Overview of Geo-mapping for Energy and Minerals program surficial geochemistry and indicator-mineral surveys and case studies in northern Canada

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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 methods were used to examine the indicator-mineral signatures identified through 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 Géocartographie de l'énergie et des minéraux (GEM), la Commission géologique du Canada a réalisé, entre 2008 et 2020, des études de cas ainsi que des levés géochimiques et de minéraux indicateurs à l'échelle de la reconnaissance jusqu'à celle d'un gisement dans le nord du Canada. Au cours de ces études, des méthodes géochimiques ont été utilisées pour déterminer les concentrations de 65 éléments dans des échantillons de sédiments lacustres, d'eau de lac, de sédiments de ruisseau, d'eau de ruisseau et de till sur une superficie d'environ 1 000 000 km^2 dans le nord du Canada. Des méthodes de pointe ont été utilisées pour examiner les signatures en minéraux indicateurs mises en évidence dans les levés de sédiments de ruisseau et de till à l'échelle régionale. Ces travaux de recherche ont permis de délimiter des secteurs présentant des concentrations anomales d'éléments et/ou de minéraux indicateurs susceptibles de révéler la présence de minéralisations dans le substratum rocheux. Les travaux ont également permis d'élaborer de nouveaux protocoles et de nouveaux modèles pour l'exploration minérale, de former une nouvelle génération de géoscientifiques et de transférer des connaissances aux communautés nordiques. La répercussion la plus immédiate des levés du programme GEM a été de stimuler l'exploration minérale dans le nord du Canada, où les activités d'exploration ont été concentrées dans des secteurs à fort potentiel minéral délimités par les levés régionaux du programme GEM. Les études menées à l'échelle régionale et à celle d'un gisement ont démontré comment les données relatives au transport glaciaire (géochimie du till, minéraux indicateurs) et les données sur les indicateurs de l'écoulement glaciaire peuvent être utilisées de façon combinée pour identifier et comprendre les écoulements glaciaires complexes et le transport glaciaire qui en découle. Des études détaillées réalisées aux gisements d'Izok Lake, de Pine Point, de Strange Lake et de Kiggavik, ainsi que dans la zone magmatique du Grand lac de l'Ours, ont révélé de nouveaux ensembles de minéraux indicateurs qui pourront être utilisés dans le cadre des futurs levés de reconnaissance et levés régionaux du till et des sédiments de ruisseau dans tout le Canada.

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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 as well as for diamonds using surficial methods
3. a new generation of professional personnel was trained through collaborative research partnerships with research organizations and academia, courses taught at universities, short courses given at conferences, and publication of journal papers and special volumes, and
4. knowledge transfer to northern communities was accomplished through consultations, presentations, hiring of local field personnel, 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, with 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 mineral deposits. The GEM geochemical and heavy-mineral surveys and case studies listed in appendices A and B are too numerous to accurately describe all results achieved; therefore, highlights from selected GEM regional-scale surveys and case studies are reported here. The highlights below include figures

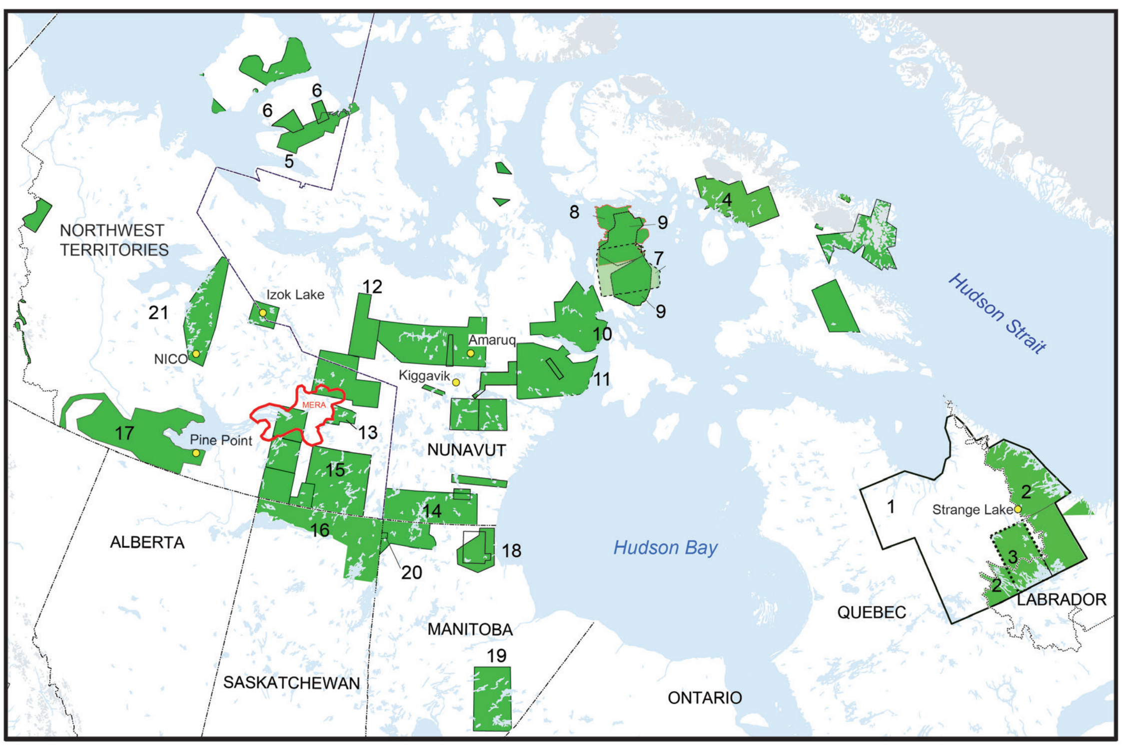


Figure 1. Locations of the reconnaissance- and regional-scale lake-sediment, stream-sediment, and till geochemical surveys conducted as part of the Geo-mapping for Energy and Minerals (GEM) program across northern Canada are indicated by green polygons. The large area covered by the joint GSC–Quebec–Newfoundland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

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 to characterize regional elemental and mineralogical concentrations and delineate anomalies as an aid in targeting future exploration at the broad scale of geological provinces down to that of 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

Sediment and water sampled from the centre of lakes

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 drainage systems (Friske, 1991). Samples are collected from the centre of lakes or the centre of bays in large lakes, away from inflows and outflows. Lake sediments consist 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 (1976), Jonasson (1976), Coker et al. (1979, 1980), and Friske (1991):

- *Inorganic sediments*: mixtures of sand, silt, clay, and hydrous oxides with minor amounts of organic matter that are commonly found near the shores of lakes, near inflows and outflows, and in lakes where surrounding vegetation is sparse (e.g. north of the treeline).
- *Organic gels*: mature, organic-rich sediments, also referred to as 'gyttja', that are generally found in deeper, less active parts of lake basins, are thixotropic and commonly green-brown to grey in colour.
- *Organic sediments:* a blend of inorganic sediments, organic gels, and immature organic debris, which usually occur near the shore or stream inflows.

The 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 the number of elements determined have progressed with technology. The GSC's use of these protocols for over the past 50 years allows comparison of new GEM data sets with older data sets, all of which may be separated one from the other by large distances or long periods of time. Each sample is air dried and sieved to recover the −80 mesh (<0.177 mm) fraction. This fraction is geochemically analyzed using aqua regia digestion combined with inductively coupled plasma atomic-emission spectrometry (ICP-ES) and inductively coupled plasma mass spectrometry (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 the Abitau Lake area of southeastern 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 from 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. The 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 for over 40 years allows comparison and integration of new GEM data sets with older GSC data sets. 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:

- 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 8*M* HNO_3 either in the field or at the GSC, in Ottawa. The FA water samples are analyzed for trace and major elements by ICP-MS and ICP-ES. The FU samples are analyzed for anions, pH, conductivity, alkalinity, and dissolved organic carbon.

- 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 aqua regia digestion combined with ICP-ES and ICP-MS, and INAA.
- 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 fragments greater than 2 mm in size. 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 heavy-mineral fraction measuring less than 0.25 mm is also geochemically analyzed.

Under the GEM program, 12 new stream-sediment and water surveys were conducted. Reanalysis 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). It is a nonsorted mixture of sediments, 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 as well as being the first derivative of bedrock in that 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 postglacial sediments (secondary or higher derivative) such as glaciofluvial, stream, beach, and 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 of till surveys and the 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 when undertaking future surveys (McClenaghan et al., 2020). Small (3 kg) till samples are air dried and 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 fraction less than 0.002 mm in size 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 SG) 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 included five detailed till studies around known mineral deposits (yellow dots in Fig. 1) to test methods and to document, for the first time, the indicator-mineral signature of these deposit types: Izok Lake volcanogenic massive sulphide (VMS) deposit, Pine Point Pb-Zn mining district, Strange Lake rare-earth element (REE) deposit, NICO and Sue-Dianne iron oxide copper-gold (IOCG) deposits, and the Kiggavik U 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 undertaken as part of a Mineral and Energy Resources Assessment (MERA) project in the area immediately to the east known as the Thaidene Nene National Park Reserve, near the East Arm of Great Slave Lake (Kerr et al., 2013; Kjarsgaard et al., 2013b; 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 that can be downloaded from GEOSCAN (https://geoscan.nrcan.gc.ca/geoscan-index.html) and the Canadian Database of Geological Surveys (CDoGS) of the Government of Canada (Adcock et al. 2013).

The public interface to the CDoGS can be found at https://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 standardization of the raw data for viewing in Google Earth™ are ongoing. More detailed information about the CDoGS website is reported in Spirito and Adcock (2010) and Adcock and Spirito (work in progress).

GEM SAMPLE ARCHIVES

A split of surficial sediment samples collected as part of the GEM program has been archived in the GSC's unconsolidated sediment-sample collection for future reference or analysis. Till-sample splits that have been archived include a plastic container of 800 g of unprocessed material; vials of at least 60 g of material smaller than 0.063 mm; and vials of heavy-density and mid-density mineral concentrate fractions and picked mineral grains. Stream-sediment sample material that was archived includes vials of at least 60 g of material smaller than 0.177 mm; and HMC fractions and picked mineral grains. Archived lake-sediment sample material consists of vials of at least 60 g of material less than 0.177 mm. 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, as well as 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 data sets from two government agencies (Quebec and Canada), the long time span involved in collecting the samples (40 years), and the slight differences in analytical digestions and methods. To merge data sets from the two different agencies, approximately 5000 GSC archived lake-sediment samples collected in Labrador (area 2 in Fig. 1) were reanalyzed in 2015 (McCurdy, 2016; McCurdy et al., 2016b) using methods similar to those that had been used for the Quebec data set (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 data set contributed new information for the geological mapping of this large region and pointed to 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 included 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 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; Rice et al., 2017a, 2020; Hagedorn et al., 2018) and indicator minerals (McClenaghan et al., 2016b; Rice et al., 2017b, this volume) for the Schefferville–Smallwood reservoir region (area 3 in Fig. 1). Highlights for these new data included 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

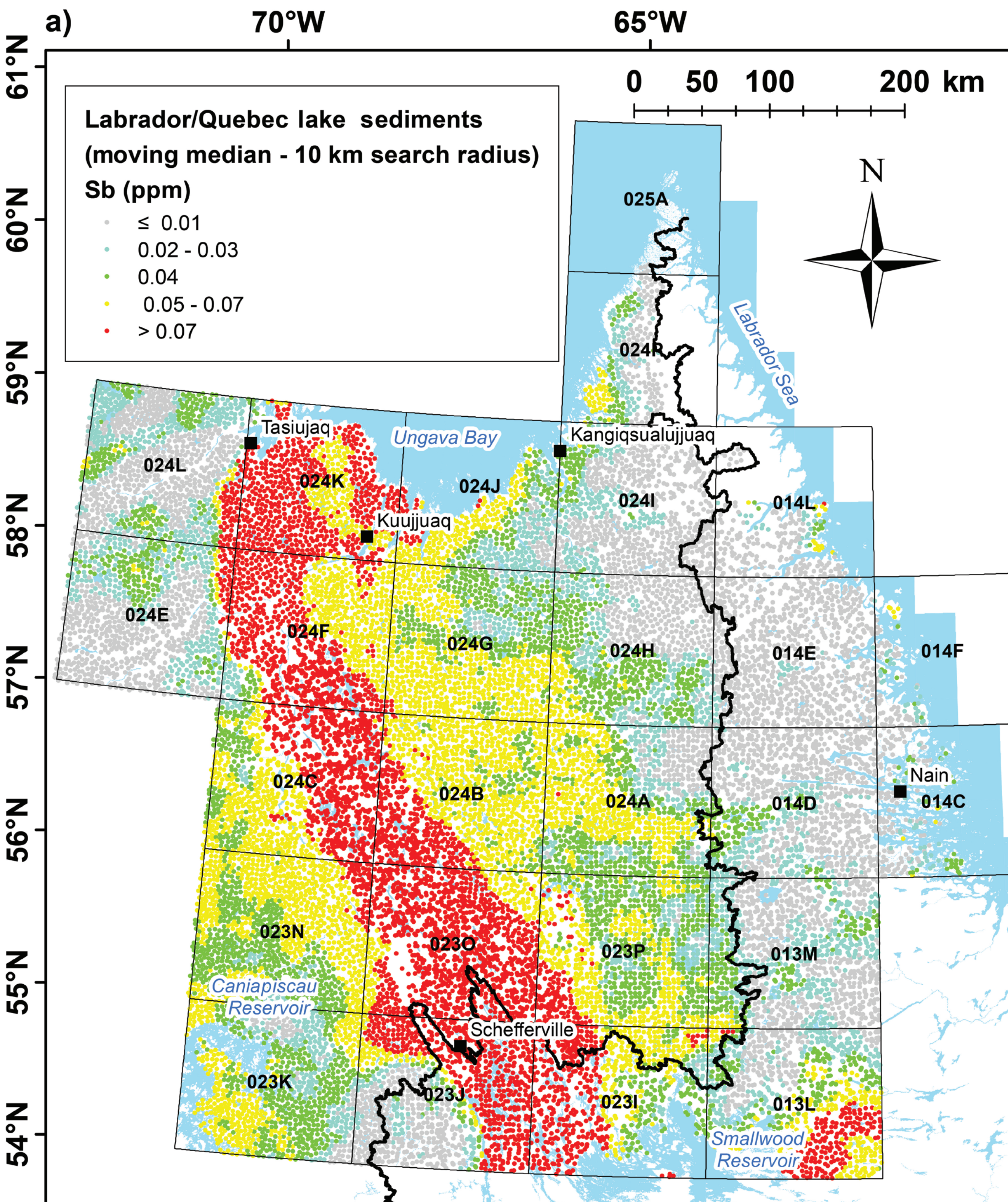


Figure 2. Distribution of trace elements in the fraction smaller than 0.177 mm of lake-sediment samples from Quebec and Labrador determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry. **a)** Antimony (Sb).

