Tremblay and Lamothe, in press). During deglaciation, this carbonate till was smeared across the northern part of the peninsula by streaming ice, overprinting the local till matrix, and masking the geochemical signal from local Precambrian bedrock. As a result, till geochemistry in the northern part of the peninsula (see area 8 in Fig. 1) reflects Paleozoic carbonate rocks to the east. In contrast, indicator mineralogical and geochemical analysis of till heavy mineral concentrates in the same area reflects the composition of local bedrock.

Across the southern Melville Peninsula (see area 9 in Fig. 1), high concentrations of Au (Fig. 5), Cu, Ni, and Zn plus pathfinder elements (As, W, Ag, Sb, Bi, Se, Sb and Hg) and indicator minerals (gold, sulfides, and sperrylite) in till overlie Penrhyn Group metasedimentary rocks. Comparisons of till matrix geochemistry data with regional lake sediment data reveal similar patterns of high metal values. For example, the highest Au values in till coincide with the elevated Au values in regional lake sediments (Fig. 5) and these areas of high concentrations appear to be most prospective (Tremblay et al., 2016a).

Tehery-Wager Bay

Results of regional-scale till sampling completed north and south of Wager Bay as part of the GEM North Wager Bay, Frontiers' Tehery-Cape Dobbs, and Tehery-Wager surficial mapping projects (McMartin et al., 2013a, b, 2015, 2019a, b) are summarized below. North of Wager Bay (see area 10 in Fig. 1), regional till geochemistry and indicator mineral content provide evidence of glacial transport by ice streaming as well as local mineral potential (McMartin et al., 2015). The Al_2O_3 content in the till matrix forms a remarkable northward converging, long-range dispersal train (Fig. 6) extending possibly as far as 125 km from unidentified bedrock sources along the coasts of Wager Bay and Roes Welcome Sound. Light REE, K_2O, and Na_2O concentrations in till display similar patterns in this area. The Al_2O_3 dispersal fan is coincident with converging streamlined landforms that are evidence of ice streaming northward into Committee Bay. To the east of the Al_2O_3 dispersal fan, the presence of calcareous till in the NNW-trending streamlined landforms also indicates relatively long glacial transport distances (tens to >100 km) over Archean gneissic rocks as part of the topographically controlled ice stream in Rae Isthmus (e.g. McMartin et al., in press). Although there is evidence of multiple ice-flow directions in the study area, the main ice-flow phase related to the ice stream flow is the predominant direction of glacial transport.

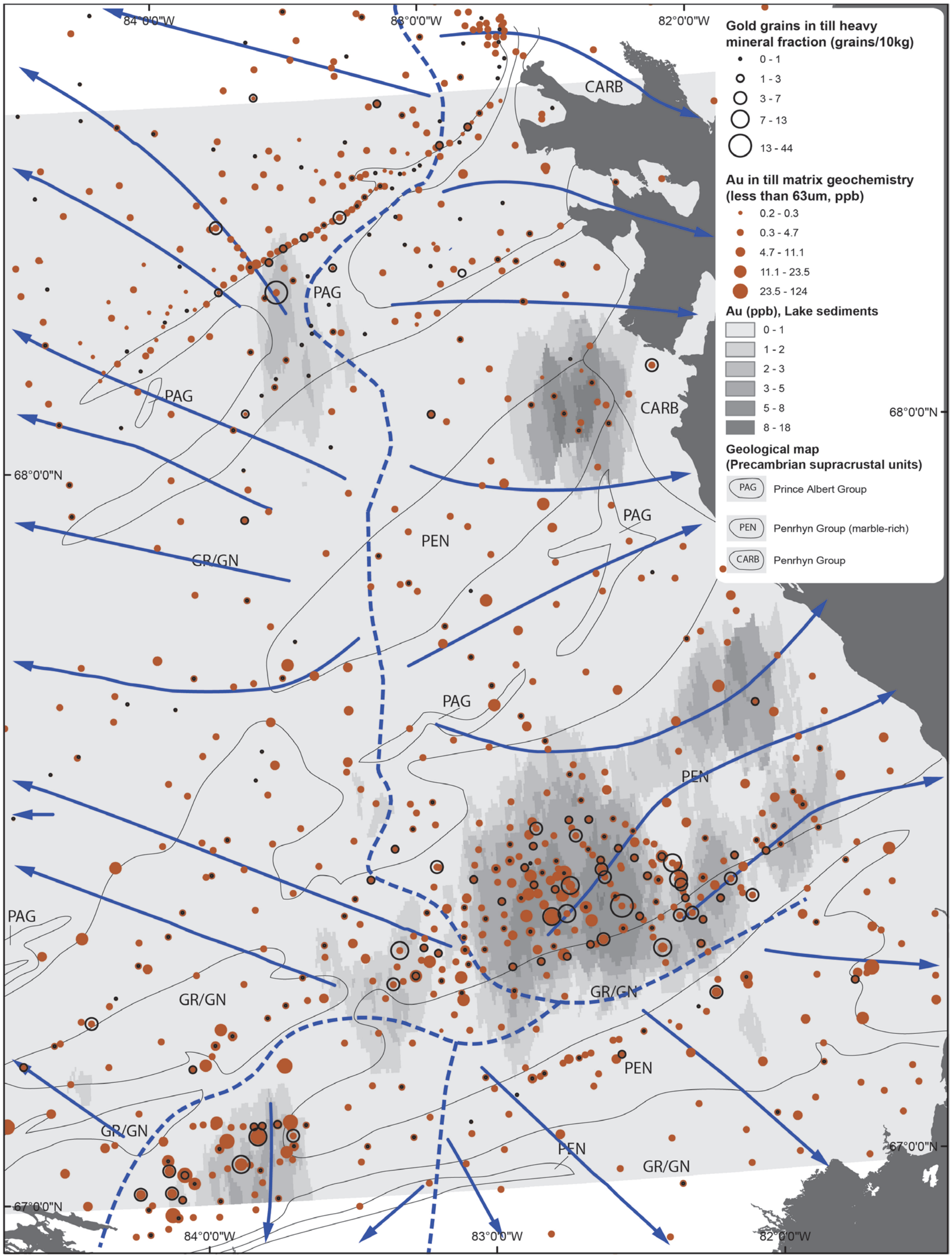

Figure 5. *Gold content in surficial sediments for southern Melville Peninsula, Nunavut: a) proportional dots (open circles) showing gold-grain abundance in the pan concentrate heavy-mineral fraction of bulk till samples (normalized to 10 kg); b) proportional dots (solid brown) showing gold (Au) concentration in the till fraction smaller than 0.063 mm determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP-MS); and c) grey contours showing Au concentration in the fraction smaller than 0.177 mm of lake sediments determined by aqua regia digestion followed by ICP-MS. Dashed blue lines indicate position of ice divide and blue arrows indicate ice-flow directions. Bedrock geology and figure after Tremblay et al. (2016a). Lake sediment data from Day et al. (2009).*

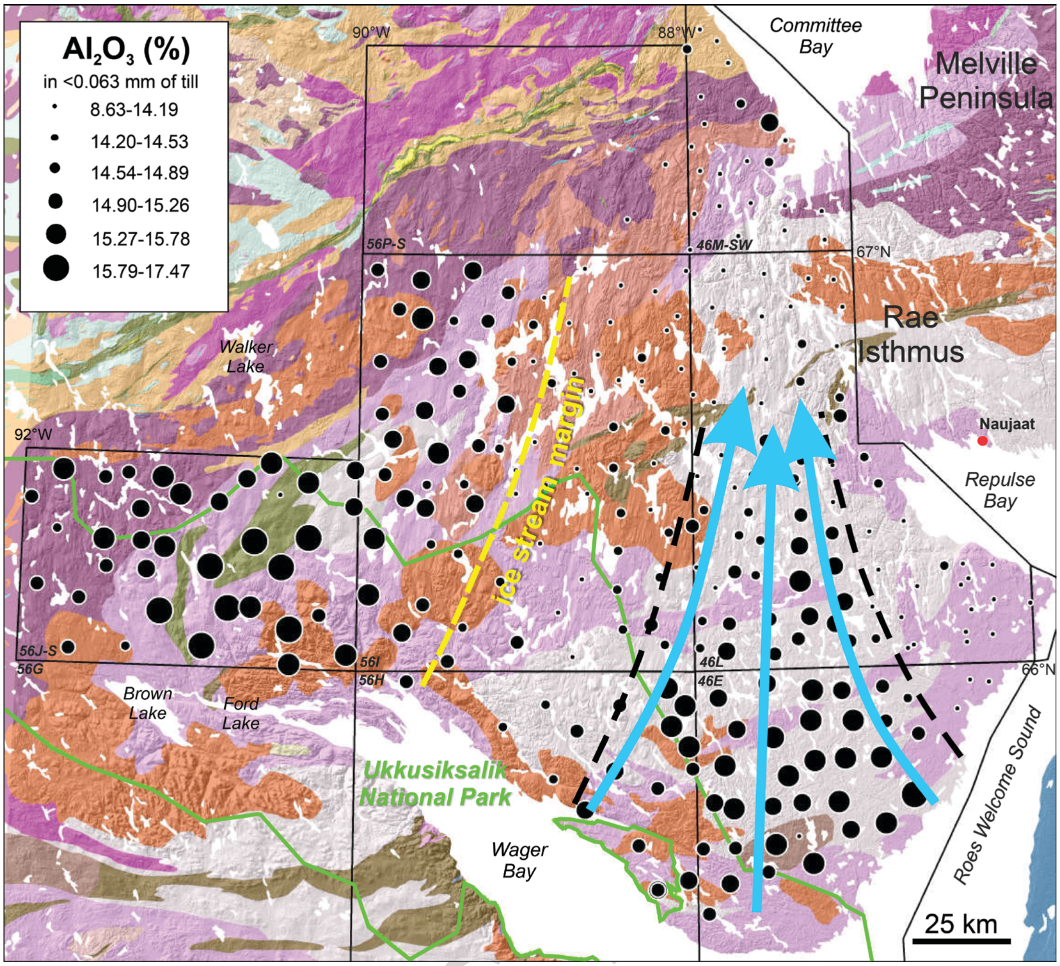

Figure 6. *Proportional-dot map of Al_2O_3 concentrations in the fraction smaller than 0.063 mm of surface till determined by borate fusion followed by inductively coupled plasma atomic-emission spectrometry. High concentrations of Al_2O_3, as well as K_2O, Na_2O, and light rare-earth elements (borate-fusion data) form a remarkable northward-converging, long-range glacial dispersal train along the coasts of Wager Bay and Roes Welcome Sound, Nunavut, that is coincident with converging streamlined landforms thought to result from ice streaming into Committee Bay. Blue arrows indicate direction of ice flow and black dashed lines outline limits of dispersal train. Bedrock geology and figure from McMartin et al. (2015).*

The area north of Wager Bay has potential to host diamondiferous kimberlites as shown by the significant number of Mg-rich olivine grains in till samples, many with high NiO contents and being coarse grained which may indicate the presence of kimberlite-derived macrocrysts. The distribution of kimberlite indicator minerals along the east side of the study area indicates long-range northwestward dispersal by the ice stream flow from the kimberlite field at Qilalugaq, north of Naujaat (formerly Repulse Bay), or from other unknown kimberlites (McMartin et al., 2015).

Regional till geochemistry and indicator mineral data indicate the area also has potential for Ni-Cu-PGE mineralization in the west part of the study area, near Walker Lake. In this area, a north-northeast trending, 35 km-long dispersal train is characterized by elevated concentrations of Ni, Cr (Fig. 7), Co, Cu and Zn, high chromite and forsterite grain counts, and the presence of large ultramafic boulder erratics in till. The source(s) of this dispersal train may be located in

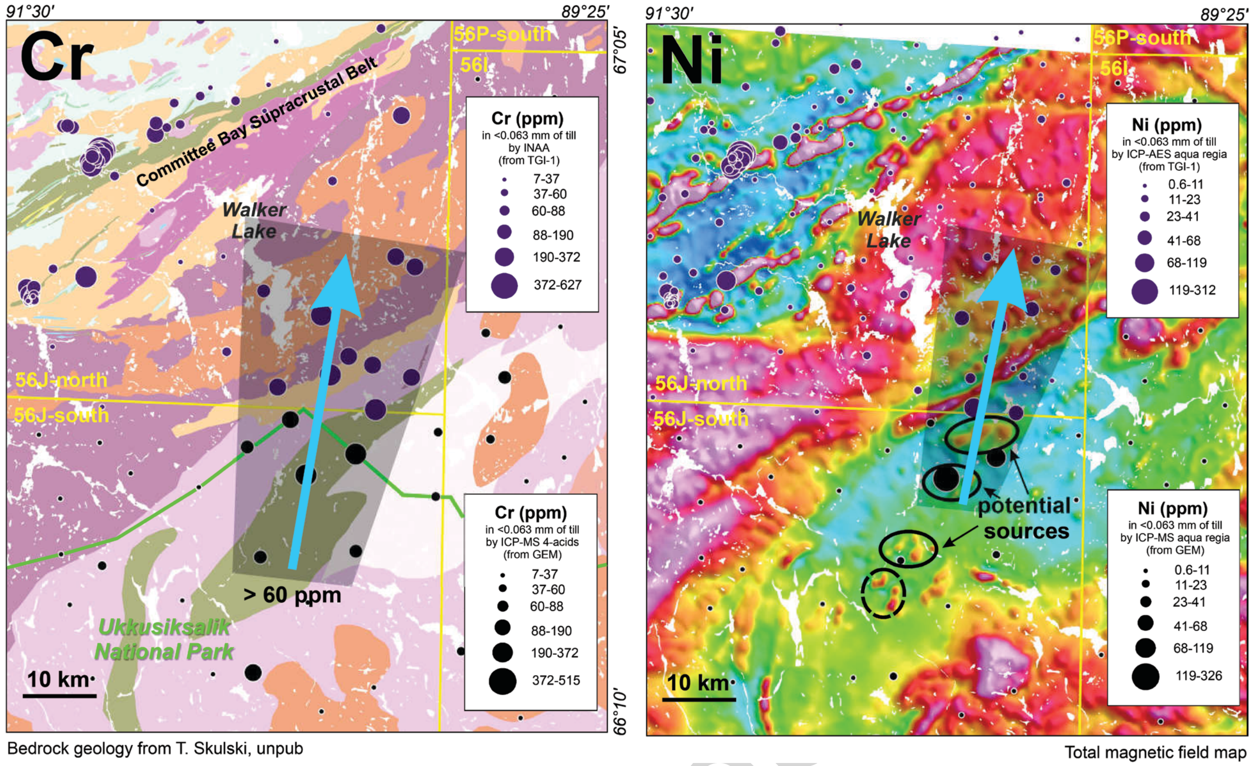

Figure 7. *Proportional-dot map of Geo-mapping for Energy and Minerals (GEM) program data showing concentrations of **a)** chromium (Cr) determined by instrumental neutron activation analysis and four acid digestion followed by inductively coupled plasma mass spectrometry (ICP-MS) and **b)** nickel (Ni) determined by aqua regia digestion followed by ICP-MS in the fraction smaller than 0.063 mm of surface till from Walker Lake area, Nunavut (refer to Figure 6 for location of Walker Lake). Targeted Geoscience Initiative program data shown in dark purple are from McMartin et al. (2013c). A glacial dispersal train having a distinct ultramafic geochemical signature (Cr, Ni) extends for at least 35 km to the north-northeast, parallel to the earliest glacial flow direction. Potential olivine-rich, crustal mafic or ultramafic rocks coincident with magnetic highs are circled in black on the airborne total magnetic field map (highly magnetic rocks in red, nonmagnetic rocks in blue). Blue arrows indicate ice flow direction. Bedrock geology and figure from McMartin et al. (2015).*

undifferentiated supracrustal rocks close to the boulder occurrence, within and/or just north of the Ukkusiksalik National Park.

South of Wager Bay (see area 11 in Fig. 1), data from two phases of the GEM program and previous GSC till sampling projects were combined to produce geochemical and indicator mineral maps and characterize glacial transport across the Keewatin Ice Divide, support bedrock mapping in areas of thick drift, and evaluate mineral potential of the region (McMartin et al., 2019a). In addition to the regional till surveys, two selected sites near the post-glacial limit of marine inundation were sampled in detail to evaluate the effects of marine reworking on geochemical composition as a support to drift prospecting in a periglacial environment (Randour, 2018).

Local, immature tills derived from poorly resistant weathered lithologies preserved under a non-erosive basal ice regime (cold-based) are predominant over the Keewatin Ice Divide zone. Glacial transport distances increase away from the ice divide and till composition reflects opposing directions of glacial transport on either side of the divide. The region hosts the Nanuq kimberlite bodies in the ice divide area just south of Wager Bay. Glacial erosion and transport of kimberlite debris formed a 60 km long dispersal train of kimberlite indicator minerals (Fig. 8) SSE of Nanuq, including Cr-pyrope, eclogitic garnet and Ca-forsterite. The presence of Cr-pyrope, eclogitic garnet, Ca-forsterite, Mg-ilmenite, low Cr-diopside, and bronzite grains in a till sample 180 km to the ESE of Nanuq in the Gordon domain (Fig. 8) indicates the potential to discover new diamondiferous kimberlites, distinct from the Nanuq kimberlite field (see sample 15MOB033 in Fig. 8). The study area also has potential to host Ni-Cu-PGE mineralization, with the greatest potential in the heavily drift-covered eastern part of the northern Lorillard belt. This potential is indicated by a relatively short (<30 km) southeast-trending dispersal train of chromite (Fig. 9) and sperrylite grains in till samples.

The detailed study undertaken near the marine limit indicates that marine reworking slightly modified the till composition by changing its texture that resulted in mineral partitioning. Till in frost boils directly below the marine limit shows a slight sand enrichment and relative clay depletion as a result of winnowing by waves - changes not particularly apparent with field observations. However, provenance remains the dominant factor controlling till composition and can explain ~80% of the variation at the two sites studied using principal component analysis of the geochemical datasets.

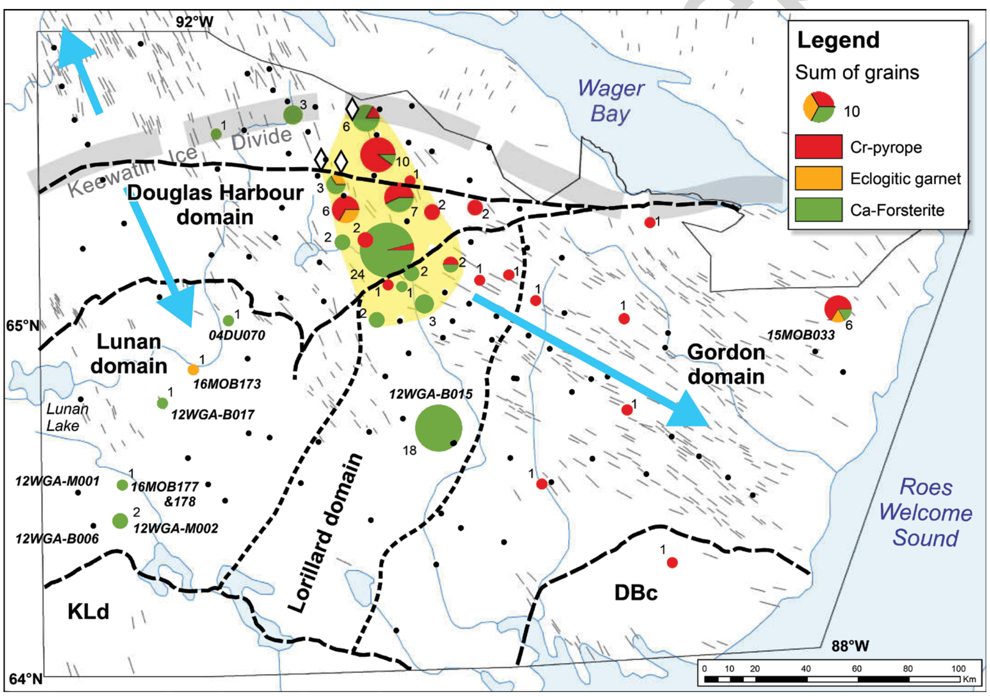

Figure 8. *Proportional-dot map of the sum of Cr-pyrope, eclogitic garnet and Ca-forsterite grains in surface till samples across the region south of Wager Bay, Nunavut. A kimberlite indicator-mineral dispersal train trending south-southeast from the Nanuq kimberlites is indicated in yellow. White diamonds indicate location of known kimberlites. Blue arrows indicate regional ice-flow directions. Figure along with bedrock domains and streamlined landforms are from McMartin et al. (2019a).*

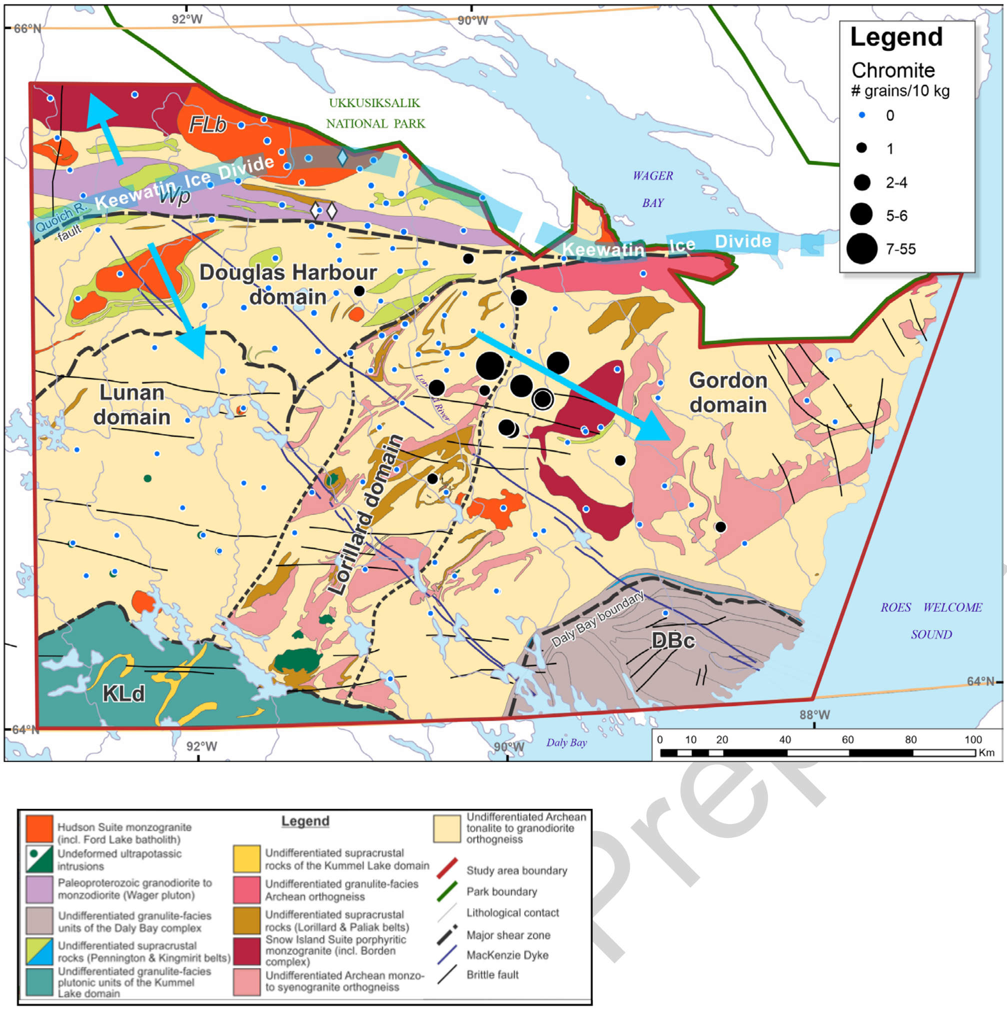

***Figure 9.** Proportional dot map of chromite abundance (normalized to 10 kg) in the 0.25–0.5 mm heavy-mineral fraction of surface till samples across the region south of Wager Bay, Nunavut. Blue arrows indicate regional ice flow directions. Figure along with bedrock geology from McMartin et al. (2019a).*

Ellice River-Thelon Tectonic Zone

Regional stream sediment and water samples were collected in the Ellice River area (see area 12 in Fig. 1), southeast of Bathurst Inlet, Nunavut as part of the GEM Frontiers' Chantrey project (McCurdy et al., 2013b, 2016b). Sampling was conducted to help evaluate resource potential of one of the most remote and poorly understood regions of Canada's north, the Thelon Tectonic Zone (TTZ), which separates the Slave and Rae cratons. These results complement till sampling to characterize regional glacial transport along transects across the TTZ (McMartin and Berman, 2015; McMartin, 2017) as well as the Queen Maud block and adjacent Rae craton to the east (McMartin et al., 2013c).

Targeted stream sediment and till sampling in 2016 (McCurdy and McMartin, 2017) focused on following up on three geochemically anomalous areas identified by the initial stream sediment surveys (McCurdy et al., 2013b, 2016b) and till sampling (McMartin et al., 2013c; McMartin and Berman, 2015):

1) *Northwestern NTS map area 76-I associated with Slave supracrustal rocks*: previous GSC sampling identified a Cu-Pb-Ni-Zn-Ag stream sediment anomaly and high counts of chalcopyrite, molybdenite, pyrite, and gahnite grains in the stream sediments (McCurdy et al., 2016b). Elevated Cu and other base metals (Pb, Ni, Zn) and chalcopyrite grains in stream sediments and tills collected in 2016 further emphasize the base metal potential of this area. Gold grains in both stream and till samples in the same area indicate a potential source or sources of precious metals within metasediments and/or metavolcanic rocks of the Slave craton.

2) *Central NTS map area 76-H southwest of Duggan Lake*: previous GSC till and stream sediment sampling identified an area of Cu-Pb-Zn-As-sulphide in till and stream sediments (McCurdy et al., 2013b, 2016b; McMartin and Berman, 2015; McMartin, 2017). Resampling in 2016 up-ice and up-stream of the anomaly identifies signatures from two distinct sources: a) a strong As±Bi-arsenopyrite-loellingite-hercynite±scheelite anomaly between metasedimentary rocks of the Ellice River domain and the main leucogranite belt, potentially indicative of contact metamorphic or Ni-Cu massive sulphide mineralization; and b) a Cu-Pb-Zn-Ag±Mo±W-chalcopyrite-sphalerite-molybdenite anomaly associated with the Ellice River domain, particularly mafic volcanic rocks.

3) *Southeastern NTS map area 76-H*: a gold anomaly was identified in stream sediments in a single watershed draining south into the Back River by McCurdy et al. (2013b). Follow-up sampling in 2016 confirms the 2013 data. Field work suggests that this anomaly may be sourced within the drainage basin in a region within metamorphosed iron formation at high grade.

A till provenance study along two transects across the Dubawnt Lake Ice Stream (DLIS) was carried out to assess the potential influence of fast ice flow on sediment transport (McMartin, 2017). Major changes in clast content, texture and geochemical composition were observed in till collected over and beyond the ice stream footprint. The till composition over the DLIS reflects a distal provenance, rich in Dubawnt Thelon Basin sandstone debris, and depleted in most trace and major elements, while beyond the ice stream, till composition reflects a more local provenance, derived from the underlying TTZ rocks. A ratio of total versus partial concentrations of Sr in till was used to evaluate glacial dispersal from the Thelon Basin and as an aid to surface mineral exploration.