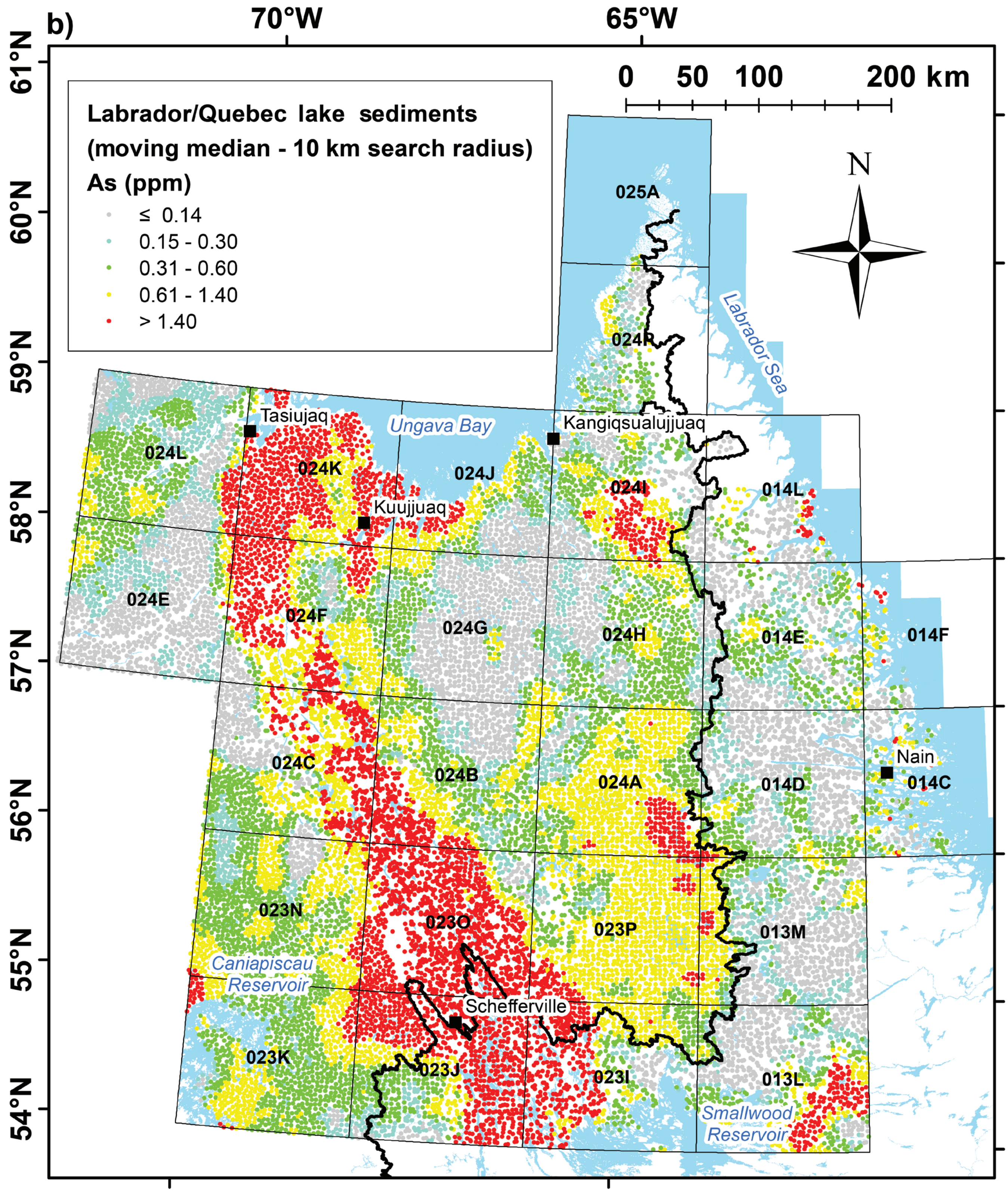


Figure 2. (cont.) b) Arsenic (As).

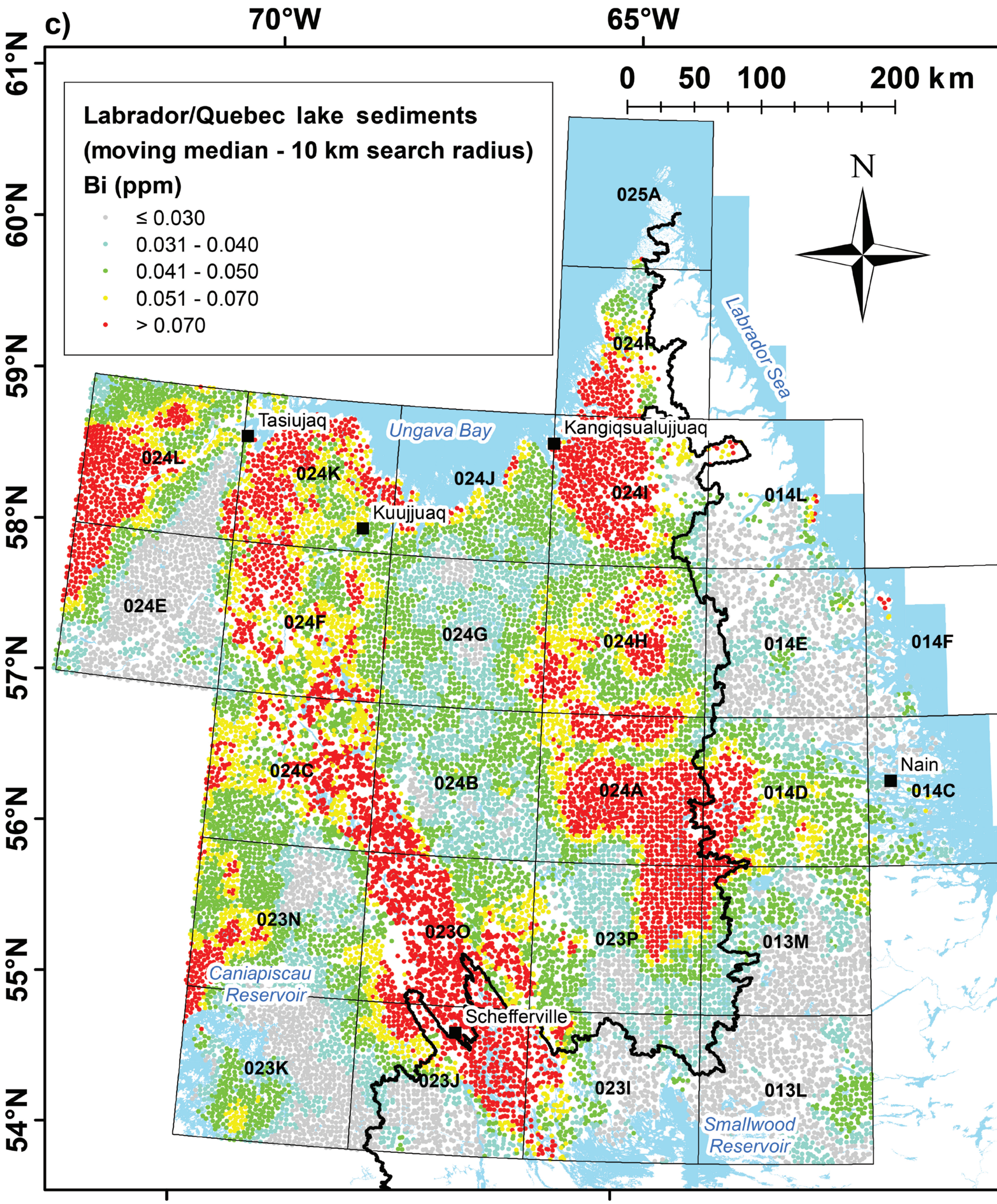


Figure 2. (cont.) c) Bismuth (Bi).

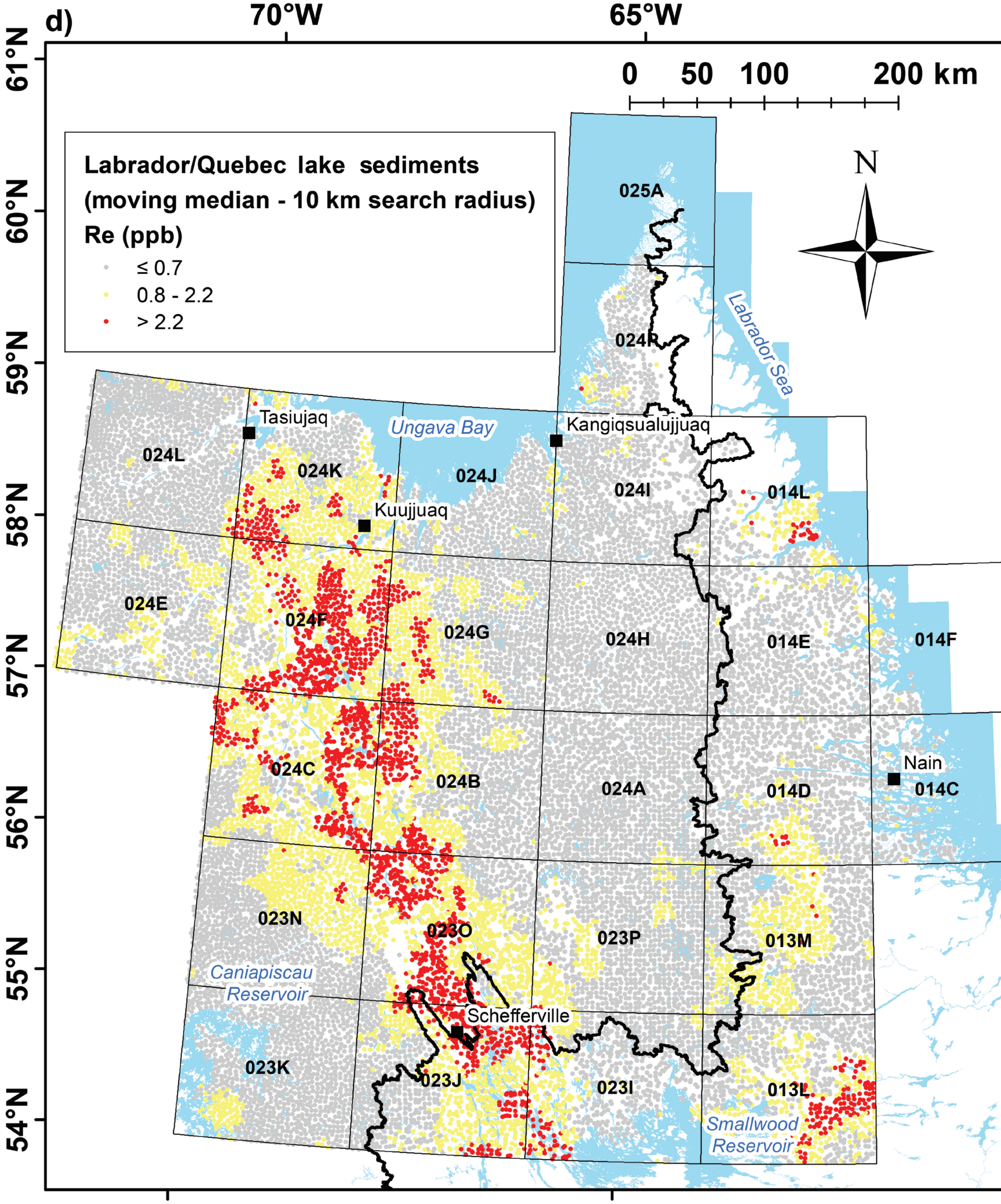


Figure 2. (cont.) d) Rhenium (Re). *Modified from* Amor et al. (2019, Fig. 23a–d).

volcanic rocks (*see* Fig. 16 *in* Rice et al., this volume). Elevated Au and Ag values in till matrix overlying the Doublet zone coincided with the elevated Au-grain content in till samples (>6 grains/10 kg), indicating the potential for Au mineralization. The presence of chalcopyrite and platinum-group minerals (sperrylite, moncheite) in till overlying the Doublet zone, and ultramafic rocks farther east, suggested that there is potential for Cu-Ni-PGE mineralization (McClenaghan et al., 2017a; Rice et al., this volume).

West-central Baffin Island

In 2018, archived GSC lake-sediment samples from west-central Baffin Island (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) provided an interpretation of the new lake-sediment data set and identified and described 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 showed 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 was the most obvious. Other highly metalliferous areas of interest included the area east of Flint Lake, farther east along the Astarte River and Flint Lake formations at the northern edge of the Paleoproterozoic basin, west of Nadluardjuk Lake overlying the Bravo Lake Formation, discrete clusters of samples farther east along the Bravo Lake Formation, and a cluster of lake-sediment samples overlying the Longstaff Bluff formation. This research provided new insights and a better understanding of this large geochemical data set in the modern metallogenic framework described by Wodicka et al. (2014).