Mary Frances Lake-Whitefish Lake-Thelon River area

GEM-funded till sampling was undertaken in 2012 in a small area east of the Mineral and Energy Resource Assessment (MERA) survey of the Thaidene Nene National Park Reserve region including, and east of, Great Slave Lake (see area 13 on Fig. 1). This earlier study had identified elevated contents of chromite, olivine, and Cr-diopside in till and esker sediments whose source was suspected to be east of the MERA study area (Kjarsgaard et al., 2013a, b,c). Highlights of the combined MERA + GEM till and esker survey are summarized below from Kjarsgaard et al. (2014a, b) and Knight et al. (2013a).

Till cover in the easternmost part of the combined MERA-GEM study area is more contiguous, thicker (1-3 m), and silica-rich (>94 wt% SiO_2). Till thickness and silica content decrease westward across the study area. This pattern is not unexpected because the till was derived from quartz sandstone in the Thelon Basin further east. Sandstone debris was glacially dispersed across the study area by westward radial glacial flow (Fig. 10a). The local sandstone-rich till dilutes the geochemical and mineralogical signatures of local bedrock in the areas of highest silica content and thickest till. The dilution is an important consideration for till sampling as part of mineral exploration programs that has also been demonstrated in other GEM glacial dispersal studies (Tremblay and Paulen, 2012; Campbell et al., 2016).

To identify geochemical patterns and anomalies that are obscured by the SiO_2 dilution, the authors normalized till geochemical data to SiO_2 content, using total Cr (borate fusion) as an example. With normalization, elevated Cr content in the till decreases down ice towards the west for 80 km (Fig. 10b). This Cr distribution in the till matrix combined with elevated chromite abundance in till and esker samples just east and west of Williams Lake suggests the presence of an unknown bedrock source close to Williams Lake.

Nueltin Lake area, Nunavut

Archived GSC lake sediment samples collected in the 1970s in the Nueltin-Kasemere lakes area, northern Manitoba (see area 14 in Fig. 1) were reanalyzed as part of the GEM Chesterfield Gold Project (McCurdy et al., 2012b). One interesting aspect of the new dataset is that areas of high concentrations of light REEs (Ce, La, Nb) and Y in the lake sediments (Fig. 11) correspond closely to Nueltin granite plutons. One large anomaly in the east part of area, shown in Figure 11, is not associated with any mapped granitic body and indicates the possible existence of unmapped Nueltin granite plutons in the region and the potential for lake sediment geochemistry to be used to identify them (Scott et al., 2012). Subsequently, Hayward et al. (2013) and Harris and Grunsky (2015) used the new lake sediment data combined with airborne geophysical data to create predictive bedrock geology maps that could be used where the bedrock geology is poorly known and to focus future field work in areas where the predicted and legacy bedrock geology were not the same.

Southeastern Northwest Territories and northern Saskatchewan

As part of the GEM South Rae project, regional-scale till sampling was conducted in the southeastern Northwest Territories (see area 15 in Fig. 1) – an area blanketed by large expanses of till that impede bedrock mapping and mineral exploration. Highlights from Pehrsson et al. (2015) and Campbell et al. (2016) reveal the area has a complex ice flow history. Well-defined indicators in cross-cutting relationships reveal a regional clockwise rotation in deglacial ice-flow directions revolving from an early southward to a late deglacial westward flow. The presence of Barrenlands Group (Thelon Basin) sandstone clasts in the southwest part of the study area are the net result of older southward ice flow followed by younger southwest ice flow (Fig. 12a). The sand content of the till matrix in the study displays a similar pattern of decreasing content from very sand-rich (>80 %) in the northeast to <65% in the southwest, reflecting glacial erosion of the quartz-rich sandstone and conglomerate in the Thelon Basin 20 km to the N-NE (Fig. 12a). A preliminary review of the major and trace element till data indicates that SiO_2 and inversely Al_2O_3 (local bedrock component proxy) best reflect the sandstone content of the till (Fig. 12b) despite the likely uptake of additional silica from local bedrock. The distally-derived sand-rich till in the NE part of the study area masks the geochemical signature of the local bedrock. Regional trace element patterns for the till matrix reflect the local bedrock domains suggesting there is a significant locally-derived component (<1km) in the till. Detailed reporting of till indicator and geochemical data will be published in the near future (Campbell et al., 2020).

Other GEM South Rae geochemical studies included reanalysis of archived GSC lake sediments collected between 1977 and 1993 (NTS map sheets 74N, O, P, 64L, M) in northern Saskatchewan and (see area 16 in Fig. 1) as part of the South Rae project (McCurdy et al., 2015). New lake sediment samples were collected in the Abitau Lake area, immediately to the north (McCurdy et al., 2016a). Copper data for these two surveys were combined with those for the GEM reanalysis of archived samples in NTS map sheets 75C, F and K (McCurdy et al., 2016d) and are plotted together in Figure 13. The high concentrations northeast of the east end of Lake Athabasca occur in an area of known Cu and Ni showings and may be of interest for Ni-Cu exploration (Acosta-Góngora et al., 2017).

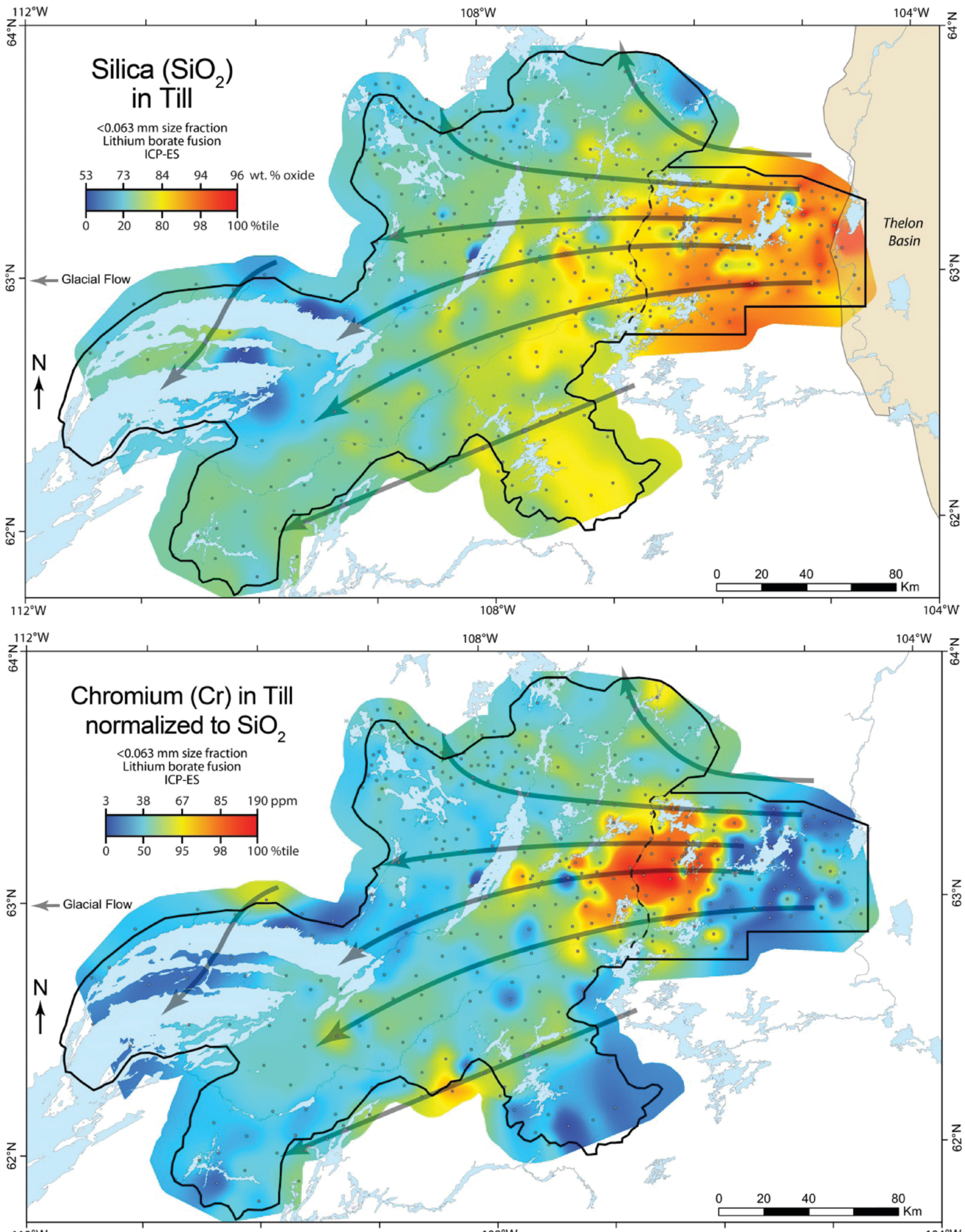

***Figure 10**. **a)** Concentration of SiO_2 in till determined by borate fusion followed by inductively coupled plasma atomic-emission spectrometry (ICP-ES) and shown as an interpolated surface. Content of SiO_2 in till decreases westward with increasing distance down ice from the Thelon Basin quartz sandstone, the bedrock source of the SiO_2-rich debris. **b)** Concentration of Cr*

determined by borate fusion followed by ICP-ES in the fraction of till smaller than 0.063 mm normalized to SiO_2 and shown as an interpolated surface. From Kjarsgaard et al. (2014a).

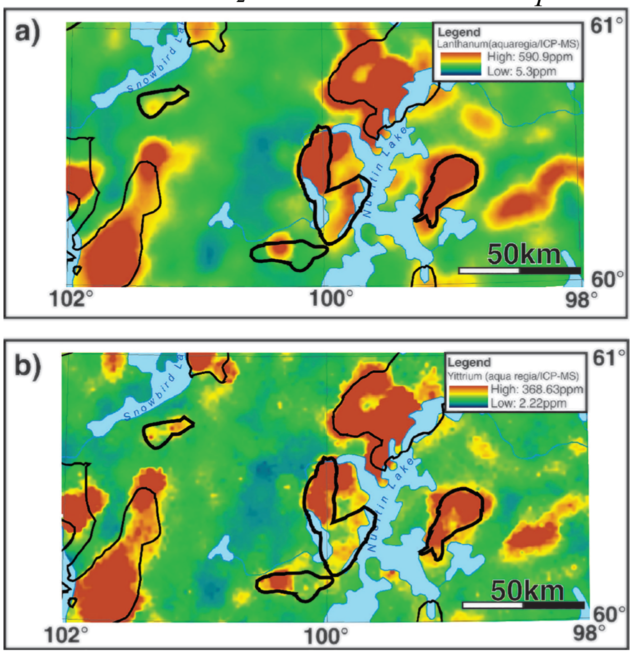

Figure 11. *Interpolated geochemical maps for* ***a)*** *lanthanum (La) and* ***b)*** *yttrium (Y) concentrations determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry in the fraction smaller than 0.177 mm of lake sediments from the Nueltin Lake area, Nunavut. High concentrations of La and Y correlate strongly with the areal extents of known Nueltin plutons outlined in black. From Scott et al. (2012).*

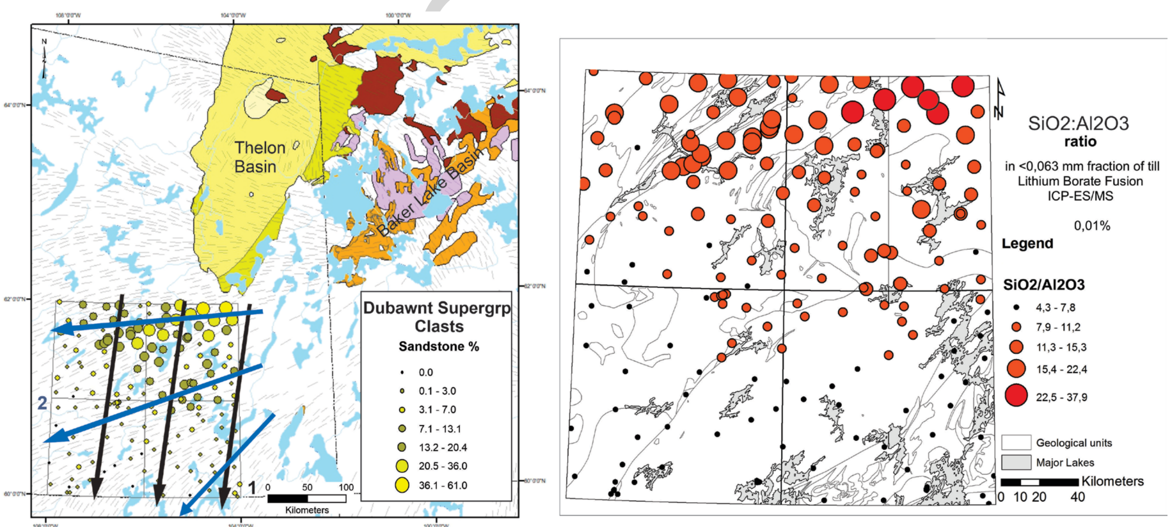

Figure 12*. **a)** Proportional-dot map of Thelon Basin (Barrenlands Group) sandstone-clast abundance in till in the southeastern Northwest Territories study area. Concentrations in till decrease from northeast to southwest down ice from Thelon sandstone bedrock (yellow polygon), a pattern similar to the decreasing sand content of the till matrix. This distribution of clasts and sand-rich till is the net result of older ice flow (black arrows) to the south followed by younger ice flow to the southwest (blue arrows). Glacial lineations (grey lines) are from Prest et al. (1968).* ***b)*** *Proportional-dot map of the ratio SiO_2:Al_2O_3 determined by borate fusion followed by inductively coupled plasma atomic-emission spectrometry/mass spectrometry of till from the boxed area*

shown in (a). The ratio is a useful chemical proxy for identifying distally derived sandstone in the till. From Campbell et al. (2020).