Victoria Island

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

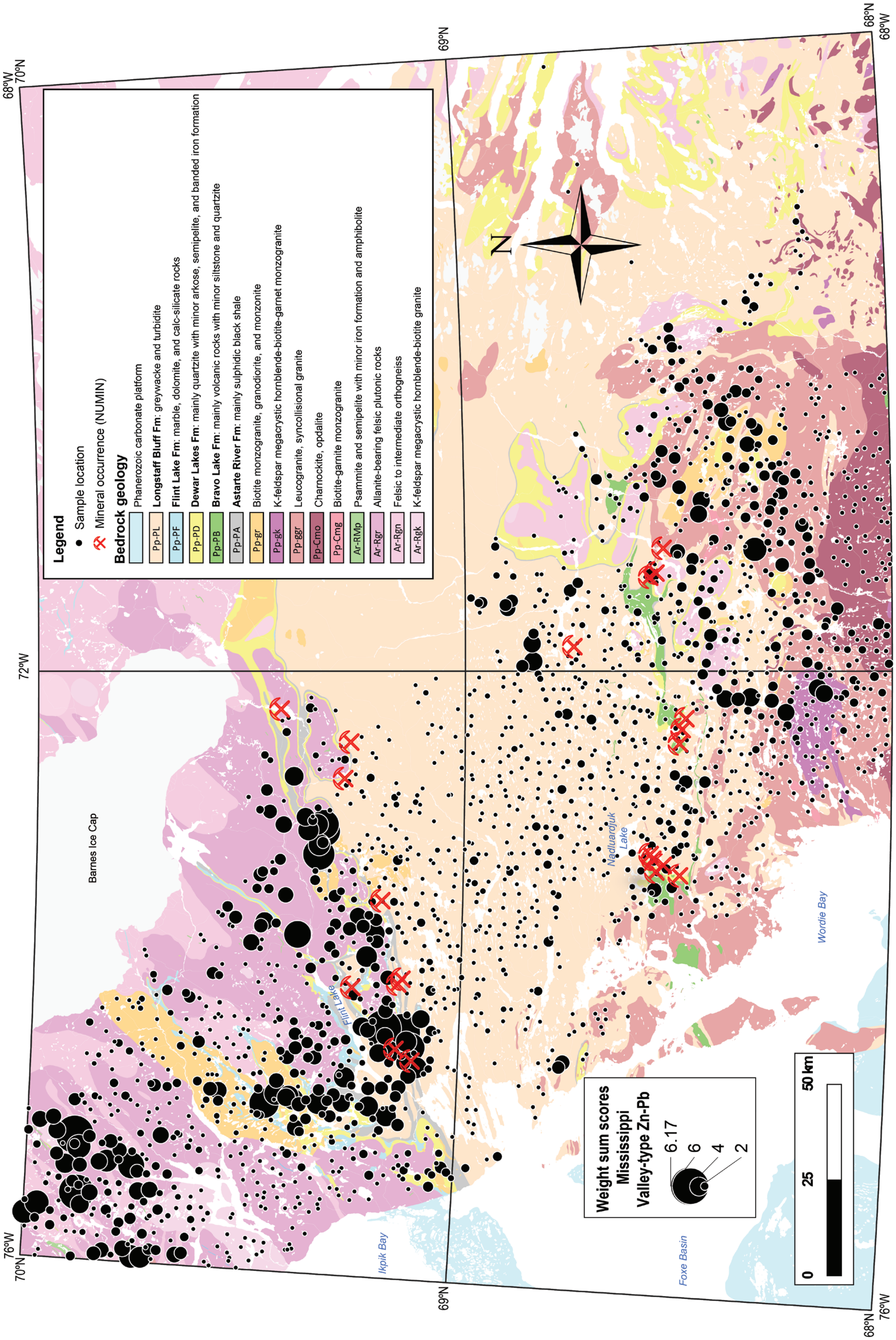
New regional stream-sediment and water samples were collected overlying Paleozoic strata with potential to host Mississippi Valley-type (MVT) Pb-Zn mineralization farther to the north on Victoria Island (area 6 in Fig. 1) in 2010 and 2011. The objective was to assess the resource potential of this previously unexplored and difficult-to-access region (McCurdy et al., 2011, 2012a). The geochemistry of stream sediments and waters indicated that high concentrations 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 recovered in the same area as elevated Pb and Zn concentrations in stream-sediment and water samples indicated 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. 4a, b) and sediments are elevated suggested there is potential for MVT mineralization in Shaler Supergroup rocks north of Minto Inlet (McCurdy et al., 2013a).

Melville Peninsula

Archived GSC lake-sediment samples from the central part of the Melville Peninsula (area 7 in Fig. 1) were reanalyzed 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, were associated with the Paleoproterozoic Penrhyn Group supracrustal rocks in southern Melville and appeared to be associated, in part, with known Zn mineral occurrences.

Regional till geochemical surveys were carried out in the mid-1980s in the northern and central part of 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) (area 8 in Fig. 1). This region has carbonate-rich till derived from Paleozoic carbonate rocks in the Foxe Basin (Tremblay and Lamothe, this volume). 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

Figure 3. Proportional-dot map of weighted-sum scores for the Mississippi Valley-type Pb-Zn 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 *modified from* Wodicka et al. (2014) and figure *from* Bonham-Carter et al. (2019).


Legend
Sample location
Mineral occurrence (NUMIN)
Bedrock geology
Pp-PL Phanerozoic carbonate platform
Pp-PL Longstaff Bluff Fm: greywacke and turbidite
Pp-PF Flint Lake Fm: marble, dolomite, and calc-silicate rocks
Pp-PD Dewar Lakes Fm: mainly quartzite with minor arkose, semipelite, and banded iron formation
Pp-PB Bravo Lake Fm: mainly volcanic rocks with minor siltstone and quartzite
Pp-PA Astarte River Fm: mainly sulphidic black shale
Pp-gr Biotite monzogranite, granodiorite, and monzonite
Pp-gk K-feldspar megacrystic hornblende-biotite-garnet monzogranite
Pp-ggr Leucogranite, syncollisional granite
Pp-Cmo Charnockite, opdalite
Pp-Cmg Biotite-garnite monzogranite
Ar-RMp Psammite and semipelite with minor iron formation and amphibolite
Ar-Rgr Allanite-bearing felsic plutonic rocks
Ar-Rgn Felsic to intermediate orthogneiss
Ar-Rgk K-feldspar megacrystic hornblende-biotite granite
Barnes Ice Cap
Flint Lake
Nadluardjuk Lake
Wordie Bay
Ikpik Bay
Foxe Basin
N
Weight sum scores
Mississippi
Valley-type Zn-Pb
6.17
6
4
2
0
25
50 km
70°N
76°W
72°W
68°W
69°N
68°N

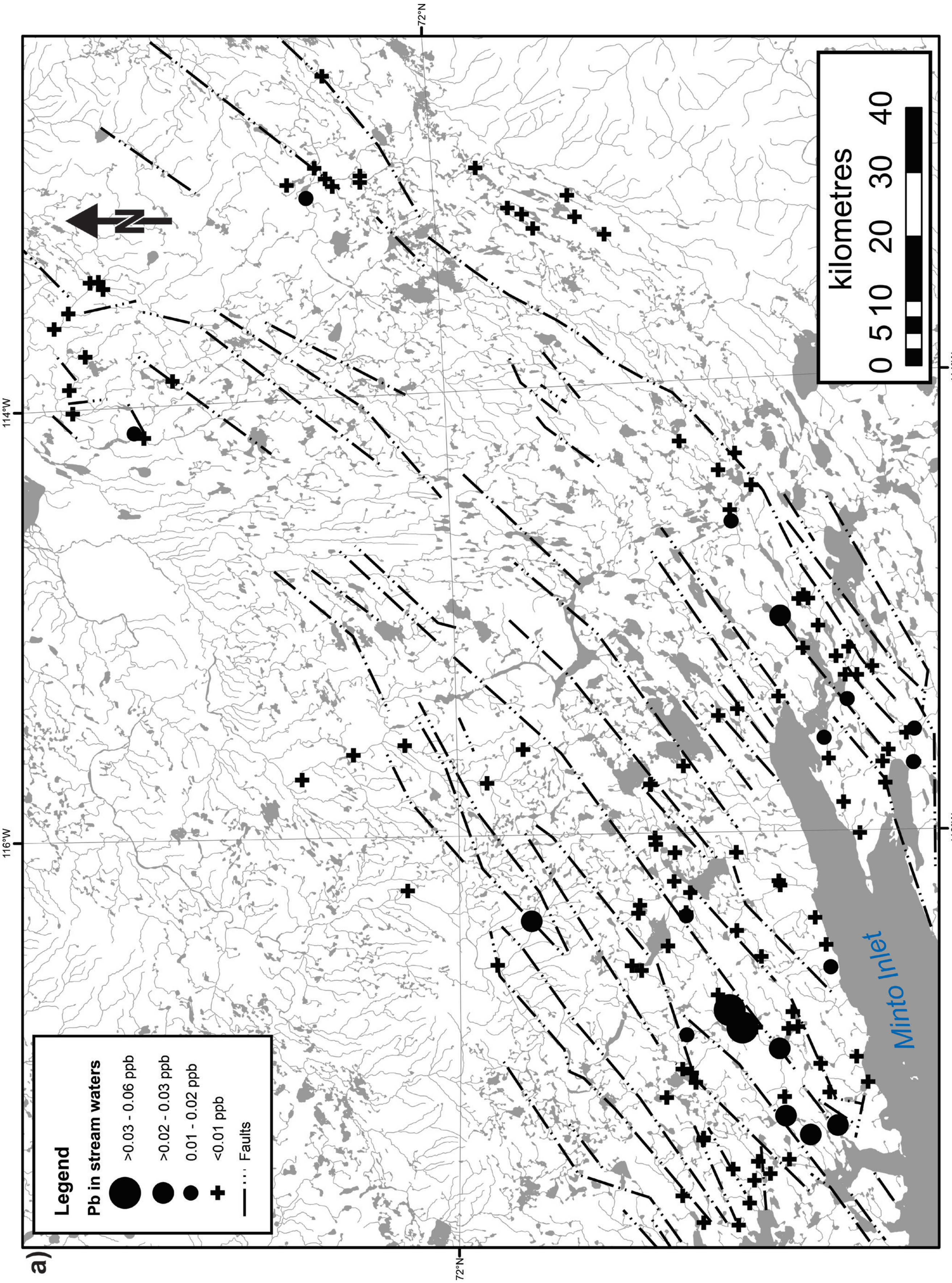


Figure 4. Proportional-dot maps of **a)** lead (Pb) concentrations in stream waters on Victoria Island, Northwest Territories (*from* McCurdy et al., 2013a).

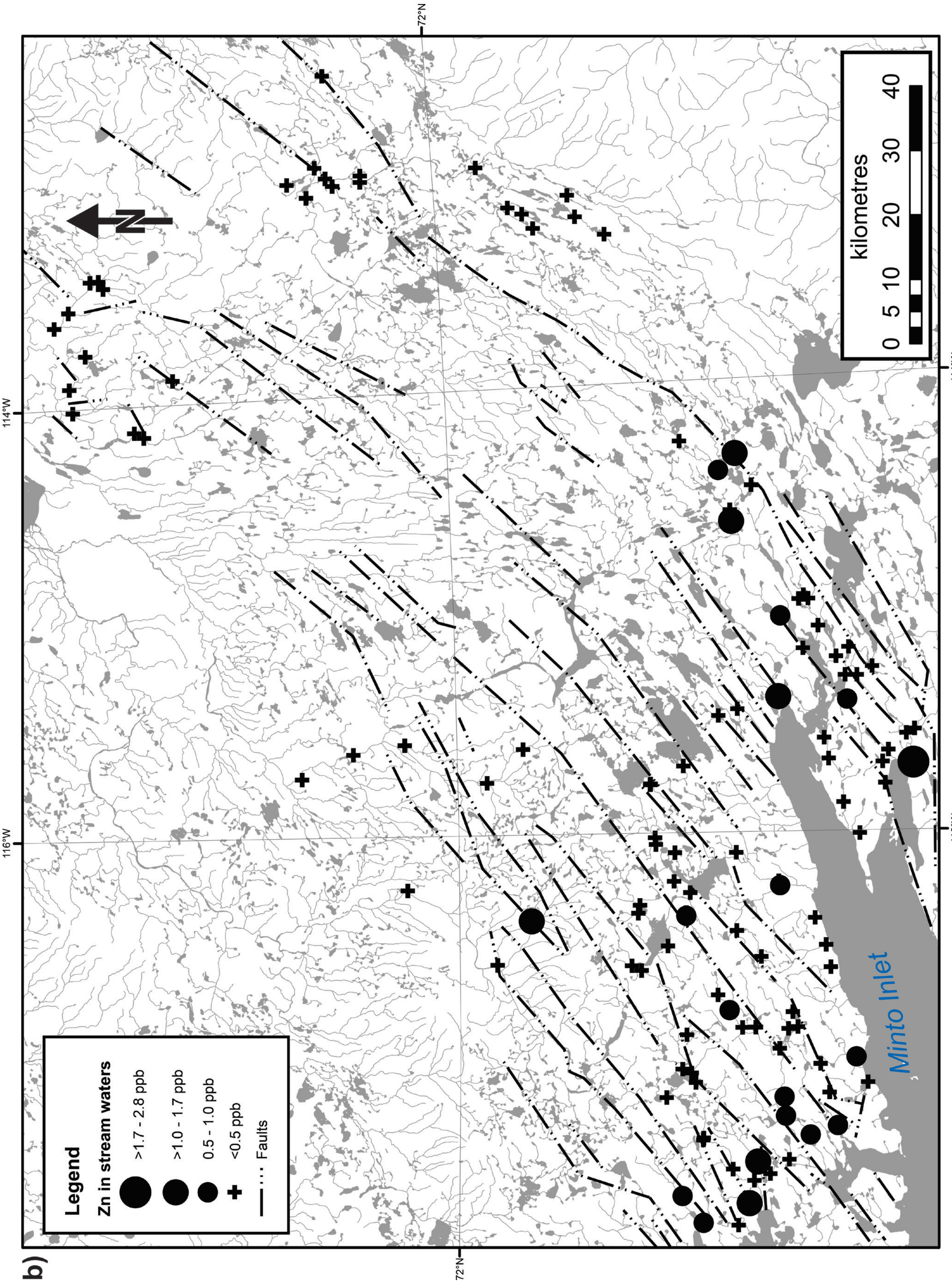


Figure 4. (cont.) b) Zinc (Zn) concentrations in stream waters on Victoria Island, Northwest Territories (*from* McCurdy et al., 2013a).

geochemistry in the northern part of the peninsula (area 8 in Fig. 1) reflects Paleozoic carbonate rocks to the east. In contrast, indicator-mineral and geochemical analyses of till heavy HMCs in the same area reflect the composition of local bedrock.

Across southern Melville Peninsula (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, sulphides, 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 coincided with the elevated Au values in regional lake sediments (Fig. 5), and these areas of high concentrations appeared to be the 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 (area 10 in Fig. 1), regional till geochemistry and indicator-mineral content provided 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 formed 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 REEs, K_2O, and Na_2O concentrations in till displayed similar patterns in this area. The Al_2O_3 dispersal fan was coincident with converging streamlined landforms that were 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 north-northwest-trending streamlined landforms also indicated relatively long glacial transport distances (tens to more than hundreds of kilometres) over Archean gneissic rocks as part of the topographically controlled Rae Isthmus ice stream (e.g. McMartin, Campbell et al., this volume). 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.