Southwestern Northwest Territories

As part of the GEM Mackenzie project, regional-scale stream sediment and water sampling and till sampling were carried out across the southwest Northwest Territories (see area 17 in Fig. 1) (Paulen et al., 2019). The surficial geology of the region had not been mapped and only limited surficial sampling has ever been conducted within it. Despite the presence of the past-producing world-class Mississippi Valley-type (MVT) Pine Point Pb-Zn district on the southern shore of Great Slave Lake and Hannigan's (2006) positive assessment of its Pb-Zn potential, almost no other mineral showings have been reported in the region.

Stream sediments and tills contain significant numbers of sphalerite (Fig. 14a), galena (Fig. 14b) and chalcopyrite grains in samples far to the west (down ice) of the Pine Point District (Day et al., 2018; Paulen et al., 2018). Sulphur and Pb-isotopic compositions of galena grains indicate that their source(s) is MVT-type mineralization, but not from Pine Point (King et al., 2018, 2019). The low hardness of galena (2.5) and its brittle nature combined with dispersal studies already conducted at Pine Point (McClenaghan et al., 2018) suggest that undiscovered buried bedrock surface sources for the galena are possibly no more than 1 km away from highly anomalous sample sites. Chalcopyrite grains may have been sourced from sediment-hosted Cu mineralization, as indicated by the significant variations in $\delta^{34}S$ values (King et al., 2018). Arsenopyrite grains have $\delta^{34}S$ values similar to orogenic Au deposits near Yellowknife, 400 km to the northeast, indicating that grains may have been eroded from similar style Au deposits in the study area (King et al., 2018). Additional GEM stream sediment and till indicator and geochemical data for southwest Northwest Territories will be published and these will help to further refine exploration targets for follow up.

East-central Manitoba

In east-central Manitoba, GEM reconnaissance-scale surface till sampling was carried out in the Great Island-Caribou Lake area (see area 18 in Fig. 1) in combination with ice-flow indicator mapping to assist in evaluating the mineral potential of the region (Campbell et al., 2012). The till geochemical results provide up-to-date estimates of background and threshold values characteristic of the region, and partly fill in part of a gap in regional coverage (Dredge and Pehrsson, 2006; Dredge and McMartin, 2007).

Further south in the God's Lake area of east central Manitoba (see area 19 in Fig. 1), archived GSC lake sediments collected in 1986 were re-analyzed under the GEM program. Areas of potential interest for mineral exploration are summarized below from McCurdy et al. (2017). Clusters of elevated Au concentrations in lake sediments occur near known gold occurrences and as well as near Joint Lake, Bigstone Lake, Knee Lake, and north of Island Lake. Silver concentrations in lake sediments are highest northeast of known Ag-bearing showings on Island Lake and around Beaver Hill Lake, west and south of Oxford Lake and southeast of Knee Lake. The highest Ni (Fig. 15) and Cu concentrations in lake sediments occur in areas of known Ni mineralization around Island Lake, as well as around Beaver Hill Lake, Cinder Lake, Oxford Lake, Knee Lake, Bigstone Lake, and Atik Lake. Concentrations of Li and REE in lake sediments are highest around known pegmatites and carbonatites as well as in areas of unknown potential.

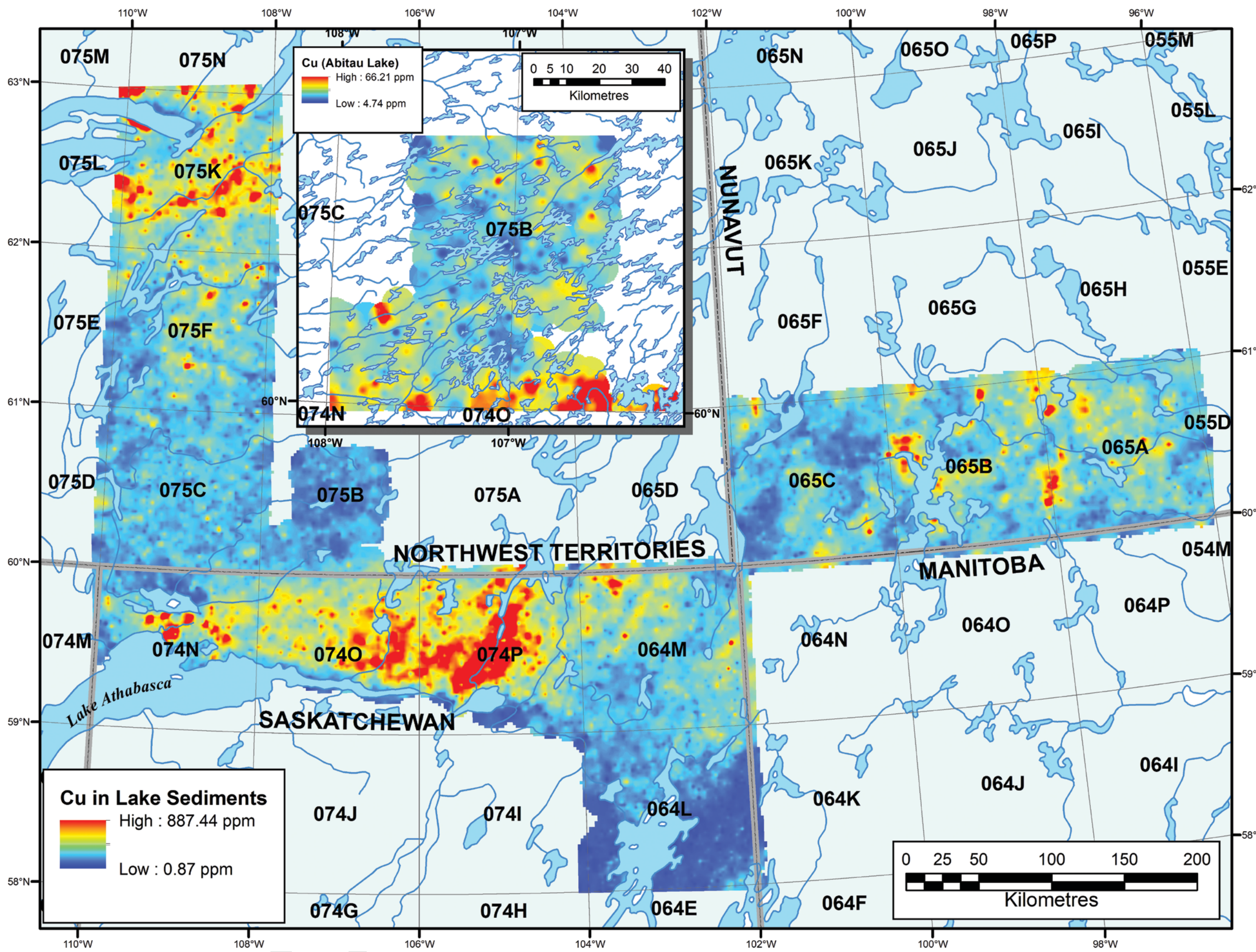

Figure 13. *Interpolated map of copper (Cu) concentrations in the fraction smaller than 0.177 mm of lake sediments in the southern Northwest Territories and northern Saskatchewan; inset map shows Cu data for lake-sediment samples in the Abitau Lake area (NTS 75B). Data from McCurdy et al. (2012b, c, 2015, 2016a).*

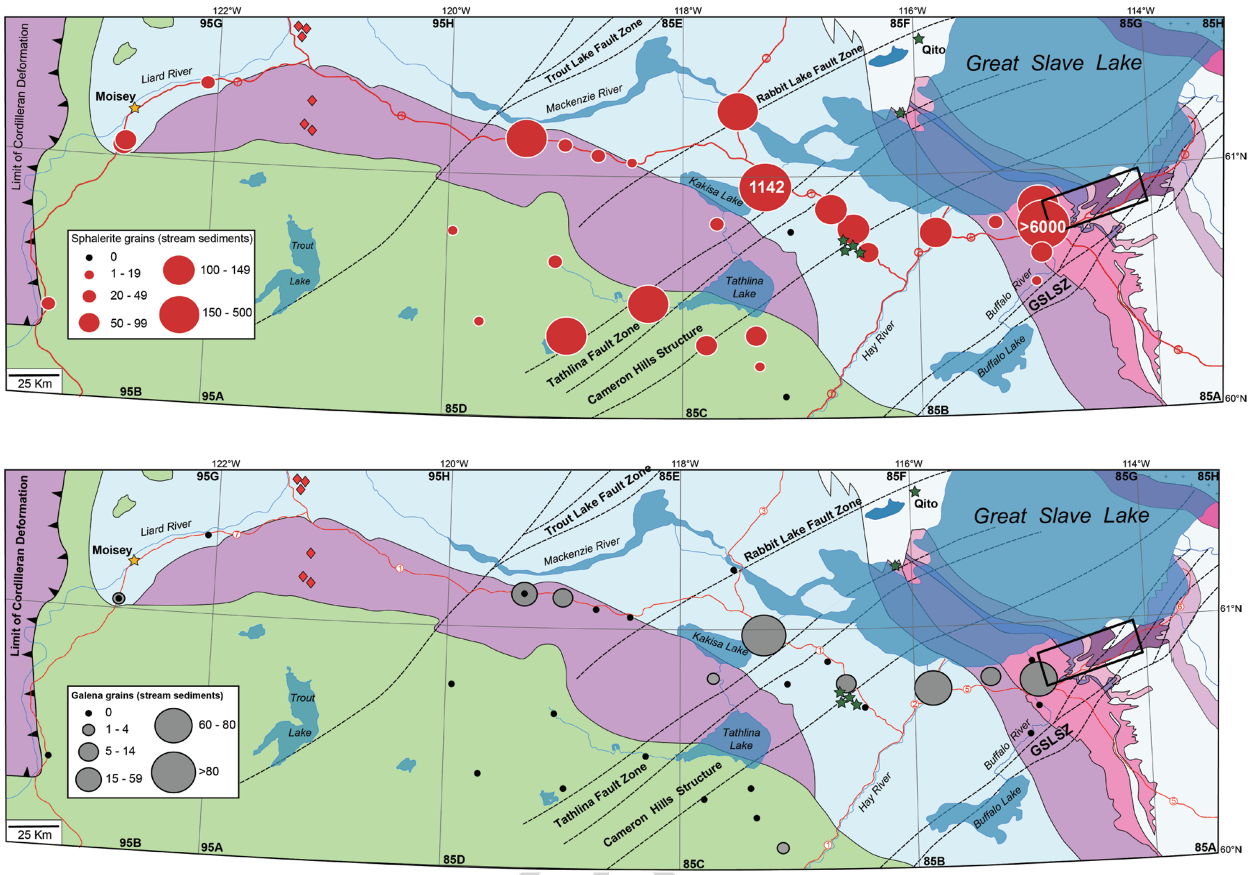

***Figure 14**. Proportional-dot maps of abundance of **a)** sphalerite and **b)** galena grains in the 0.25–0.5 mm heavy-mineral fraction (normalized to a 50 g heavy-mineral fraction weight) of stream-sediment samples in the southwestern part of the Northwest Territories. The large rectangle outlined in black represents the Pine Point Pb-Zn mining district. From Paulen et al. (2018).*

Snyder–Grevstad lakes area, northwestern Manitoba

As part of GEM, a regional till geochemical study was carried out in 2011 in the far northwestern corner of Manitoba (see area 20 in Fig. 1). The work was conducted in conjunction with detailed bedrock mapping to provide a modern geoscience knowledge base and provide baseline data for regional mineral exploration (Trommelen et al., 2013). This area has a complex ice-flow history consisting of at least five different phases that are recorded by erosional ice-flow indicators and streamlined landforms. Regional-scale surface till sampling was accompanied by a small, local study of dispersal from uranium mineralization that demonstrates dispersal by different ice flow events. In general, U and Th content in till appears to be associated with elevated concentrations of calcareous clasts and higher concentrations of reductant phases such as graphite/molybdenite–bearing clasts in the till. Even though most surface till deposits are streamlined landforms, glacial transport distance of subglacial till appears to be short (<500 m). Geochemical anomalies in till that are not related to known bedrock mineralization in the study area occur in two till samples in the northeast part of the study that contain high (>99th percentile of this dataset) concentrations of most analyzed elements. These high values in till likely indicate the presence of polymetallic-type mineralization, containing base and precious metals and REE, that may be skarn-related.

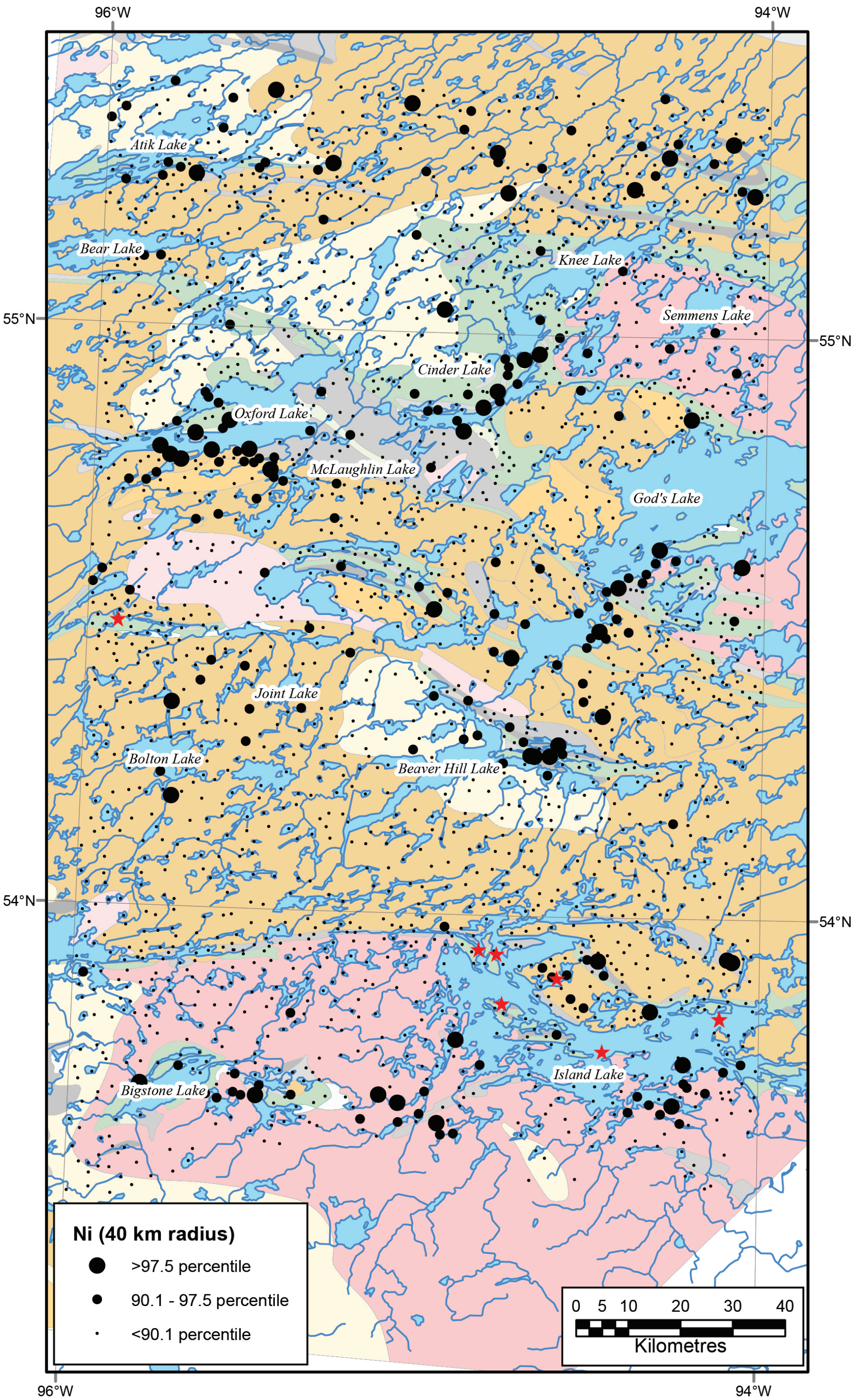

Figure 15. *Proportional-dot map of nickel (Ni) concentrations in the fraction smaller than 0.177 mm of lake sediments determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry in the Gods Lake area, Manitoba. Value at each sample site represents the rank with respect to all values within a radius of 40 km. The location of known mineral occurrences that contain Ni as a commodity are indicated with red stars. Bedrock geology and figure from McCurdy et al. (2017).*

DEPOSIT-SCALE SURVEYS

In addition to GEM regional-scale till sampling surveys, detailed till sampling studies were conducted by the GSC around the following known mineral deposits: i) Izok Lake volcanogenic massive sulphide deposit, ii) Kiggavik U deposit, iii) Pine Point Pb-Zn Mining District, iv) iron oxide copper gold (IOCG) deposits in the Great Bear Magmatic Zone, and v) Strange Lake rare earth element (REE) deposit. Some GEM support was also provided to the study around the Amaruq gold deposit (de Bronzac de Vazelhes, 2019; de Bronzac de Vazelhes et al., 2021). Highlights from four of these case studies are described below.

Izok Lake Zn-Cu-Pb-Ag VMS deposit

The Izok Lake VMS deposit in western Nunavut (Fig.1) is one of the largest undeveloped Zn-Cu VMS resources in North America (Morrison, 2004). This site was chosen for detailed till sampling as part of the GEM Tri-Territorial Indicator Mineral project because the deposit was in an area affected by a complex ice flow history and was known to contain gahnite (Spry and Scott 1986a, b; Heimann et al., 2005; Gosh and Praveen, 2008; O'Brien et al., 2014), a Zn-spinel that is visually distinctive (Fig. 16) and physically robust. Using gahnite, glacial dispersal from the deposit was shown to be a complex, fan-shaped train that was formed by two main ice-flow phases, an older southwest ice flow and younger northwest ice flow (Fig. 17) (McClenaghan et al., 2012a, b,2013b, 2015; Paulen et al., 2013). Re-examination of archived GSC till heavy mineral concentrates to look for gahnite revealed that the gahnite dispersal fan extends at least 40 km down ice (Fig. 18). The recognition of the fan-shaped pattern emphasizes the importance of field-based ice-flow indicator mapping to document all phases of glacial flow, not just the most recent one, when conducting regional till surveys or exploration programs and the value of heavy mineral concentrate archives. The GEM program also supported Makvandi et al. (2015, 2016a, b) in their investigation of the utility of magnetite as an indicator mineral for detecting VMS mineralization in glaciated terrain.

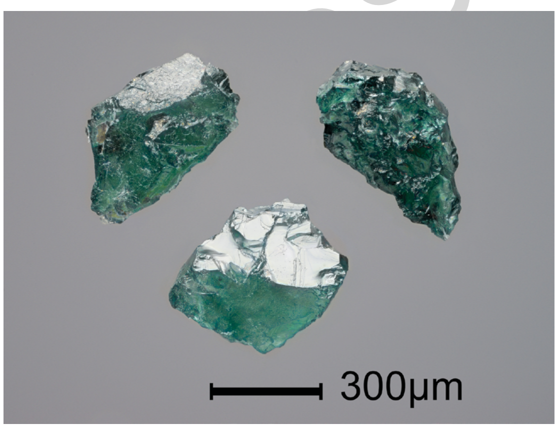

***Figure 16**. Colour photograph of blue-green, sand-sized gahnite grains used as an indicator mineral to map dispersal from the high-grade metamorphosed Izok Lake volcanogenic massive sulphide deposit, Nunavut. Photograph by Michael J. Bainbridge Photography.*

Glacial dispersal of metal-rich till from the Izok Lake VMS deposit was detected up to 6 km down ice using till geochemistry of closely spaced (500 m) till samples (Hicken et al., 2012; McClenaghan et al., 2012a, 2015). Indicator elements for the deposit include Cu, Pb, Zn, and Ag, and pathfinder elements include As, Bi, Cd, Hg, In, Sb, Se, and Tl.

The Izok Lake case study confirms that till sampling is a viable VMS exploration method in the region and demonstrates that indicator minerals and till geochemistry (transport data) combined with detailed ice-flow mapping define a palimpsest pattern of glacial dispersal in the region. Results from this case study suggest that the 5 to 10 km sample spacing from the GSC's 1994 reconnaissance-scale till geochemistry survey (Dredge et al., 1996) was too large to detect geochemical dispersal patterns from the Izok Lake deposit but was useful for detecting gahnite dispersal (McClenaghan et al., 2012b).

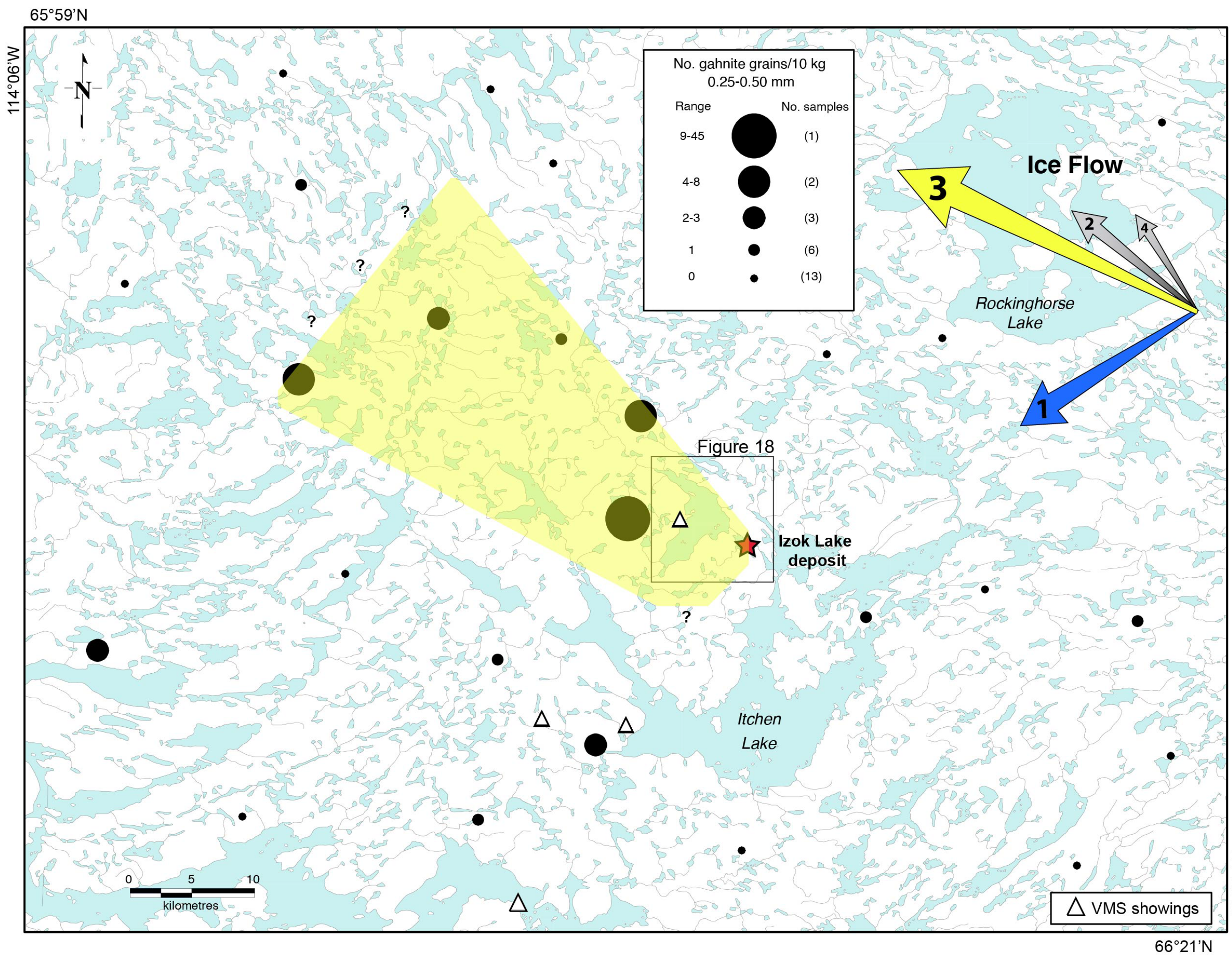

Figure 17. Proportional-dot map of gahnite abundance in surface till normalized to a 10 kg sample mass, showing a 40 km long dispersal fan (yellow polygon) formed by northwest ice flow across the Izok Lake volcanogenic massive sulphide (VMS) deposit. Arrows indicate regional relative ice-flow chronology (1 = oldest) and vigour (arrow size) of flow events. Modified from McClenaghan et al. (2015). Location of gahnite samples from Figure 18 is shown.

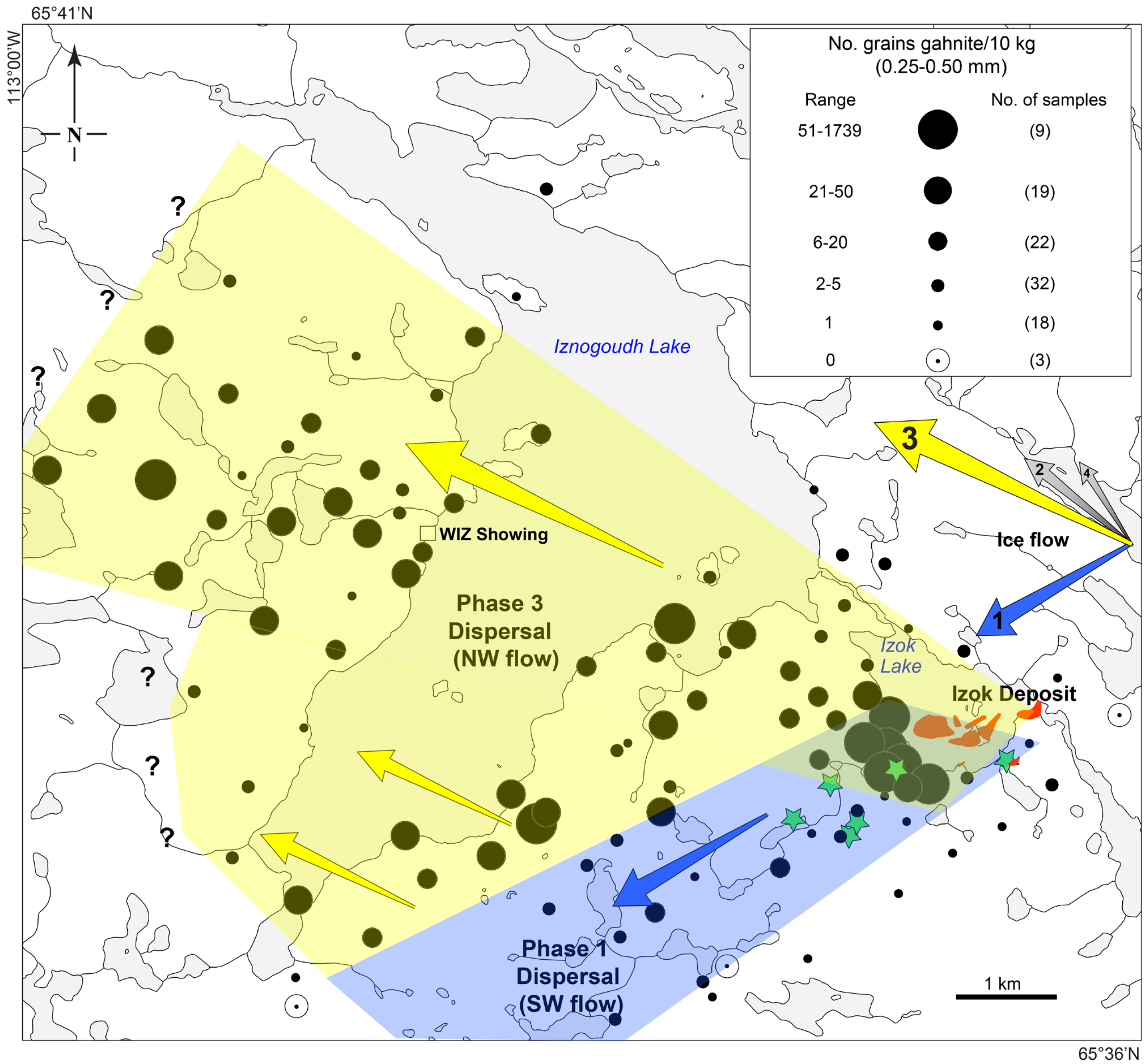

Figure 18. *Proportional-dot map of gahnite abundance in surface till normalized to a 10 kg sample mass around the Izok Lake volcanogenic massive sulphide (VMS) deposit, showing the proximal part of the 40 km long dispersal fan formed by older southwest (blue polygon) and younger northwest (yellow polygon) ice flow across the Izok Lake VMS deposit. Arrows indicate relative ice-flow chronology (1 = oldest) and vigour (arrow size) of flow events. Modified from Paulen et al. (2013) and McClenaghan et al. (2015). Locations of gahnite-bearing rocks at surface indicated by green stars and location of massive sulphide indicated by solid red polygons (unpub. data, MMG).*