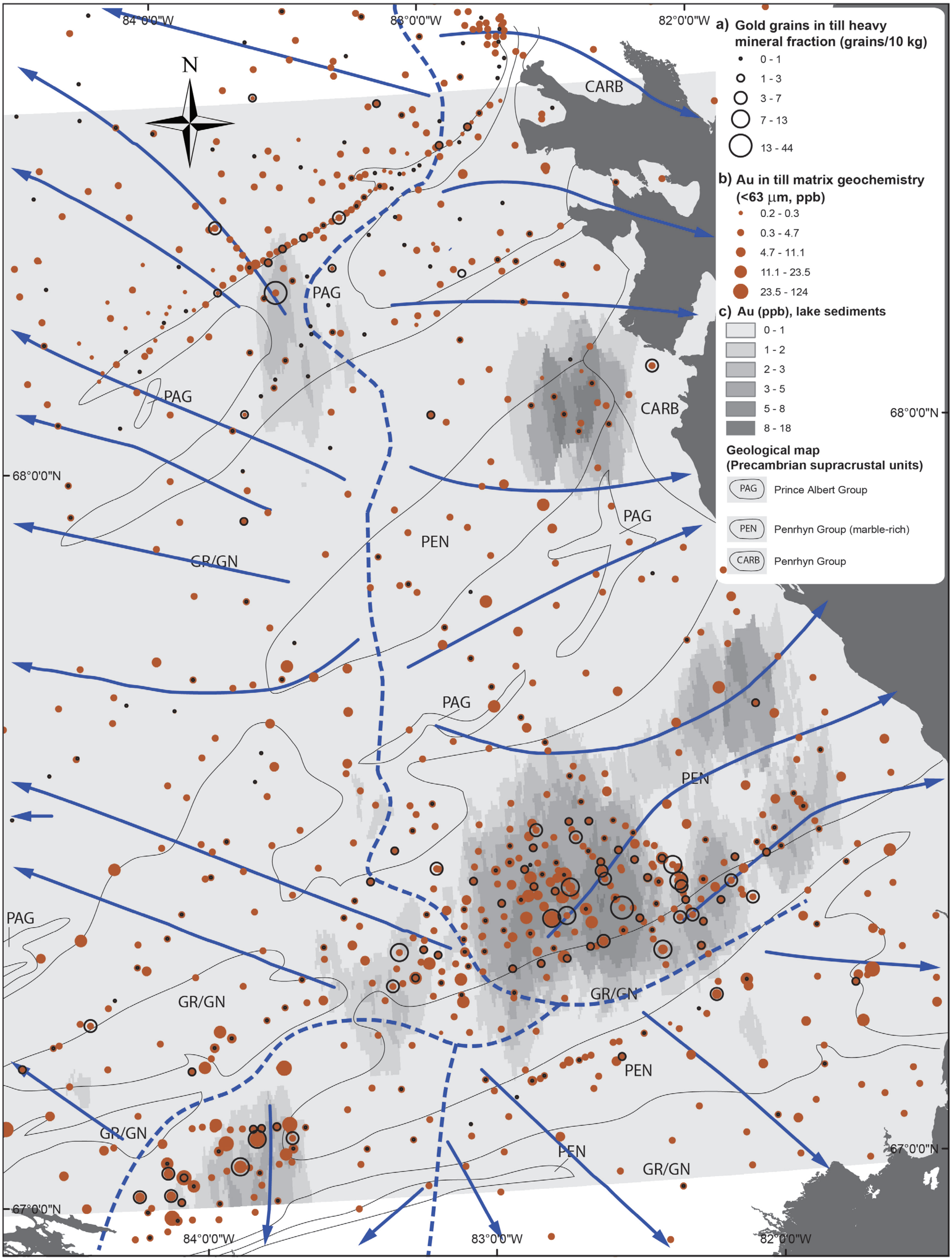
The area north of Wager Bay has potential to host diamondiferous kimberlites, as shown by the significant number of Mg-rich olivine grains in till samples; many of these have Mg-olivine with high NiO contents and are coarse grained, which may indicate the presence of kimberlite-derived macrocrysts. The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

Regional till geochemistry and indicator-mineral data indicated the area also has potential for Ni-Cu-PGE mineralization in the western 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 Cr, Ni (Fig. 7a, b), Co, Cu and Zn, high chromite and forsterite grain counts, and the presence of large ultramafic erratic boulders in till. The source(s) of this dispersal train may be located in undifferentiated supracrustal rocks close to the boulder occurrence, within and/or just north of Ukkusiksalik National Park.

South of Wager Bay (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 characterizing glacial transport across the Keewatin Ice Divide, support bedrock mapping in areas of thick drift, and evaluate the mineral potential of the region (McMartin et al., 2019a). In addition to the regional till surveys, two selected sites near the postglacial 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 rock units preserved under a nonerosive 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) south-southeast of the Nanuq property, 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 east-southeast of the Nanuq property in the Gordon domain (Fig. 8) indicates that new diamondiferous kimberlites, distinct from the Nanuq kimberlite field (*see* sample 15MOB033 in Fig. 8), could be discovered. The study area also has the potential to host Ni-Cu-PGE mineralization, with the heavily drift-covered eastern part of the northern Lorillard belt showing the greatest potential. 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, which 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; the changes are not particularly apparent when observations are being made in the field. However, provenance remains the dominant factor controlling



a) Gold grains in till heavy mineral fraction (grains/10 kg)
0 - 1
1 - 3
3 - 7
7 - 13
13 - 44
b) Au in till matrix geochemistry (<63 µm, ppb)
0.2 - 0.3
0.3 - 4.7
4.7 - 11.1
11.1 - 23.5
23.5 - 124
c) Au (ppb), lake sediments
0 - 1
1 - 2
2 - 3
3 - 5
5 - 8
8 - 18
Geological map (Precambrian supracrustal units)
PAG Prince Albert Group
PEN Penrhyn Group (marble-rich)
CARB Penrhyn Group
N
84°0'0"W
83°0'0"W
82°0'0"W
68°0'0"N
67°0'0"N
CARB
PAG
PEN
GR/GN

Figure 5. Gold content in surficial sediments for southern Melville Peninsula, Nunavut: **a)** proportional dots (open circles) showing gold-grain abundance in the panned 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 *from* Tremblay et al. (2016a).

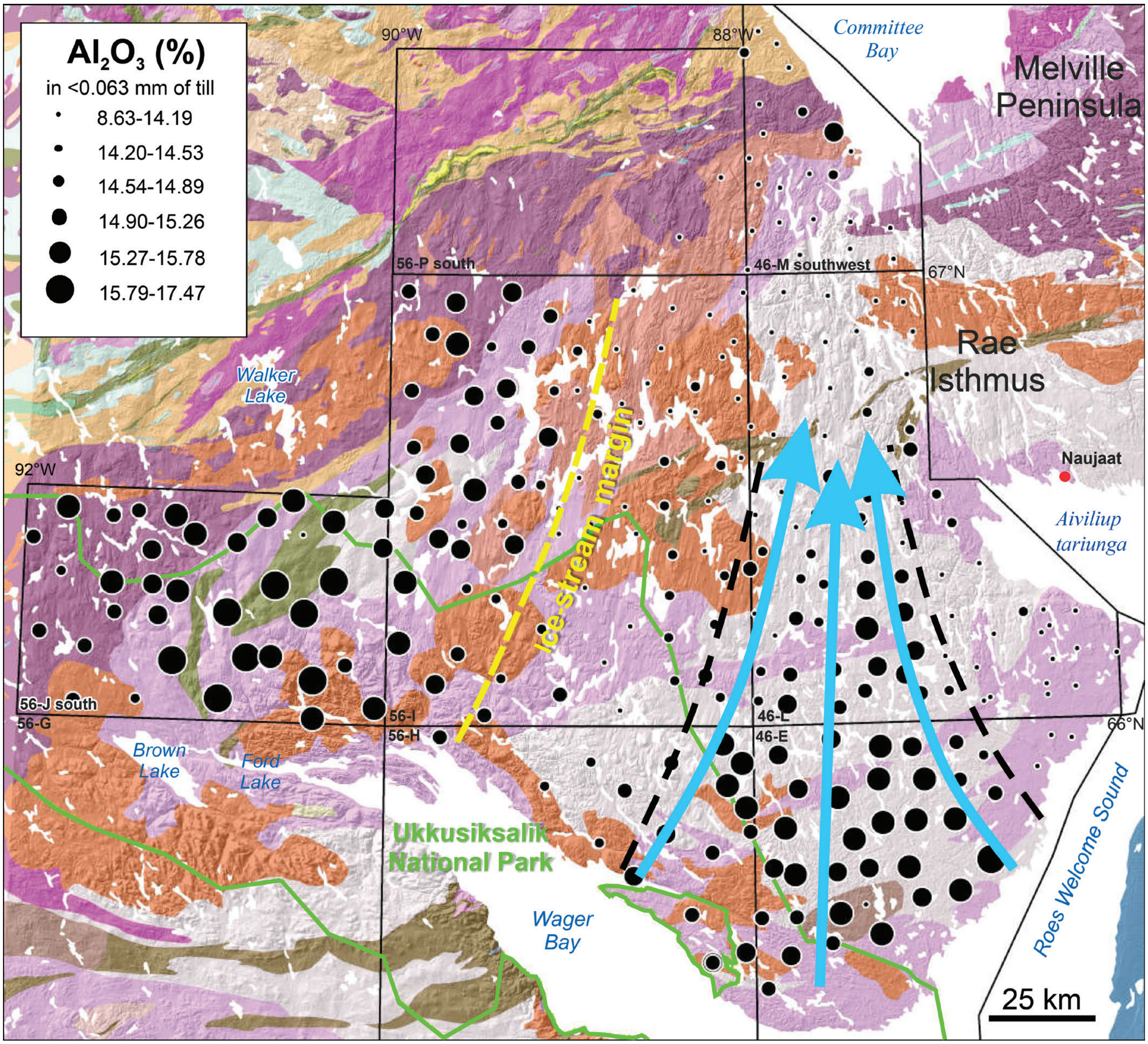


Figure 6. Proportional-dot map of Al_2O_3 concentrations in the fraction smaller than 0.063 mm of surface till determined by borate fusion followed by inductively coupled plasma atomic-emission spectrometry. High concentrations of Al_2O_3, as well as K_2O, Na_2O, and light rare-earth elements (borate-fusion 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 *modified from* McMartin et al. (2015).

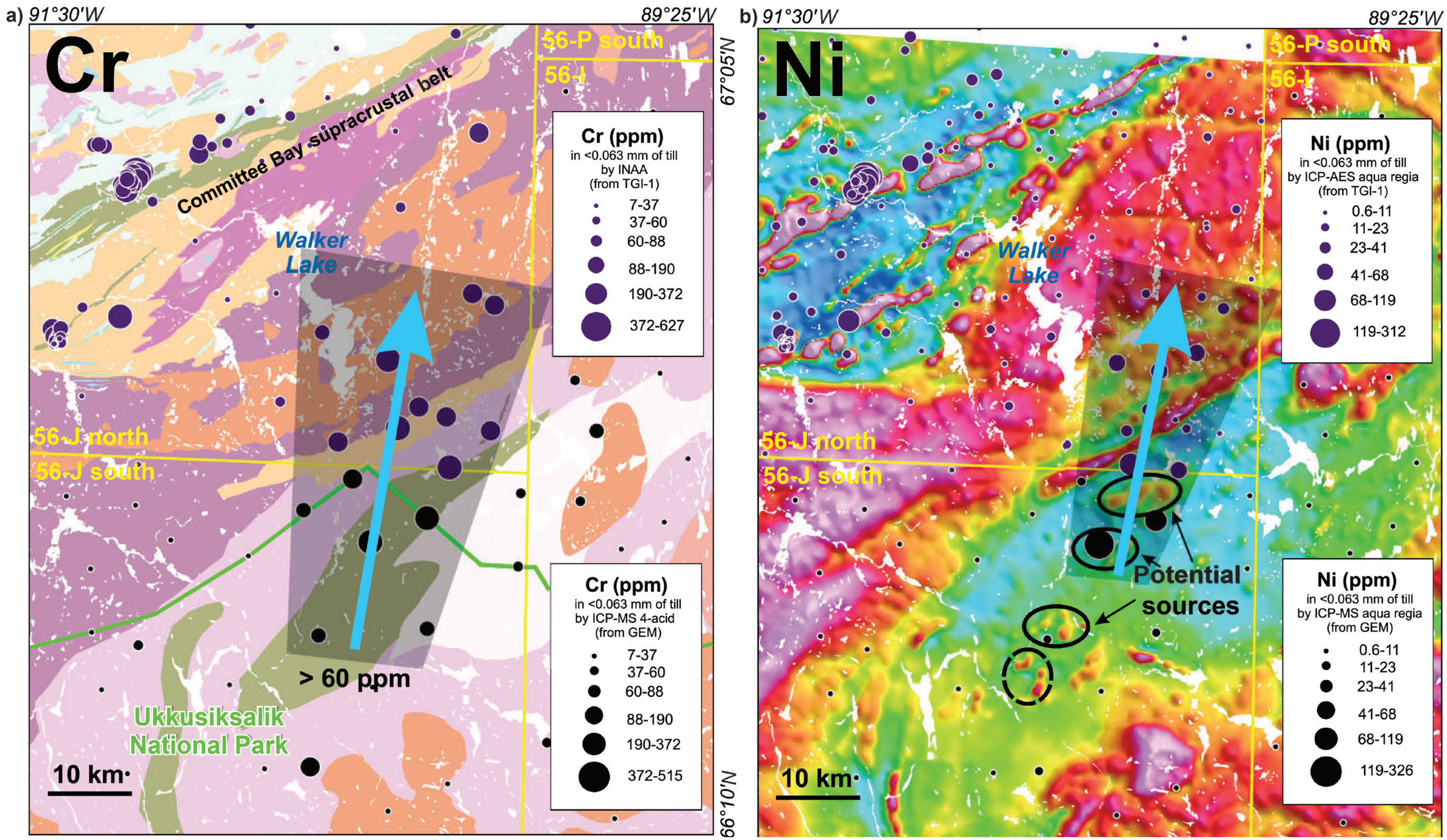


Figure 7. Proportional-dot map of data from the Geo-mapping for Energy and Minerals (GEM) and Targeted Geoscience Initiative (TGI) programs, showing **a)** chromium (Cr) concentration determined by instrumental neutron activation analysis (INAA) and four-acid digestion followed by inductively coupled plasma mass spectrometry (ICP-MS) (bedrock geology *from* Skulski et al., 2018); and **b)** nickel (Ni) concentration 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, in the westernmost part of the proportional-dot map shown in Figure 6. Targeted Geoscience Initiative (TGI) program data shown in dark purple *modified 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, mafic or ultramafic crustal rocks coincident with magnetic highs are circled in black on the airborne total magnetic field map (Natural Resources Canada, 2021), which shows the most magnetic rocks in red and the least magnetic rocks in blue. Blue arrows indicate ice-flow direction. Bedrock geology and figure *modified from* McMartin et al. (2015).