Pine Point MVT Pb-Zn deposits

A GEM Tri-Territorial Indicator Mineral Project case study was also conducted in the former Pine Point MVT Pb-Zn mining district in the Northwest Territories (Fig. 1). This study was undertaken to understand the dispersal of Pb and Zn sulphides in a carbonate-rich till (McClenaghan et al., 2012c, 2018; Oviatt, 2013; Oviatt et al., 2013a, b, 2015). Ice-flow history in this region was found to be much more complicated than previously reported by Prest et al. (1968) and Lemmen (1990, 1998a,b). Evidence for multiple ice-flow phases, each with an erosional and depositional record across the district, includes cross-striated bedrock surfaces, streamlined landforms, and till clast fabrics (Rice, 2013; Rice et al., 2013, 2019; Oviatt et al., 2015). At the O-28 open pit, two main phases of ice flow eroded and dispersed metal-rich debris to the southwest and northwest, producing a fan-shaped palimpsest dispersal train defined best by sphalerite (Fig. 19a, b), galena, and Zn (Fig. 19c,d) and Pb concentrations. The last ice-flow phase during deglaciation had a minimal effect on the dispersal train geometry (McClenaghan et al., 2018).

The Ca-rich (~25% CaO) till matrix in the Pine Point region acts as a buffer during surficial weathering and soil formation, maintaining a high soil pH and limiting the oxidation of detrital sulphide minerals in the till. As a result, surface till (0 to 4 m depth) in the district contains large numbers of fresh sulphide grains (Fig. 20). In contrast, carbonate and sulphide minerals in till are easily and quickly destroyed by post-glacial weathering and soil formation in areas of naturally carbonate-poor till (e.g., Canadian Shield, Appalachians, Cordillera; cf., Shilts, 1975, 1976, 1996; McMartin and McClenaghan, 2001; Averill, 2014). Pathfinder elements in the till matrix that also help define dispersal from the MVT deposits in the District include Zn, Pb, Cd, Tl and S.

Oviatt et al.'s (2015, 2017) comparisons of S and Pb isotopes for galena and sphalerite in bedrock and till indicate that minerals derived from Pine Point-type mineralization can be distinguished from those sourced from other types of carbonate-hosted mineralized systems (e.g., Cordilleran Zn-Pb deposits). Furthermore, their work demonstrates that the methods tested here can be used as exploration tools for identifying MVT deposit provenance or potential (e.g. King et al., 2018, 2019).

The Pine Point study confirms that till sampling is a viable exploration method in the carbonate platform of the Western Canada Sedimentary Basin and was the impetus for the GEM Mackenzie regional survey in southwest Northwest Territories (Paulen et al., 2019). In the eastern part of the Pine Point district where the till is generally thin (<5 m), surface till sampling is cost effective; further west where till cover can exceed 30 m overburden drilling methods will be needed to collect till samples at depth (Smith et al., 2019). Indicator minerals and till geochemistry (transport data) combined with the ice-flow data define a palimpsest pattern of glacial transport in the region that should be considered when following anomalies in till or stream sediments.

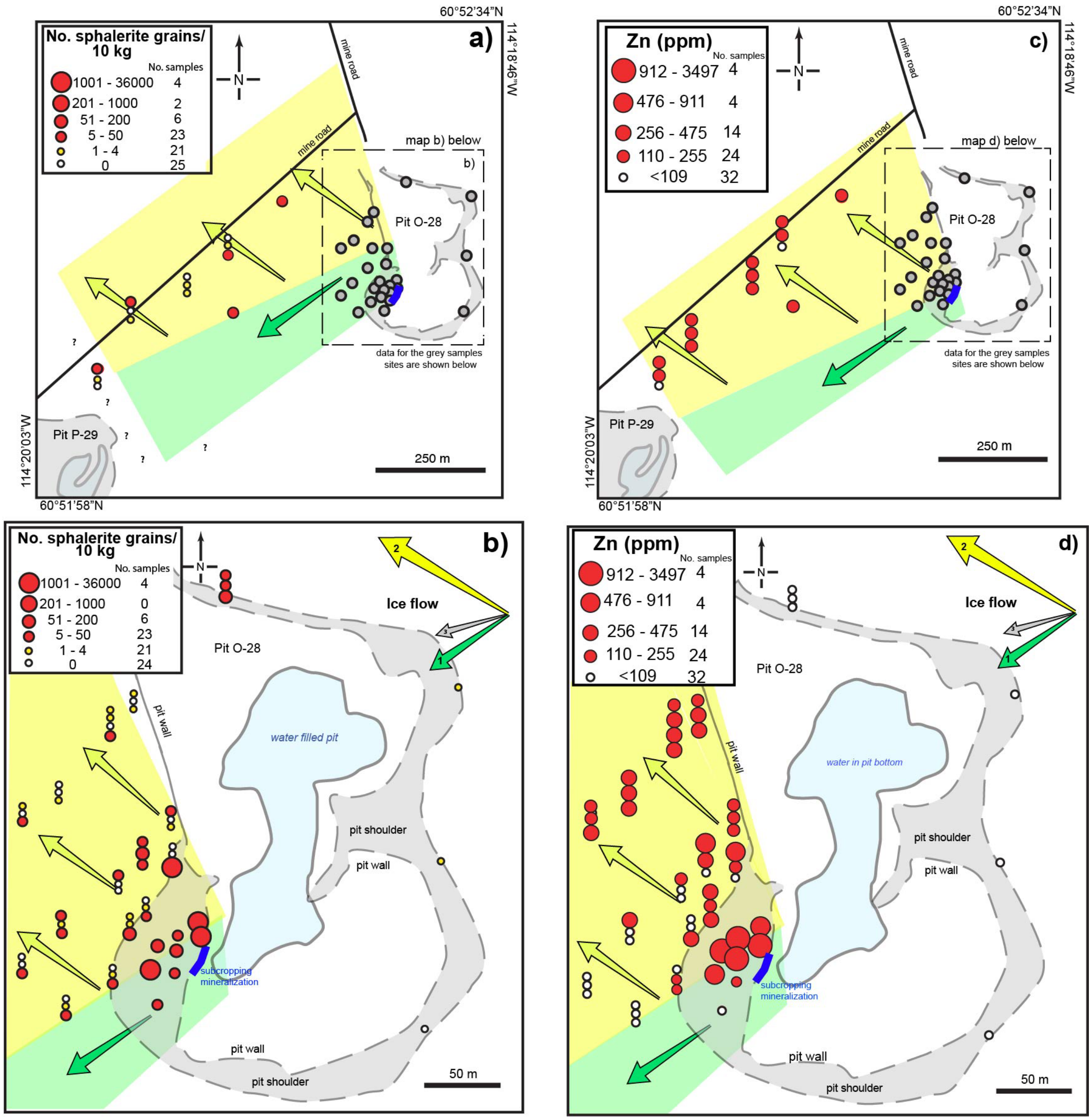

Figure 19. *Till composition and ice-flow trends in the area of pit O-28 in the eastern part of the Pine Point Pb-Zn mining district, Northwest Territories. Distribution of sphalerite grains in the 0.25–0.5 mm nonferromagnetic heavy-mineral fraction of till in the area:* ***a)*** *west and southwest of the deposit; and* ***b)*** *immediately west of the open pit. Distribution of Zn (ppm) in the fraction smaller than 0.063 mm of till in the area:* ***c)*** *west and southwest of deposit; and* ***d)*** *immediately west of the open pit. At sites where more than one till sample was collected at different depths, the data are plotted as vertically stacked symbols. Green polygons outline metal-rich till dispersed by the older southwest ice flow. Yellow polygons outline metal-rich till dispersed to the northwest from the mineralization (blue line) and/or re-entrained from the older southwest dispersal train. White dots indicate barren till samples. Arrows indicate relative ice-flow chronology (1 = oldest) and vigour (arrow size) of the flow events. From McClenaghan et al. (2018).*

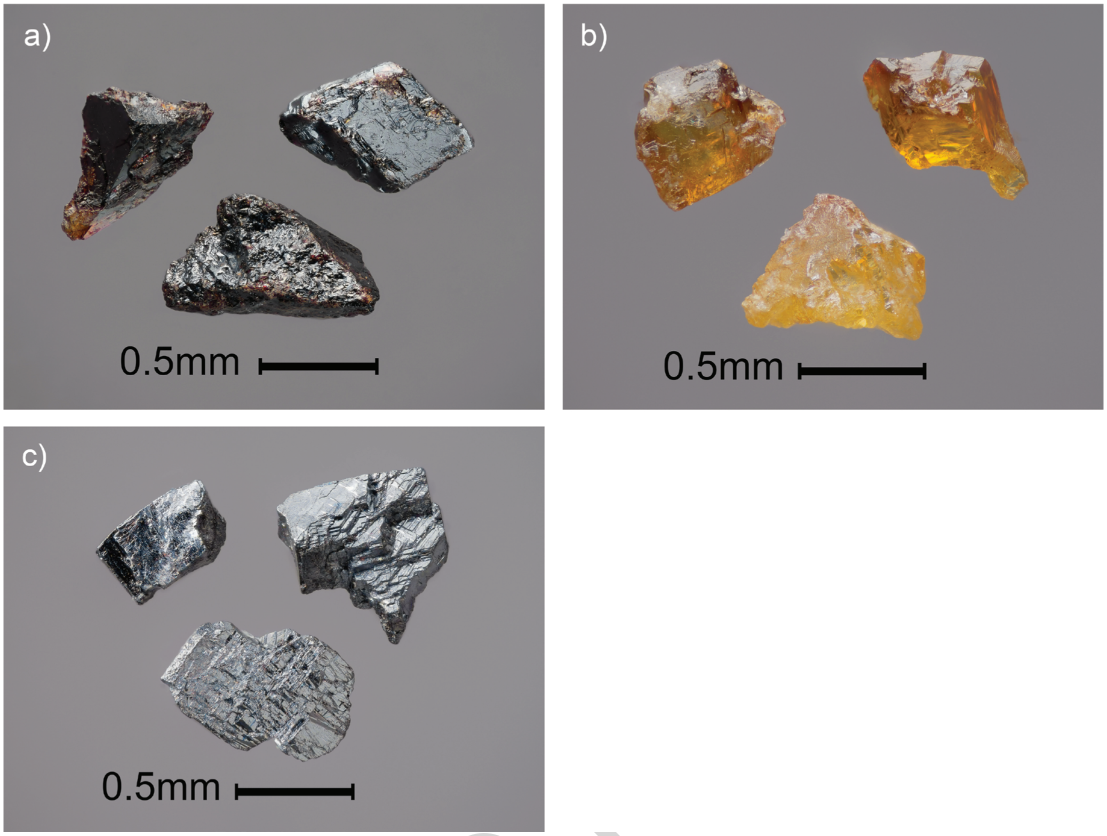

Figure 20. *Colour photographs of indicator-mineral grains recovered from till in the Pine Point Pb-Zn mining district:* ***a)*** *black sphalerite;* ***b)*** *honey brown sphalerite;* ***c)*** *galena. From McClenaghan et al. (2018). Photograph by Michael J. Bainbridge Photography.*

Strange Lake Rare Earth Element deposit

As part of the GEM Hudson-Ungava project, a study of rare earth element indicator minerals and glacial dispersal was carried out at the Strange Lake Zr-Y-heavy REE deposit in northern Quebec and Labrador (Fig. 1). The deposit was discovered in 1979 during the investigation of a GSC lake sediment geochemical anomaly (Hornbrook et al. 1979; McConnell and Batterson 1987; Zajac 2015).

The heavy mineral (>3.2 SG) and mid-density (3.0-3.2 SG) non-ferromagnetic fractions of mineralized bedrock from the deposit and till up to 50 km down ice of the deposit were examined to determine the potential of using REE and high field strength element (Hf, Zr, Nb and Ta) indicator minerals for exploration (McClenaghan et al., 2017b,c, 2019). The deposit contains oxide, silicate, phosphate, and carbonate indicator minerals, some of which (cerianite, uraninite, fluorapatite, rhabdophane, thorianite, danburite, and aeschynite) have not been reported in previous bedrock studies of Strange Lake. Indicator minerals that could be useful in the exploration for similar deposits include: Zr-silicates (zircon, secondary gittinsite and other hydrated Zr±Y±Ca-

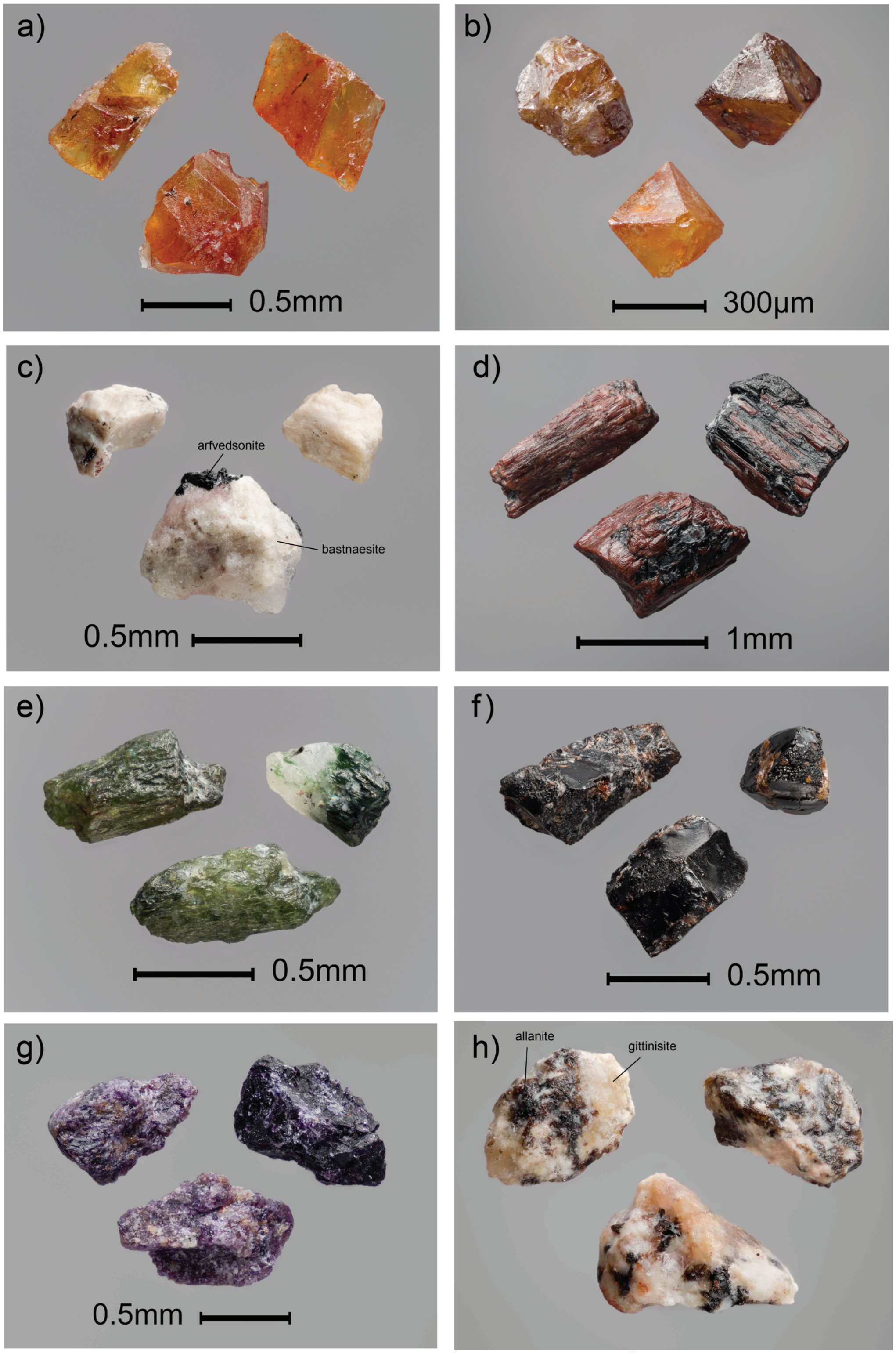

Figure 21. *Colour photographs of selected indicator minerals from bedrock or from till samples overlying and down ice of the Strange Lake rare-earth element deposit:* ***a)*** *orange monazite;* ***b)*** *orange-brown octahedral pyrochlore;* ***c)*** *white bastnaesite grains;* ***d)*** *reddish brown to black fibrous arfvedsonite;* ***e)*** *dark green acicular aegirine;* ***f)*** *black chevkinite;* ***g)*** *dark purple fluorite;* ***h)*** *dark brown allanite intergrown with white gittinsite. Photographs by Michael J. Bainbridge Photography. From McClenaghan et al. (2019)*

silicates), pyrochlore, thorite, as well as REE-minerals monazite, chevkinite, parisite, bastnäsite, kainosite, and allanite (Fig. 21) (McClenaghan et al., 2019).

The Strange Lake dispersal train has a remarkable ribbon-shape that extends more than 50 km down ice to the ENE that is defined by high REE element concentrations in till and equivalent thorium (eTh) values in airborne gamma-ray spectrometry data (Geological Survey of Canada, 1980; Batterson, 1989; Batterson and Taylor, 2009; Zajac, 2015; Paulen et al., 2017). The train was originally attributed to a consistent regional ice flow regime of the Laurentide Ice Sheet (Batterson and Taylor, 2009). Recent reconstruction of the Laurentide Ice Sheet history places the Strange Lake train directly within the trunk of the Kogaluk River ice stream (KRIS), one of a number of ice streams that operated near the centre of the Labrador ice dome and drained into the Atlantic Ocean (Margold et al., 2015). This ice stream formed mega-scale glacial lineations (streamlined landforms) up to 5 km long, with length to width ratios exceeding 12 within the train.

Ice streams are corridors within an ice sheet that flow more rapidly than the surrounding ice. They act as arteries to discharge large amounts of ice over large distances and are the source of well-defined trains of far-travelled glacial debris (e.g. Dredge, 2000; Ross et al., 2009). Few studies have focused on the geochemical and mineralogical dispersal patterns formed or modified by ice streams, in part because former ice stream tracts were not previously recognized or identified in areas covered by the Laurentide Ice Sheet. Within KRIS, the concentration gradient of dispersed debris, as shown by Th content in till, decreases linearly down ice (Fig. 22a) as the result of rapid ice flow transporting debris far from source with little dilution, similar to the idealized linear distribution curve of Klassen (1997) (Fig. 22b). Dispersal patterns produced by ice streams in northern Canada, such as the Strange Lake train, may provide additional insight into many unexplained indicator mineral anomalies, the bedrock sources of which remain to be discovered.

This detailed research combined with the new Core Zone regional lake sediments data described above (Amor et al., 2016, 2019; McCurdy et al., 2018), show that the distributions of Hf, Sn and Zr in lake sediments define a glacial dispersal train from Strange Lake that is much longer (150 km) than originally recognized. This study also demonstrates that lake sediment geochemical data can be used to identify glacial dispersal trains formed by ice streams.

Great Bear magmatic zone iron-oxide copper gold deposits

The potential use of till geochemistry and indicator mineral methods to explore for iron oxide copper-gold (IOCG) deposits was evaluated in focused studies around the NICO, Sue-Dianne and Fab deposits (see area 21 in Fig. 1) in the Great Bear magmatic zone (GBMZ) in the Northwest Territories (Normandeau and McMartin, 2013; Lypaczewski et al., 2013; Normandeau, 2018). This research was funded, in part, by the GEM program.

Gold grain abundance, size and shape as well as magnetite and hematite compositions reflect the NICO mineralization in till down ice (McMartin et al., 2011a, b; Dupuis et al., 2012; Sappin et al., 2014). Normandeau et al. (2018) documented apatite texture, geochemistry, and cathodoluminescence response and apatite alteration zones in the GBMZ as a first step in the development of using apatite as an indicator mineral in surficial sediments to detect IOCG deposits.

The vectoring potential of till geochemistry in the GBMZ is variable depending on till cover, size fraction of till analyzed (<0.063 mm vs <0.002 mm), elemental enrichments in individual deposits, and the complexity and size of the bedrock alteration systems (Normandeau, 2018). Anomalous concentrations of Fe, Co, Ni, Cu, As, Mo, Bi, La, Th, U and W in till down ice indicates their potential as vectoring elements within the study area. At the Sue-Dianne deposit, for example, Fe and Co (4-acid/ICP-ES/MS) in the <0.063 mm fraction and Cu (Fig. 23), Mo and Bi (aqua regia/ICP-MS) in the <0.002 mm fraction of till are the most useful pathfinders to mineralization.

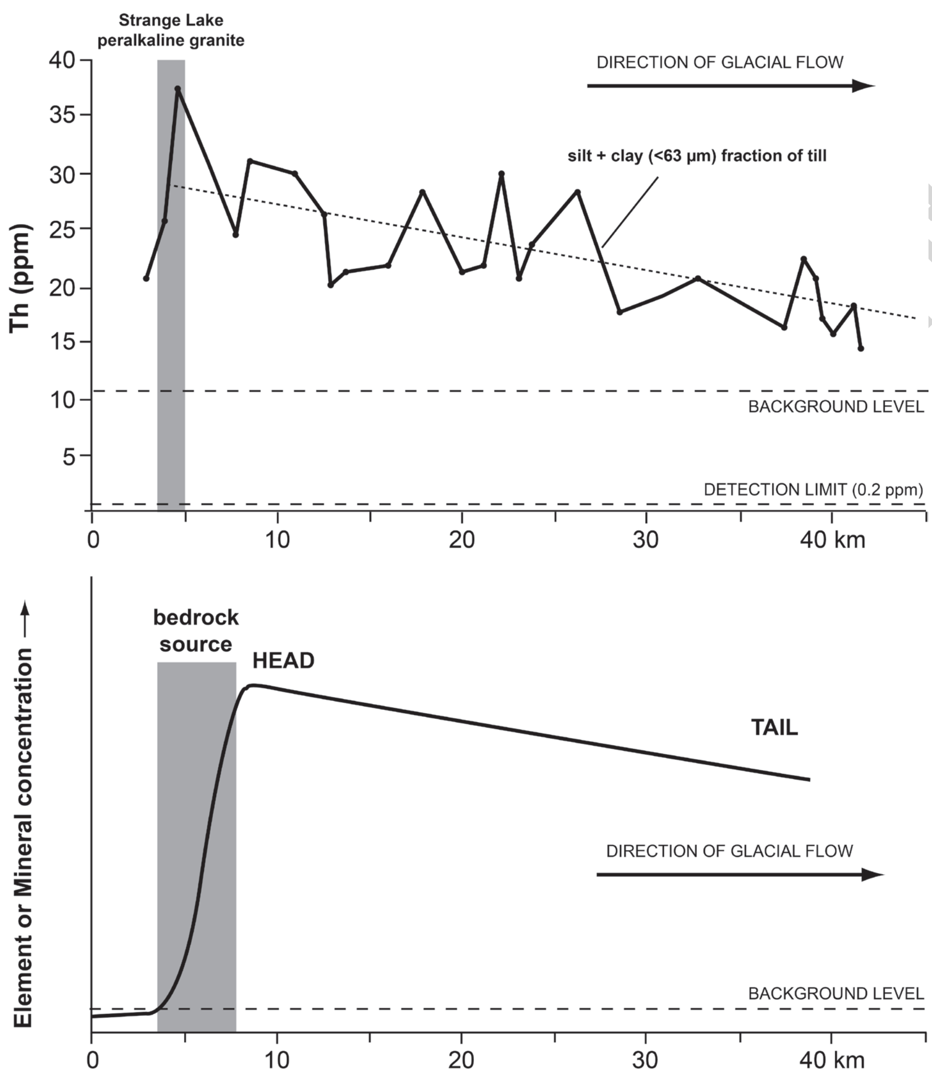

Figure 22. ***a)*** *Line plot of thorium (Th) concentration in the fraction smaller than 0.063 mm of surface till, down ice of the Strange Lake rare-earth element deposit in northern Quebec and Labrador, with the best-fit data curve shown as a dashed line. Data are from Batterson and Taylor (2009).* ***b)*** *Idealized glacial dispersal train, modified from Klassen (1997), showing the linear relationship between the source, head, and tail of a dispersal train formed by a paleoice stream. From Paulen et al. (2017).*

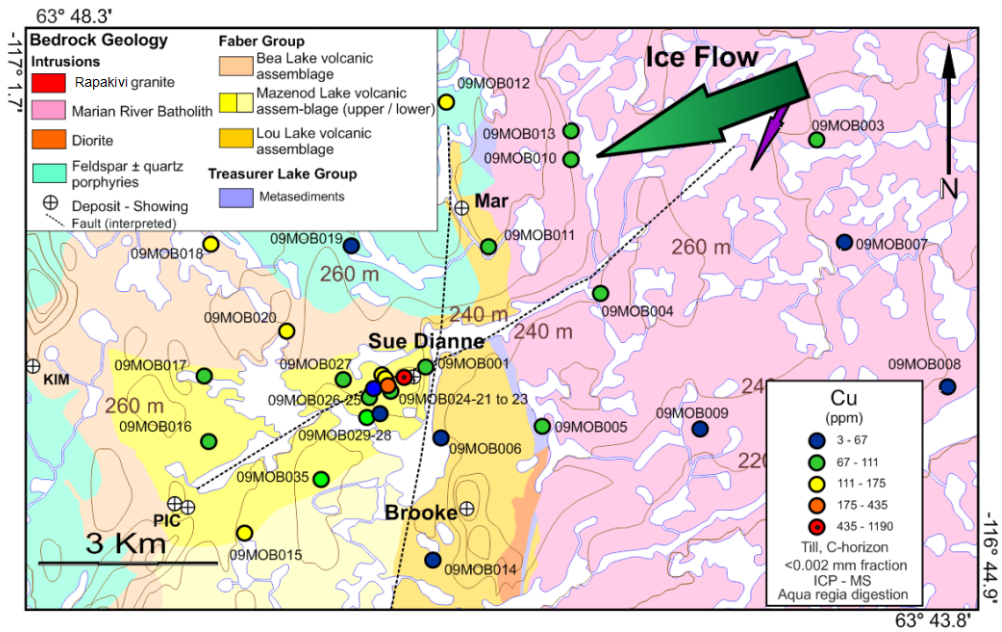

Figure 23. *Dot map of copper (Cu) concentrations in the < 0.002 mm fraction of surface till determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry around the Sue-Dianne Cu-Ag-Au deposit in the Great Bear magmatic zone, Northwest Territories (from Normandeau, 2018).*

REVIEWS OF KEY CONCEPTS AND METHODS

Indicator minerals and till geochemical methods for exploration

The GEM program's contributions to surficial geochemistry and mineralogy include timely reviews of key concepts and methods. The most comprehensive paper is McClenaghan and Paulen's (2018) overview of glacial dispersal processes and the application of drift prospecting to mineral exploration in the glaciated terrains of Canada. These authors review the importance of using both ice-flow indicator data and transport data together to understand the complexity of continental ice-sheet dynamics and the resulting glacial dispersal patterns to successfully search for mineral deposits. Boulder tracing and till geochemistry are well established exploration tools that have been used in Canada for more than 60 years. Indicator mineral methods have become another important exploration tool, especially for the GSC during the past 12 years of the GEM program and throughout the GSC's Targeted Geoscience Initiative (TGI) program (e.g. McClenaghan et al., 2016c). All three of these methods are now used to explore for a broad range of commodities and deposit types in Canada, including diamonds, precious, base and critical metals, and uranium. McClenaghan and Paulen (2018) report examples of till geochemical and indicator mineral signatures for a broad suite of mineral deposit types that include key GEM results.