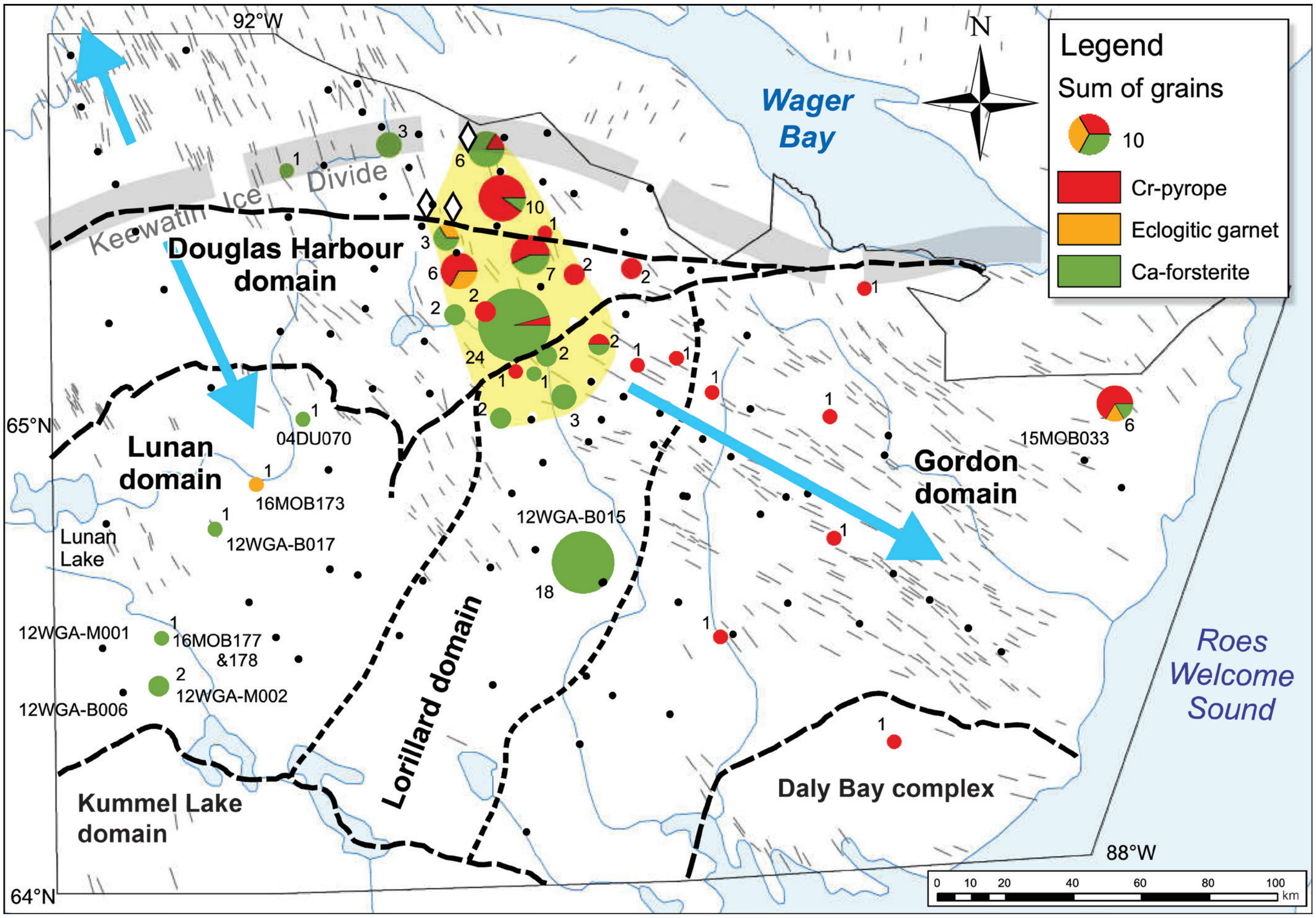


Figure 8. Proportional-dot map of the sum of Cr-pyrope, eclogitic garnet, and Ca-forsterite grains in surface-till samples across the region south of Wager Bay, Nunavut. A kimberlite indicator-mineral dispersal train trending south-southeast from the Nanuq kimberlites is indicated in yellow. White diamonds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

till composition and can explain approximately 80% of the variation at the two sites studied using principal component analysis of the geochemical data sets.

Ellice River–Thelon tectonic zone

Regional stream-sediment and water samples were collected in the Ellice River area (area 12 in Fig. 1), southeast of Bathurst Inlet, Nunavut, as part of the GEM Frontiers' Chantrey project (McCurdy et al., 2013b, 2016c). 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 along transects across the TTZ, to characterize regional glacial transport (McMartin and Berman, 2015; McMartin, 2017), as well as the Queen Maud block and adjacent Rae Craton to the east by 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, 2016c) and till sampling (McMartin et al., 2013c; McMartin and Berman, 2015):

- Northwestern NTS map area 76-I associated with Slave Province 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., 2016c). The presence of elevated Cu and other base metals (Pb, Ni, Zn), and chalcopyrite grains in stream sediments and tills collected in 2016, further emphasized the base-metal potential of this area. Gold grains in both stream and till samples in the same area indicated a potential source or sources of precious metals within metasediments and/or metavolcanic rocks of the Slave Craton.

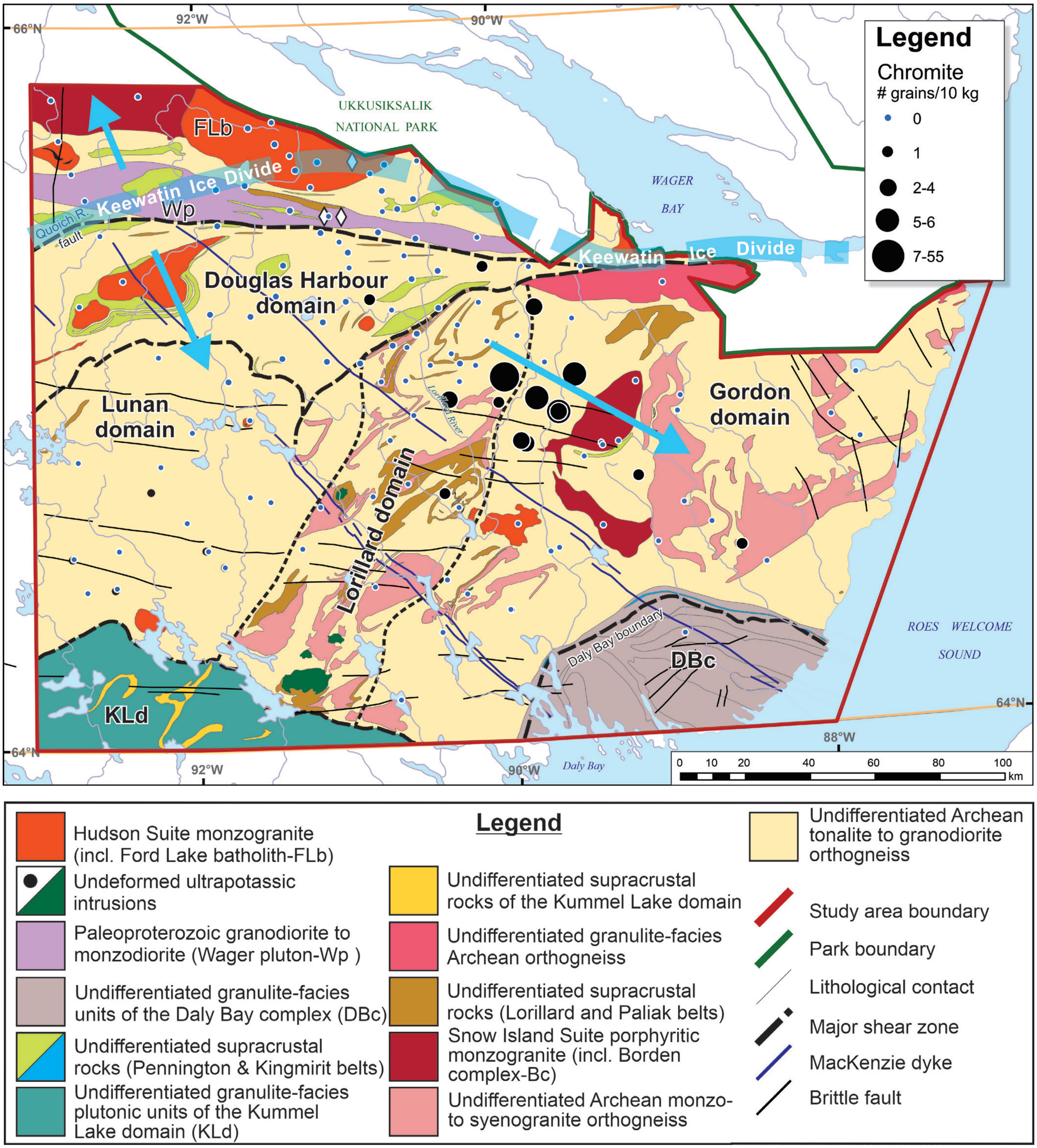


Figure 9. Proportional dot map of chromite abundance (normalized to 10 kg) in the 0.25–0.5 mm heavy-mineral fraction of surface till samples across the region south of Wager Bay, Nunavut. Blue arrows indicate regional ice-flow directions. Figure along with bedrock geology *modified from* McMartin et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

- Central NTS map area 76-H southwest of Duggan Lake: previous GSC stream-sediment and till sampling identified an area of Cu-Pb-Zn-As-sulphide in stream sediments and till (McCurdy et al., 2013b, 2016c; McMartin and Berman, 2015; McMartin, 2017). Resampling in 2016 up-ice and upstream of the anomaly identified signatures from two distinct sources: 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 a Cu-Pb-Zn-Ag±Mo±W-chalcopyrite-sphalerite-molybdenite anomaly associated with the Ellice River domain, particularly mafic volcanic rocks.
- 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 confirmed the 2013 data. Results of fieldwork suggested that the source of this anomaly may be a high-grade metamorphic iron formation hosted in a region within the drainage basin.

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 reflected a distal provenance, rich in Thelon Basin sandstone debris from the Dubawnt Supergroup, and depleted in most trace and major elements, whereas beyond the ice stream, till composition reflected 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

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

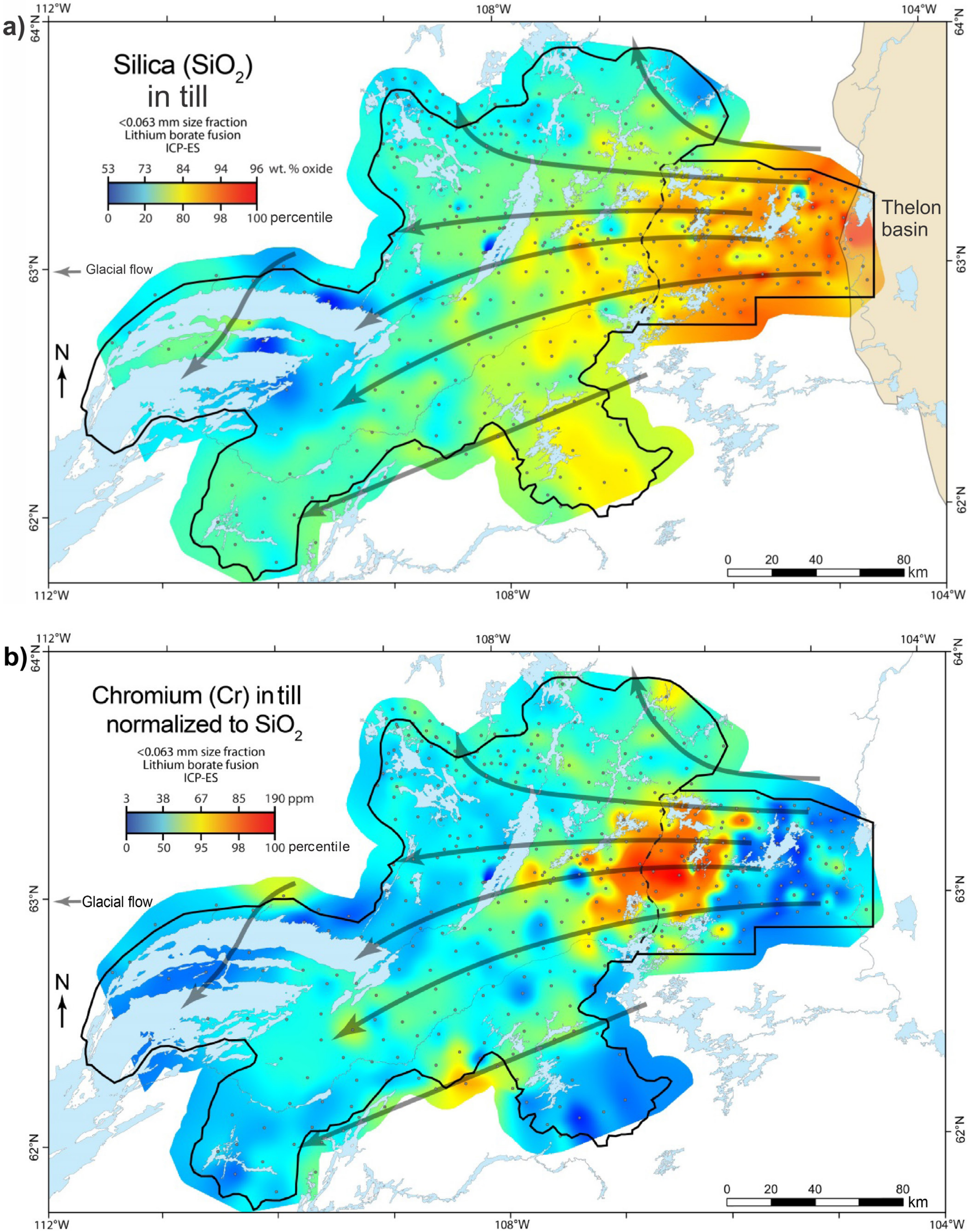
Till cover in the easternmost part of the combined MERA–GEM study area is more contiguous, thicker (1–3 m), and silica rich (>94 wt % SiO_2). Till thickness and silica content decrease westward across the study area. This pattern is not unexpected, because the till was derived from quartz sandstone in the Thelon Basin farther east. Sandstone debris was glacially dispersed across the study area by a westward-trending, 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 a part of mineral-exploration programs and has also been noted 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 decreased down ice toward 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, suggested the presence of an unknown Cr-bearing bedrock source close to Williams Lake.

Nueltin Lake area, Nunavut

Archived GSC lake-sediment samples collected in the 1970s in the Nueltin–Kasmere lakes area, northern Manitoba (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 data set was that those areas of high concentrations of light REEs (Ce, La, Nb) and Y in the lake sediments (Fig. 11) corresponded closely to Nueltin granite plutons. One large anomaly in the eastern part of the area, shown in Figure 11, was not associated with any mapped granitic body and indicated the possible existence of unmapped Nueltin granite plutons in the region as well as the potential for lake-sediment geochemistry being 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

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 in the Northwest Territories study area 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).


a)
Silica (SiO2) in till
<0.063 mm size fraction
Lithium borate fusion
ICP-ES
53 73 84 94 96 wt. % oxide
0 20 80 98 100 percentile
Glacial flow
Thelon basin
N
0 20 40 80 km
112°W
108°W
104°W
64°N
63°N
62°N
b)
Chromium (Cr) in till normalized to SiO2
<0.063 mm size fraction
Lithium borate fusion
ICP-ES
3 38 67 85 190 ppm
0 50 95 98 100 percentile
Glacial flow
N
0 20 40 80 km

be used where the bedrock geology is poorly known and to focus future fieldwork in areas where the predicted bedrock geology differed from the legacy bedrock geology.

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 (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) revealed the area had a complex ice-flow history. Well defined indicators in crosscutting relationships revealed a regional clockwise rotation in deglacial ice-flow directions revolving from an early southward to a late deglacial westward flow. The presence of Thelon Basin sandstone clasts in the southwestern part of the study area was the net result of older southward ice flow followed by younger southwest ice flow (Fig. 12a). The sand content of the till matrix from the study displayed a similar pattern of decreasing content from over 80%, or very sand rich, in the northeast to less than 65% in the southwest, reflecting glacial erosion of the quartz-rich sandstone and conglomerate in the Thelon Basin, 20 km to the north-northeast (Fig. 12a). A preliminary review of the major- and trace-element till data indicated that SiO_2 and, inversely, Al_2O_3 (local bedrock-component proxy) best reflected 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 northeastern part of the study area masked the geochemical signature of the local bedrock. Regional trace-element patterns for the till matrix reflected the local bedrock domains, which suggested there was a significant locally derived component (<1 km) in the till. Detailed reporting of till indicator-mineral and geochemical data were published in Campbell et al. (2020).