GEM's contributions to surficial geochemistry and mineralogy also include two sets of conference workshops notes (Paulen and McClenaghan, 2013; McClenaghan and Layton-Matthews, 2017). These notes were written by some of the most experienced government, industry and academic practitioners in their fields. Indicator mineral methods for the exploration for a broad range of deposit types were reviewed, including orogenic gold, diamonds, volcanogenic massive sulphide, porphyry copper, rare metals, and intrusion-hosted tungsten. Topics also included heavy mineral sample processing methods and microanalytical techniques for indicator minerals.

GEM also supported the publication of conference workshop notes which focused on using geochemistry and indicator minerals to assist exploration in northern Canada, the western Interior Plains, and the Cordillera (Paulen and McMartin, 2009). Some of the papers in the workshop notes (e.g., Stea et al., 2009; Paulen, 2009a, b; Campbell, 2009) provided the impetus for GEM research on the use of indicator minerals at Izok Lake, Pine Point, and Kiggavik.

Till sampling protocols

For more than 50 years, researchers at the GSC have developed, tested, and refined till geochemical and indicator mineral methods that are applied to mineral exploration, provenance studies, and environmental research in glaciated terrains across Canada. The cumulative experience and knowledge were used to produce the GSC's first comprehensive field and laboratory methods protocol manual for GEM till geochemical and mineralogical surveys in 2011 (Spirito et al. 2011; McClenaghan et al., 2013a; Plouffe et al., 2013; Geological Survey of Canada, 2017). Because the protocols were so widely used by GSC scientists and clients, they have been updated and expanded to accommodate more detailed explanations, advancing analytical methods, departmental and industry big data initiatives, and new metadata reporting guidelines (McClenaghan et al., 2020).

The new version of the protocol manual presents the major concepts of till as a sample medium and glacial dispersal, as well as field and laboratory procedures. The protocols are used by the GSC to guide till sample collection, sample processing, geochemical and indicator mineral analyses, implementation of quality assurance/quality control (QA/QC) procedures, archiving methods, and data reporting. Using consistent sample media and making diligent field notes and observations are also considered fundamental to the protocols. Adopting a common set of protocols allows the GSC, other researchers, and exploration geologists to directly compare till geochemical and indicator mineral datasets from various parts of Canada and ensures proper minimum levels of QA/QC and metadata reporting for all till geochemical and indicator mineral surveys.

Esker indicator mineral studies

Esker sediments have been sampled to recover indicator minerals to assist in the preliminary stages of diamond and gold exploration of large regions (e.g. Lee, 1965; Pertunnen, 1989; Parent et al., 2002; Brushett and Amor, 2013; Duran et al., 2019). However, indicator mineral dispersal in esker sedimentary systems is poorly understood and the optimal methods to collect esker samples or interpret mineral distribution data have not been established (Cummings et al., 2011). To address these challenges, a preliminary conceptual framework for esker sedimentary systems based on insights from the published literature on modern glaciers, lab experiments, and gravel-bed streams was presented by Cummings et al. (2011) with partial funding provided by GEM. The authors also presented a research strategy that could be carried out to address the knowledge gaps and improve the effectiveness of esker sampling for mineral exploration.

In a study partially funded by GEM, Cummings et al. (2014) conducted one of the first investigations of the rate at which kimberlite indicator minerals break down in a tumbling mill - a proxy for abrasion and breakage during glaciofluvial transport. In the experiment, pyrope grains broke into tens to hundreds of angular fragments, producing abundant sand-sized particles, in addition to abundant silt + clay-sized fragments. Cr-diopside and ilmenite grains remained relatively intact and lost mass primarily by edge rounding, which produced a comparatively small amount of silt and clay-sized fragments and little to no sand-sized fragments. Their results suggest that the relative abundance of kimberlite indicator minerals in glaciofluvial sediments may become progressively finer downstream relative to fragments of other minerals.

Glacial dispersal train map

Partly funded by the GEM program, Cummings et al. (2018) produced a map depicting 52 till dispersal trains for northern Canada that was synthesized from published literature and includes scans of published images of the glacial dispersal trains. Details about how the map was produced are available in Cummings and Russell (2018). The map was published as a compressed digital file (.kmz file) designed to be opened in Google Earth™. It is a useful summary of dispersal train locations that will guide the user to the published detailed information and explanations about individual glacial dispersal trains in a particular region of interest.

METHODS DEVELOPMENT

GEM research included testing of portable X-ray fluorescence (pXRF) spectrometry to determine metal contents of till samples in the field and/or in the laboratory. The technique can be applied using hand-held or bench-top equipment. In the field, it can be used to detect geochemical anomalies and actively guide till sampling (Arne et al., 2014). In the laboratory, it can be used to sequence sediment samples prior to submitting them for conventional laboratory-based geochemical or mineralogical analysis, i.e. so that suspected metal-rich samples can be processed last. Some GEM till sampling surveys took advantage of this new technology by deploying pXRF equipment in field camps to guide daily till sampling (e.g. Plourde et al., 2013; McClenaghan et al., 2014a). Protocols for pXRF sample collection and use in till sampling programs are now part of the GSC's till protocols summarized in McClenaghan et al. (2020).

Several studies report the advantages of applying pXRF analyses to dry versus moist till, unsieved versus sieved till, and making determinations through plastic sandwich bags if nothing else is available (Peter et al., 2010; Hall and McClenaghan, 2013; Plourde et al., 2013; Kjarsgaard et al., 2014a, b; Sarala et al., 2015; Sarala, 2016; Hall et al., 2016). Knight et al. (2013b) and Rukholov (2013) have tested the operating conditions of, and reference materials for, pXRF analysis of sediment samples that can be useful to others using pXRF methods.

CONCLUSIONS AND IMPLICATIONS FOR MINERAL EXPLORATION

• Under the GEM Program, modern geochemical methods were used to determine up to 65 elements for lake sediment, lake water, stream sediment, stream water, and till surveys. State-of the-art indicator methods were used to examine the indicator mineral signatures in regional stream sediment, till and, in two surveys, some esker samples. Using both geochemistry and indicator mineral methods, the GSC generated new data for about 1 million km^2 in northern Canada to assess the potential for hosting precious, base, rare and strategic metals, uranium and diamonds.

• Indicator mineral and till geochemical data are essential components of all GEM surficial mapping projects (Kerr et al., in press). These data provide important insights into till provenance that are essential to understanding and deciphering the complex ice flow history of Canada's north.

• The most immediate impact of the GEM geochemical and mineralogical surveys has been the stimulation of mineral exploration in Canada's north, focussing exploration efforts into high mineral potential areas. Areas were identified that contain significant concentrations of metals and/or indicator minerals that are indicative of bedrock mineralization for a broad range of commodities. The rresults will also help direct the GSC's future regional bedrock and metallogenic mapping activities to where they can be most productive.

• The GSC's archive collection of regional geochemical and heavy mineral samples of lake sediments, stream sediments, and till is a vast and irreplaceable resource. More than 26,000 lake sediment samples covering all or part of 49 NTS map areas were re-analyzed under the GEM program resulting in cost savings of at least $400,000 per NTS map area that would have been incurred to collect new samples.

• Detailed till sampling around known mineral deposits demonstrates how transport data (till geochemistry, indicator minerals) and ice-flow indicator data can be used together to identify and understand complex ice flow and glacial transport histories. Detailed studies of the Izok Lake deposit also demonstrate the robustness of gahnite as an indicator mineral. Studies at Pine Point MVT mining district demonstrate that sulphide minerals are particularly useful indicators in carbonate-rich terrain and that isotopes can help differentiate between bedrock sources of sphalerite and galena grains in till. At Strange Lake and in the GBMZ, new suites of indicator minerals were identified for REE and IOCG deposits respectively, that can now be applied in future reconnaissance- and regional-scale stream sediment and till surveys across Canada.

FUTURE WORK

• Geochemical and indicator mineral mapping coverage of northern Canada is far from complete. GEM geochemical and indicator mineral surveys covered about 1 million km^2 of northern Canada. This new coverage, combined with earlier GSC and territorial geochemical surveys, leaves about 1/3 of Canada's north still to be assessed in the future and the data released to the public.

• Areas such as the Slave Craton that are considered to have high mineral potential should be the priorities for new geochemical and indicator mineral reconnaissance- or regional-scale surveys. The sample medium most appropriate will depend on access, topography, and regional glacial history. The potential role of groundwater as a sample medium in regional-scale geochemical surveys should be assessed.

• Future geochemical research at the GSC should investigate how field and lab geochemical methods such as portable XRF (pXRF), laser-induced breakdown spectrometry (LIBS), and portable Fourier transform infrared spectrometry (pFTIR) can assist delivery of regional geochemical survey results.

• Future indicator mineral research should continue to broaden mineral suites and mineral chemistry for fertility assessments and to test automated mineralogy methods that can be applied to surficial sediments through completion of new case studies around known mineral deposits.

• The GSC archives hold samples from several reconnaissance- and regional-scale lake and stream sediment and till geochemical surveys that have not yet been reanalyzed using modern analytical methods. Reanalysis of these remaining sample sets will prove useful to future GSC bedrock and mineral resource mapping.

• The role of ice streaming on glacial dispersal patterns (geochemical and indicator minerals) is not yet fully understood. Re-examining the glacial landscape of northern Canada using modern glacial concepts and newer high-resolution remote sensing data (McMartin et al., in press), combined with collection of geochemical and indicator mineral (transport) data for areas within and outside of ice streams, will allow better interpretation of unsourced anomalies that occur in surficial sediments and that may be products of long-distance transport by fast flowing ice.

• The influence of relict glacial landscapes on the nature of sediment transport and the impact for surface exploration methods remain poorly known. The interpretation of newly mapped glacial land systems and new ages determined for surface materials (TCN, IRSL, ^{14}C) will help evaluate the significance of inheritance for glacial erosion. The net effect of complex ice flow dynamics and changing basal ice thermal regimes will increase our understanding of sediment provenance in key regions of the Canadian Shield covered by glacial sediments (McMartin et al., in press; Parent, in press; Rice et al., in press; Tremblay and Lamothe, in press).

• GSC protocols for collection and analysis of till, lake, and stream sediments will continue to evolve, including improved analytical methods, lower analytical detection limits, and faster more efficient data capture in the field such as those used in Australia (e.g. Noble et al., 2020).

• GEM and older GSC geochemical and indicator mineral datasets present new opportunities for mineral exploration using artificial intelligence-deep learning initiatives. Combining till and lake and stream sediment data as part of the interpretation will be particularly insightful to data mining and analytics.

ACKNOWLEDGEMENTS

This overview of GEM surficial geochemical and indicator mineral surveys was written with the help of many colleagues, including Roger Paulen, Isabelle McMartin, Janet Campbell, Rod Smith, Dan Kerr, and Tommy Tremblay, who shared geological data, reports, insights, and/or figures. Robert Garrett is thanked for his help with interpretations and assessments of many of the GEM datasets that are summarized here. Shauna Madore and Joeli Plakholm helped to compile GEM geochemical and indicator mineral publications and survey coverage, and sample totals. The GSC Sedimentology Lab staff, Shauna Madore, Miriam Wygergangs, Claudia Moore, and Alain Grenier, are thanked for their expert handling, preparation and archiving of GEM geochemistry samples, and assistance with proof reading. Steve Cook and Roger Paulen are thanked for their thoughtful reviews of the paper. This manuscript was completed during the national COVID-19 lockdown and social distancing in the Spring of 2020. Thanks to all colleagues who endeavored to help with this manuscript in spite of our unusual working conditions.

GEM regional-scale geochemical and indicator mineral surveys and archive sample reanalysis were conducted in collaboration with the Canada-Nunavut Geoscience Office, Manitoba Geological Survey, Geological Survey of Newfoundland and Labrador, Ministère de l'Énergie et des Ressources naturelles du Québec, and the Northwest Territories Geological Survey.

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