Other GEM South Rae geochemical studies included reanalysis of archived GSC lake sediments collected between 1977 and 1993 (NTS map areas 74-N, -O, -P, 64-L, -M) in northern Saskatchewan (area 16 in Fig. 1) and 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 collected in NTS map areas 75-C, -F, and -K (McCurdy et al., 2016d) and are plotted together in Figure 13. The high concentrations northeast of the eastern 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).

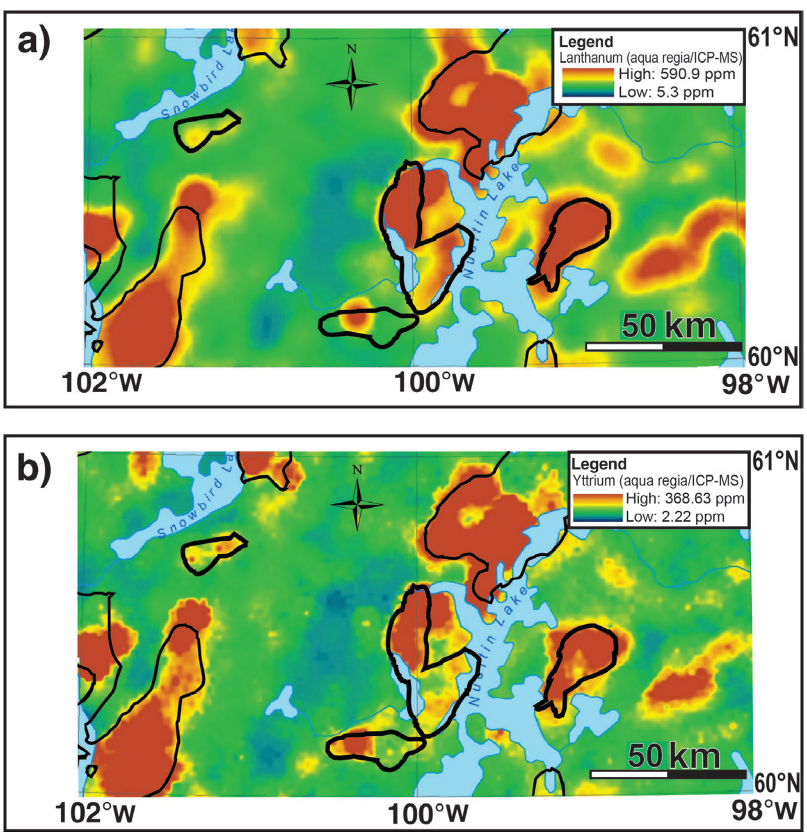


Figure 11. Interpolated geochemical maps for **a)** lanthanum (La) and **b)** yttrium (Y) concentrations determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP-MS) in the fraction smaller than 0.177 mm of lake sediments from the Nueltin Lake area, Nunavut. High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

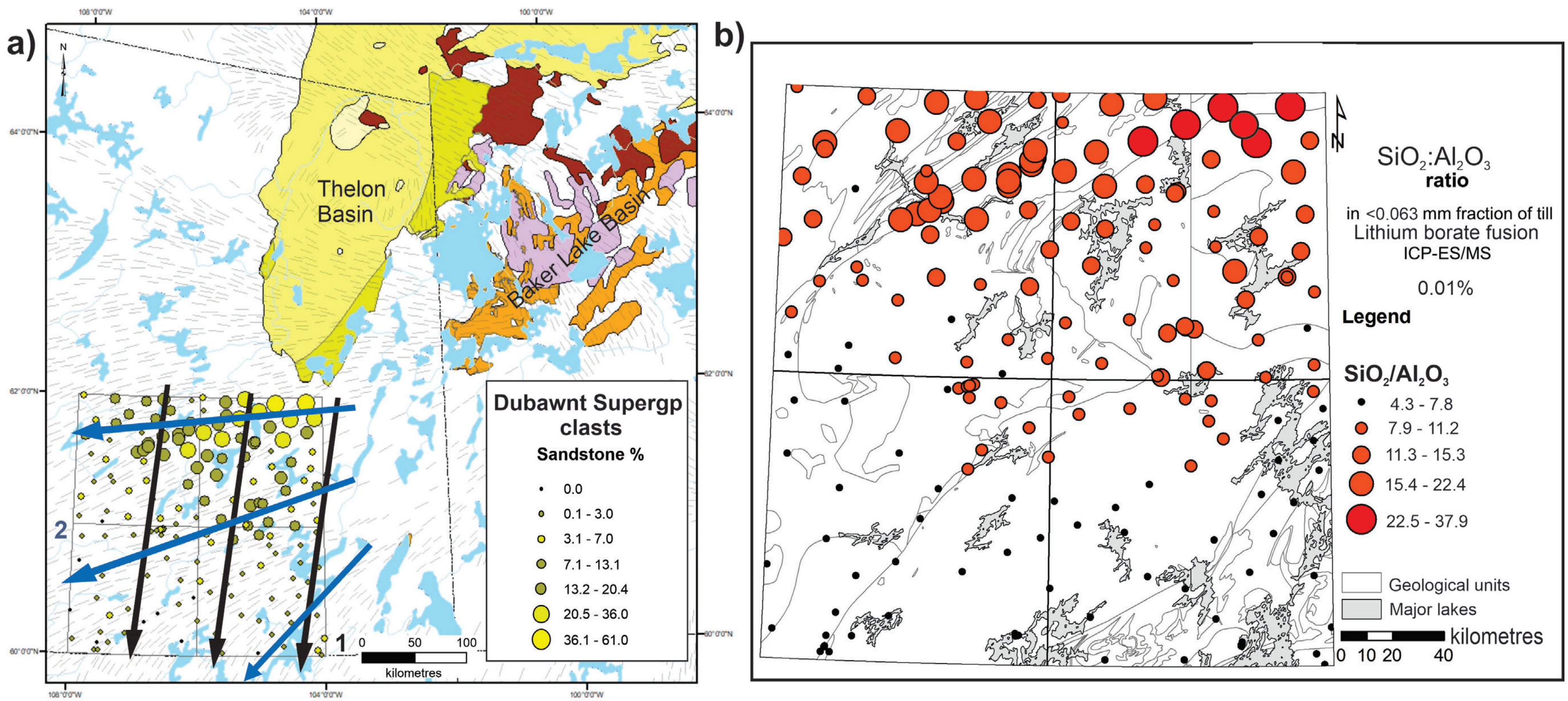


Figure 12. **a)** Proportional-dot map of Thelon Basin sandstone-clast abundance in till in the southeastern Northwest Territories study area. Concentrations in till decrease from northeast to southwest down ice from Thelon sandstone bedrock (yellow polygon), a pattern similar to the decreasing sand 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 *modified 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. *Modified from* Campbell et al. (2020).

Southwestern Northwest Territories

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

Stream sediments and tills contained 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 indicated that their source(s) is MVT 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), suggested that undiscovered buried bedrock sources for the galena were 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 had $\delta^{34}S$ values similar to those of 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-mineral and geochemical data for the southwestern region of the Northwest Territories will be published, and these will help to further refine exploration targets for subsequent investigation.

East-central Manitoba

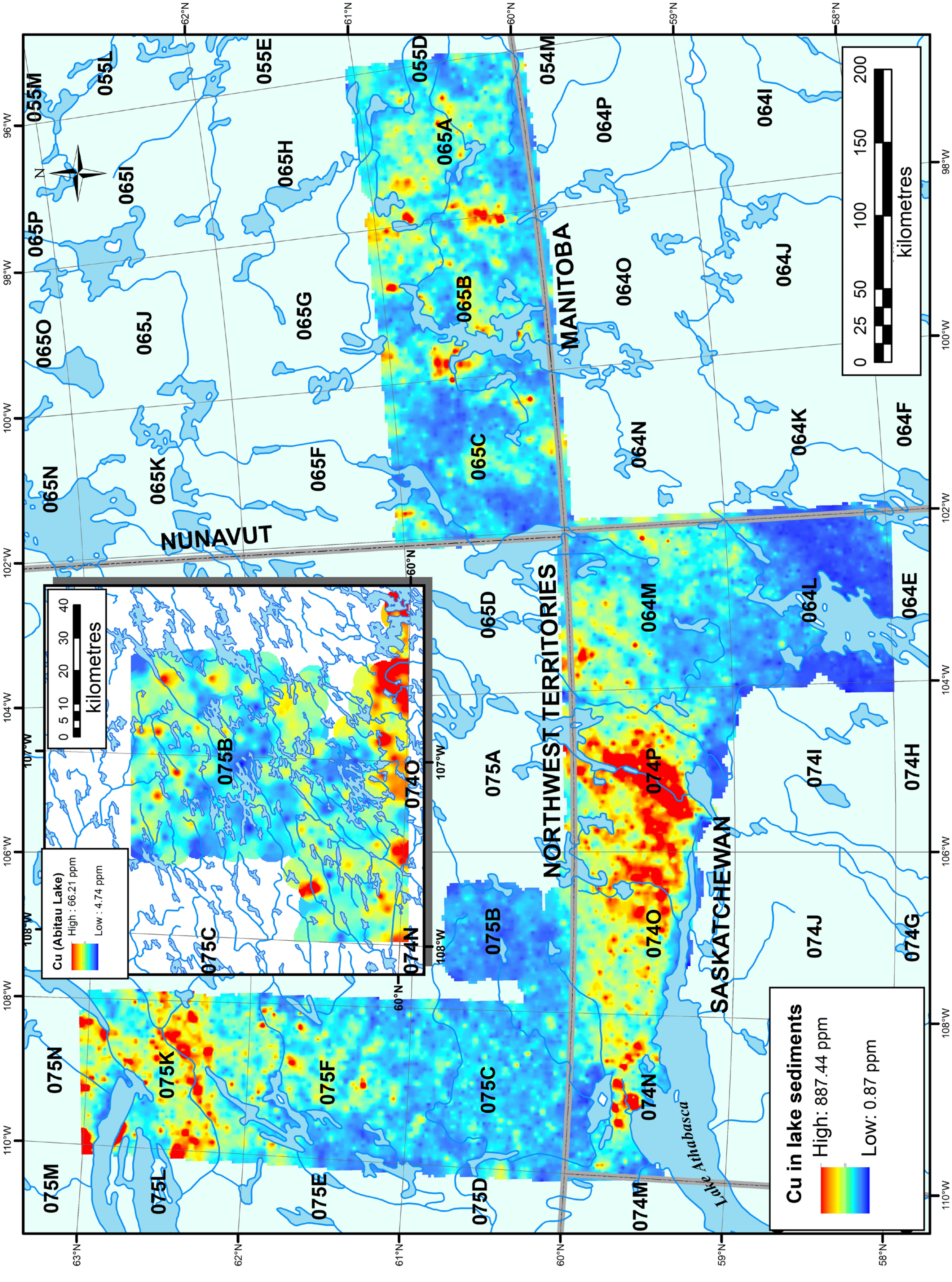
In east-central Manitoba, GEM reconnaissance-scale surface-till sampling was carried out in the Great Island–Caribou Lake area (area 18 in Fig. 1) in combination with ice-flow indicator mapping to assist in evaluating the mineral potential of the region (Campbell et al., 2012). The till geochemical results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

Farther south, in the Gods Lake area of east-central Manitoba (area 19 in Fig. 1), archived GSC lake sediments collected in 1986 were reanalyzed 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 are apparent in the dataset near known Au occurrences, as well as near Bigstone Lake, Joint Lake, Knee Lake, and north of Island Lake. Silver concentrations in lake sediments were 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 occurred in areas of known Ni mineralization around Island Lake, as well as around Beaver Hill Lake, Bigstone Lake, Cinder Lake, Gods Lake, Knee Lake, and Oxford Lake. Concentrations of Li and REEs in lake sediments are highest around known pegmatite and carbonatite units, as well as in areas of unknown potential.

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 (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). The ice-flow history of this area was complex, consisting of at least five different phases that were 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 demonstrated dispersal by different ice-flow events. In general, U and Th content in till appeared to be associated with elevated concentrations of calcareous clasts and higher concentrations of reductant phases such as graphite and/or molybdenite-bearing clasts in the till. Even though most surface-till deposits were streamlined landforms, glacial transport distance of subglacial till appeared to be short (<500 m). Geochemical anomalies in till that were not related to known bedrock mineralization in the study area occurred in two till samples from the northeastern part of the study area that contained high (>99th percentile of this data set) concentrations of most analyzed elements. These high values in till likely indicate the presence of polymetallic-type mineralization, containing base and precious metals, and REEs, which may be skarn-related.

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 75-B). Data *adapted from* McCurdy et al. (2012b, c, 2015, 2016a).


Cu in lake sediments
High: 887.44 ppm
Low: 0.87 ppm
kilometres
0 25 50 100 150 200
Cu (Abitau Lake)
High : 66.21 ppm
Low : 4.74 ppm
kilometres
0 5 10 20 30 40
NUNAVUT
MANITOBA
NORTHWEST TERRITORIES
SASKATCHEWAN
Lake Athabasca
075M
075N
075L
075K
075E
075F
075D
075C
075B
075A
074M
074N
074O
074P
074I
074J
074G
074H
064L
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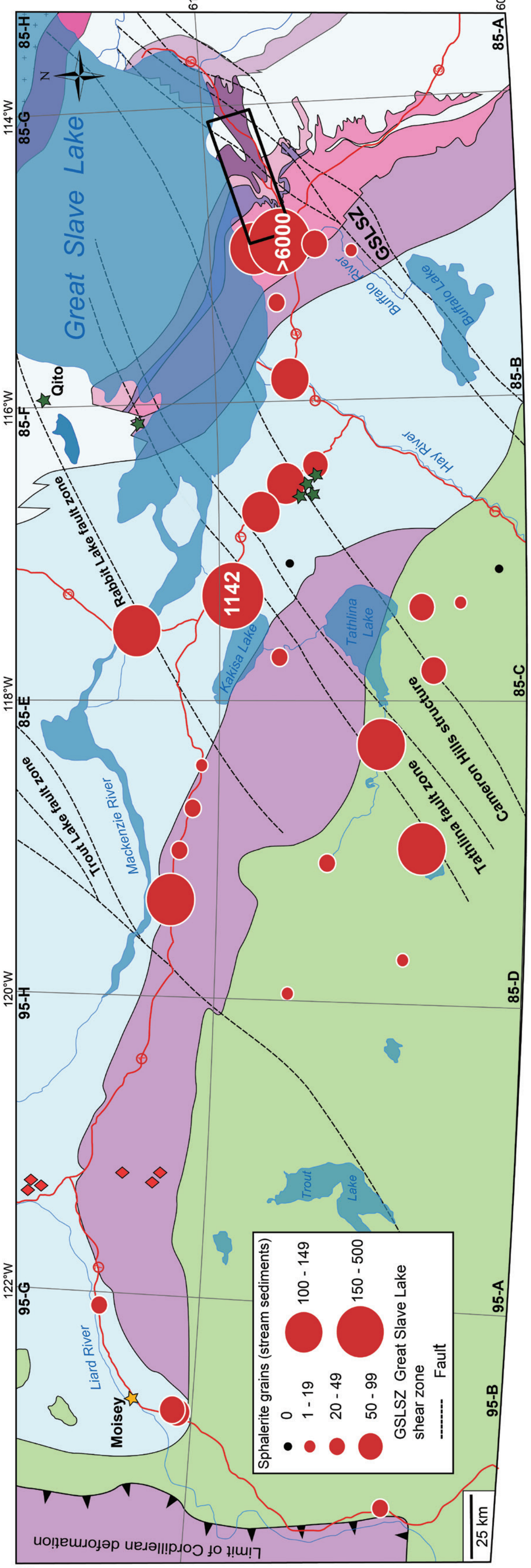
065K
065N
065B
065G
065J
065O
065P
065I
065H
065A
055D
055E
055L
055M
054M
N

a)


Great Slave Lake
GSLSZ
>6000
1142
Buffalo River
Buffalo Lake
Hay River
Qito
Rabbit Lake fault zone
Kakisa Lake
Tathlina Lake
Cameron Hills structure
Tathlina fault zone
Trout Lake fault zone
Mackenzie River
Trout Lake
Liard River
Moisey
Limit of Cordilleran deformation
25 km
Sphalerite grains (stream sediments)
0
1 - 19
20 - 49
50 - 99
100 - 149
150 - 500
GSLSZ Great Slave Lake shear zone
Fault
61°N
60°N
114°W
116°W
118°W
120°W
122°W
85-H
85-G
85-F
85-E
95-H
95-G
85-A
85-B
85-C
85-D
95-A
95-B

b)

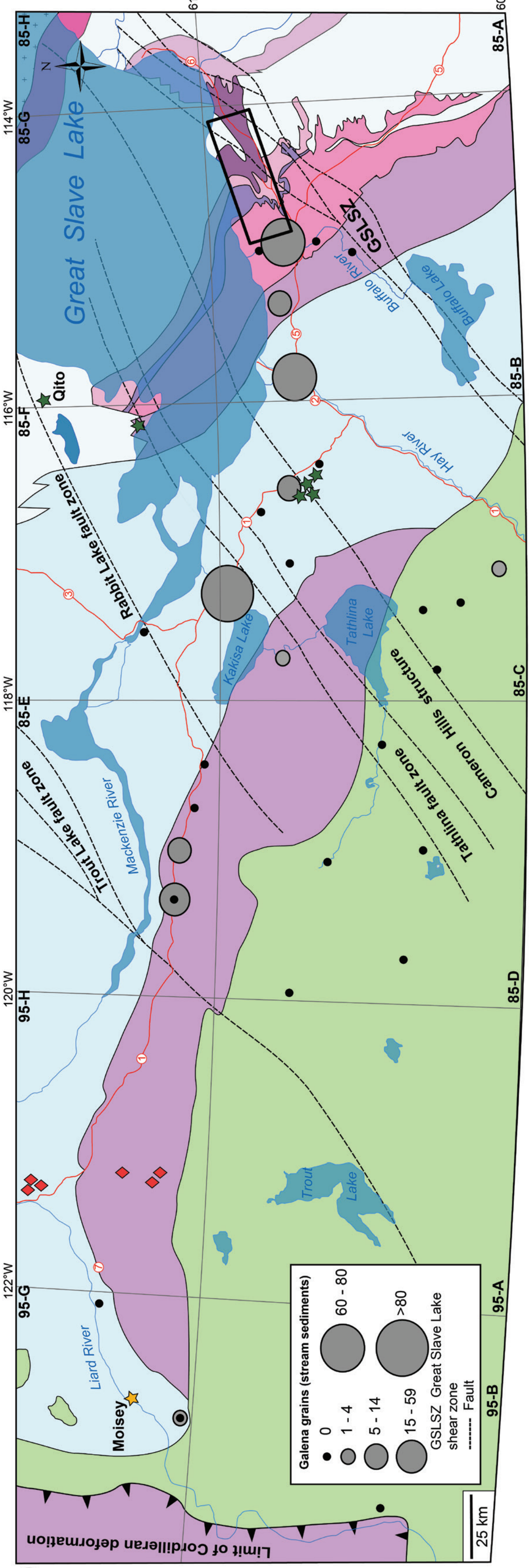

Great Slave Lake
GSLSZ
Buffalo River
Buffalo Lake
Hay River
Qito
Rabbit Lake fault zone
Kakisa Lake
Tathlina Lake
Cameron Hills structure
Tathlina fault zone
Trout Lake fault zone
Mackenzie River
Trout Lake
Liard River
Moisey
Limit of Cordilleran deformation
25 km
Galena grains (stream sediments)
0
1 - 4
5 - 14
15 - 59
60 - 80
>80
GSLSZ Great Slave Lake shear zone
Fault
61°N
60°N
114°W
116°W
118°W
120°W
122°W
85-H
85-G
85-F
85-E
95-H
95-G
85-A
85-B
85-C
85-D
95-A
95-B

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; location of Cu (yellow stars) and other Pb-Zn (green stars) occurrences as well as kimberlite pipes (red diamonds) is shown. *After* Paulen et al. (2018).

DEPOSIT-SCALE SURVEYS

In addition to GEM regional-scale till-sampling surveys, detailed till-sampling studies were conducted by the GSC around the five following known mineral deposits: 1) Izok Lake volcanogenic massive sulphide (VMS) deposit, 2) PinePoint Pb-Zn mining district, 3) Strange Lake REE deposit, 4) iron oxide copper-gold (IOCG) deposits in the Great Bear magmatic zone, and 5) Kiggavik U deposit. Some GEM support was also provided to the study around the Amaruq gold deposit (de Bronac de Vazelhes, 2019; de Bronac de Vazelhes et al., 2021). Highlights from the first 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; Ghosh and Praveen, 2008; O'Brien et al., 2014), a Zn-spinel that is visually distinctive (Fig. 16) and physically robust. With the use of 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 a younger northwest ice flow (Fig. 17) (McClenaghan et al., 2012a, b, 2013b, 2014a, 2015; Paulen et al., 2013). Re-examination of archived GSC till HMCs to look for gahnite revealed that the gahnite dispersal fan extended 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 HMC 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.

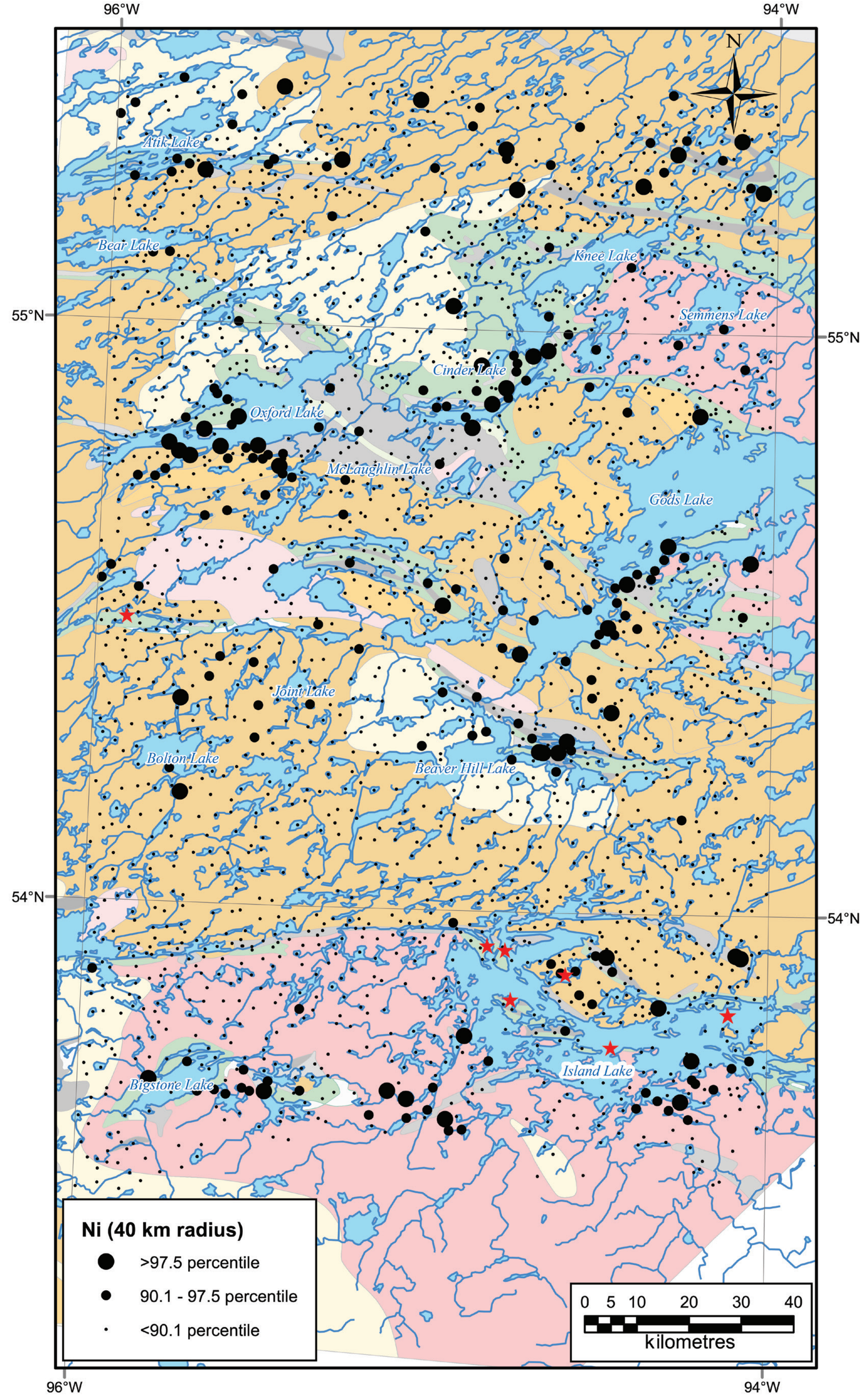
Glacial dispersal of metal-rich till from the Izok Lake VMS deposit was detected up to 6 km down ice by using till geochemistry of closely spaced (500 m) till samples (Hicken et al., 2012; McClenaghan et al., 2015). Indicator elements for the deposit include Cu, Pb, Zn, and Ag, and pathfinder elements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

The Izok Lake case study confirmed that till sampling is a viable VMS exploration method in the region and demonstrated that a palimpsest pattern of glacial dispersal in the region could be defined using indicator minerals and till geochemistry (transport data), combined with detailed ice-flow mapping. Results from this case study suggested 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 allow detection of geochemical dispersal patterns from the Izok Lake deposit but was useful for detecting gahnite dispersal (McClenaghan et al., 2012b).

Pine Point MVT Pb-Zn deposit

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, included 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

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. The 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 (red stars) is indicated. Bedrock geology and figure *from* McCurdy et al. (2017).


96°W
94°W
N
Atik Lake
Bear Lake
Knee Lake
Semmens Lake
55°N
Cinder Lake
Oxford Lake
McLaughlin Lake
Gods Lake
Joint Lake
Bolton Lake
Beaver Hill Lake
54°N
Island Lake
Bigstone Lake
Ni (40 km radius)
>97.5 percentile
90.1 - 97.5 percentile
<90.1 percentile
0 5 10 20 30 40
kilometres

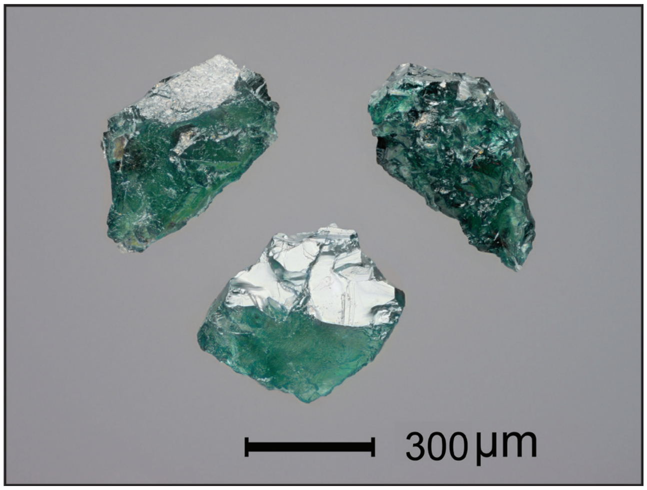


Figure 16. Colour photograph of blue-green, sand-sized gahnite grains used as an indicator mineral to map dispersal from the high-grade metamorphosed Izok Lake volcanogenic massive sulphide deposit, Nunavut. Photograph by Michael J. Bainbridge Photography.

dispersal train defined best by sphalerite (Fig. 19a, b), galena, and Zn (Fig. 19c, d) as well as by 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 acted 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 (0–4 m depth) in the district contained large numbers of fresh sulphide grains (Fig. 20). In contrast, carbonate and sulphide minerals in till were easily and quickly destroyed by postglacial 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 mining district included Zn, Pb, Cd, Tl, and S.

Comparisons by Oviatt et al. (2015, 2017) of S and Pb isotopes for galena and sphalerite in bedrock and till indicated 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 demonstrated 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 confirmed 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 the southwestern region of the Northwest Territories (Paulen et al., 2019). In the eastern part of the Pine Point mining district, where the till is generally thin (<5 m), surface-till sampling is cost effective; farther 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, defined a palimpsest pattern of glacial transport in the region that should be considered when tracing anomalies in till or stream sediments.

Strange Lake REE deposit

As part of the GEM Hudson–Ungava project, a study of REE 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) nonferromagnetic 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 contained oxide, silicate, phosphate, and carbonate indicator minerals, some of which (cerianite, uraninite, fluorapatite, rhabdophane, thorianite, danburite, and aeschynite) had not been reported in previous bedrock studies of Strange Lake. Indicator minerals (Fig. 21) that could be useful in the exploration for similar deposits included Zr-silicates (zircon, secondary gittinsite and other hydrated Zr±Y±Ca-silicates), pyrochlore, and thorite, as well as the REE-containing minerals monazite, chevkinite, parisite, bastnaesite, kainosite, and allanite (McClenaghan et al., 2019).

The Strange Lake dispersal train had a remarkable ribbon shape that extended more than 50 km down ice to the east-northeast that was defined by high REE 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 placed the Strange Lake train directly within the trunk of the Kogaluk River ice stream (KRIS), one of several 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:width ratios exceeding 12 within the train.

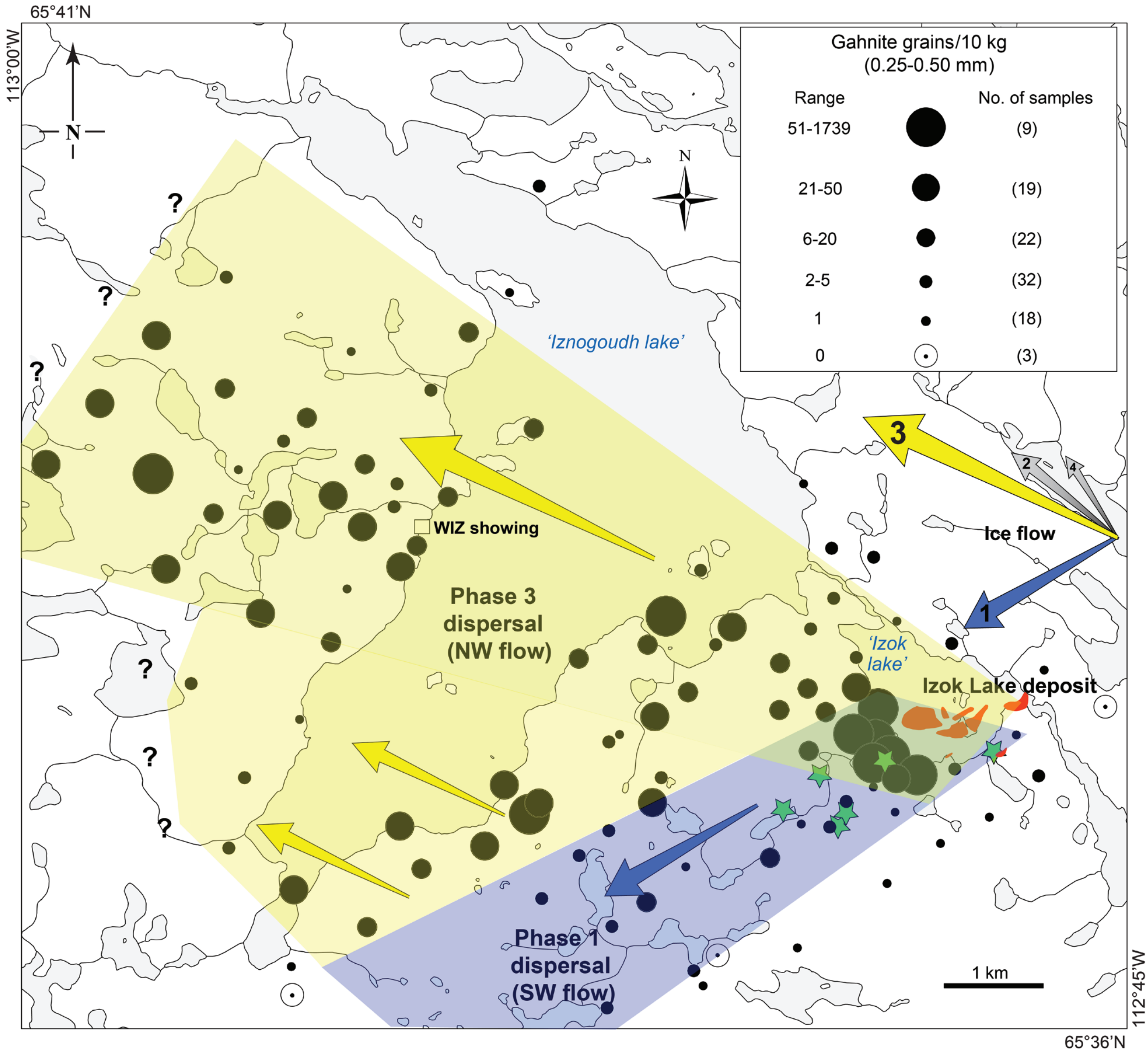


Figure 17. Proportional-dot map of gahnite abundance in surface till normalized to a 10 kg sample mass around the Izok Lake volcanogenic massive sulphide (VMS) deposit, showing the proximal part of the 40 km long dispersal fan formed by older southwest (blue polygon) and younger northwest (yellow polygon) 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* McClenaghan et al., 2015). Locations of gahnite-bearing rocks at surface indicated by green stars and locations of massive sulphide indicated by solid red polygons (MMG Ltd., unpub. data, 2012).

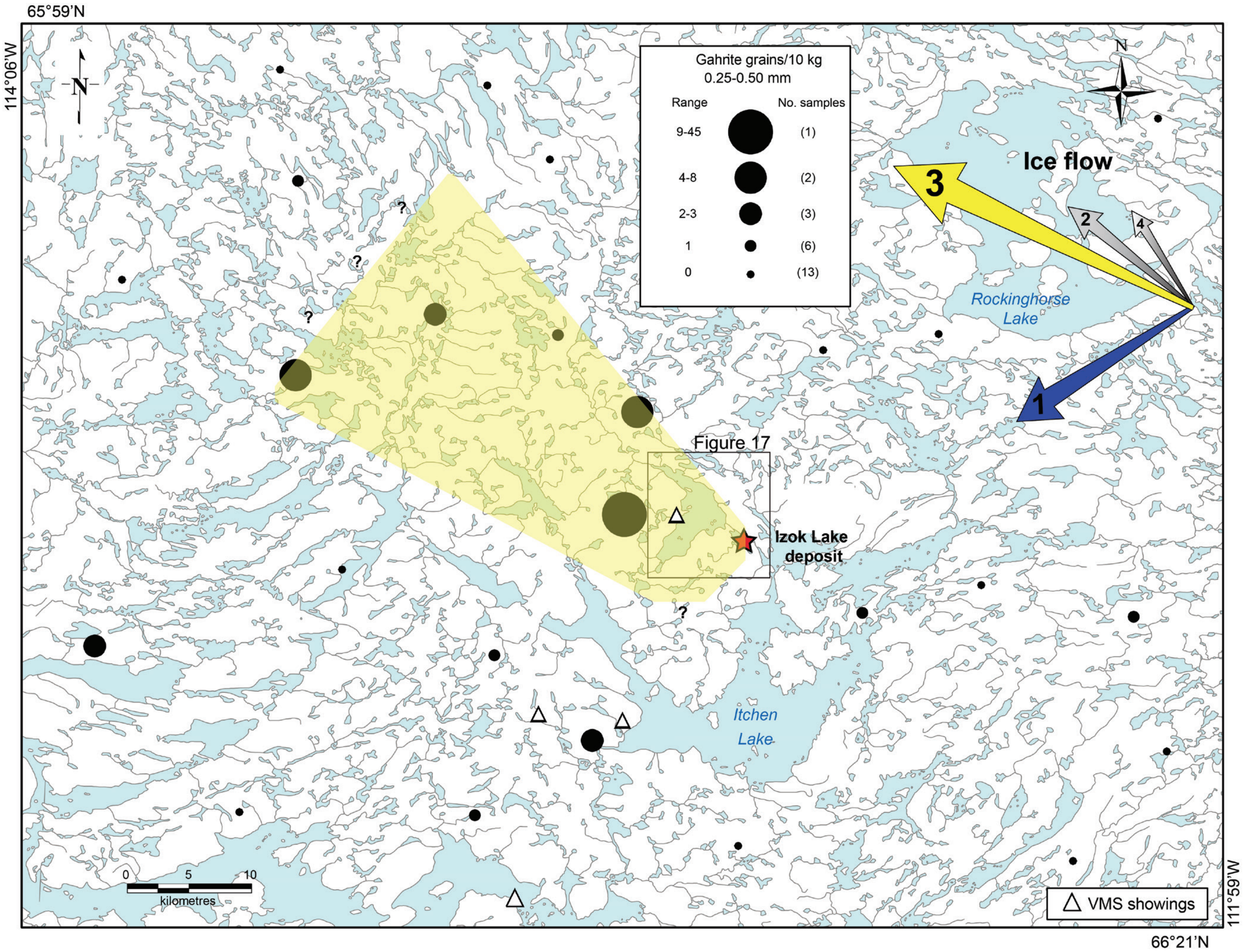


Figure 18. Proportional-dot map of gahnite abundance in surface till normalized to a 10 kg sample mass, showing a 40 km long dispersal fan (yellow polygon) formed by northwest ice flow across the Izok Lake volcanogenic massive sulphide (VMS) deposit. Arrows indicate regional relative ice-flow chronology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

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 the 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 its source with little dilution, similar to Klassen's idealized linear distribution curve (Fig. 22b; Klassen, 1997). 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-sediment data described above (Amor et al., 2016, 2019; McCurdy et al., 2018), showed that the distributions of Hf, Sn, and Zr in lake sediments defined a glacial dispersal train from Strange Lake that was much longer (150 km) than originally recognized. This study also demonstrated that lake-sediment geochemical data can be used to identify glacial dispersal trains formed by ice streams.

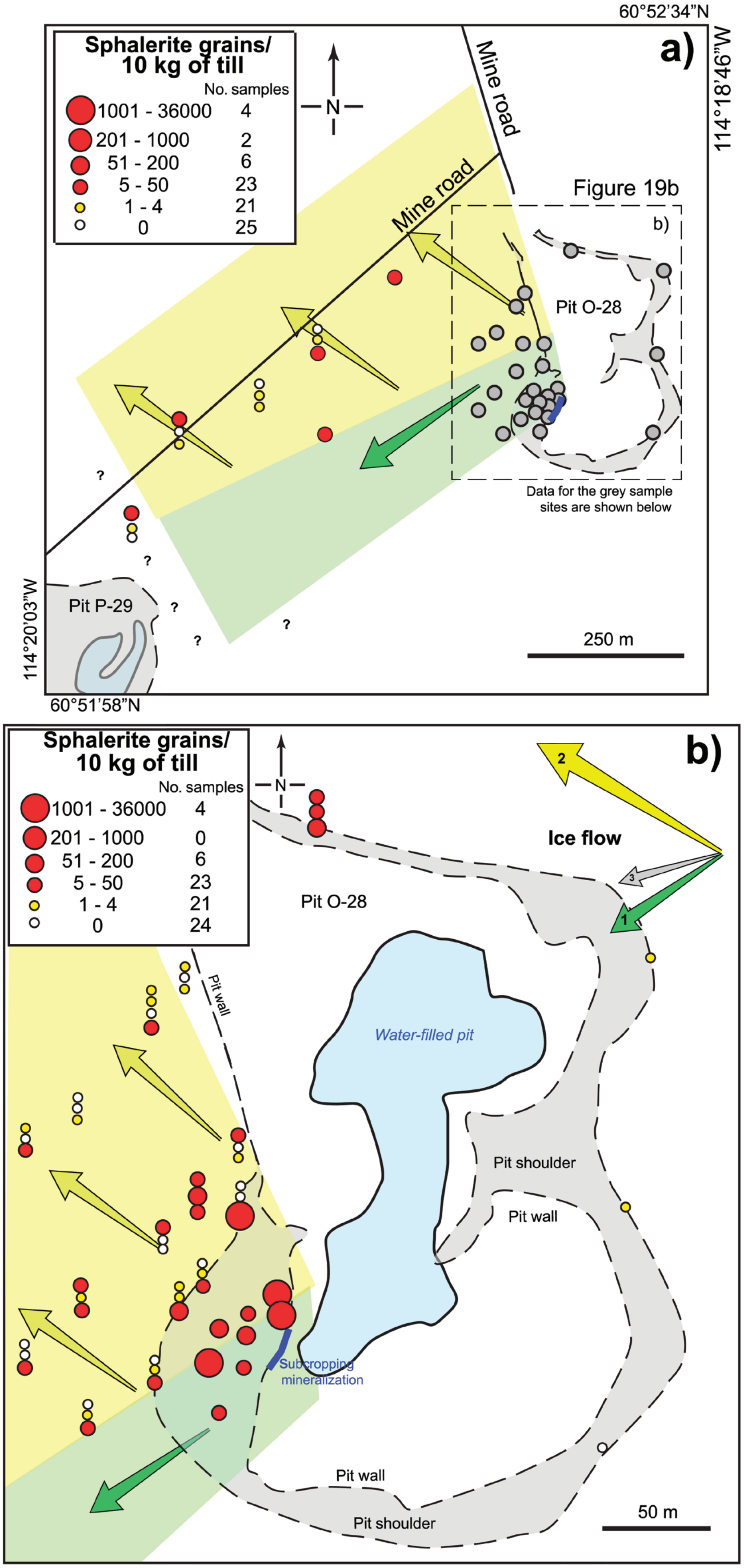
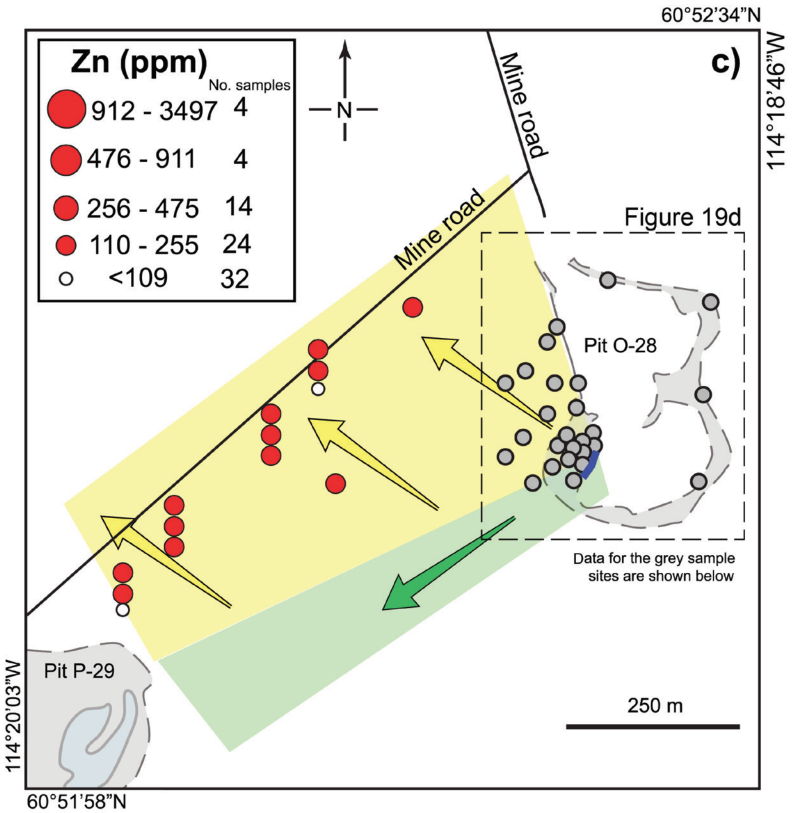


Figure 19. Till composition and ice-flow trends in the area of pit O-28 in the eastern part of the Pine Point Pb-Zn mining district, Northwest Territories. Distribution of sphalerite grains in the 0.25–0.5 mm nonferromagnetic heavy-mineral fraction of till in the area: **a)** west and southwest of the deposit; **b)** immediately west of the open pit.



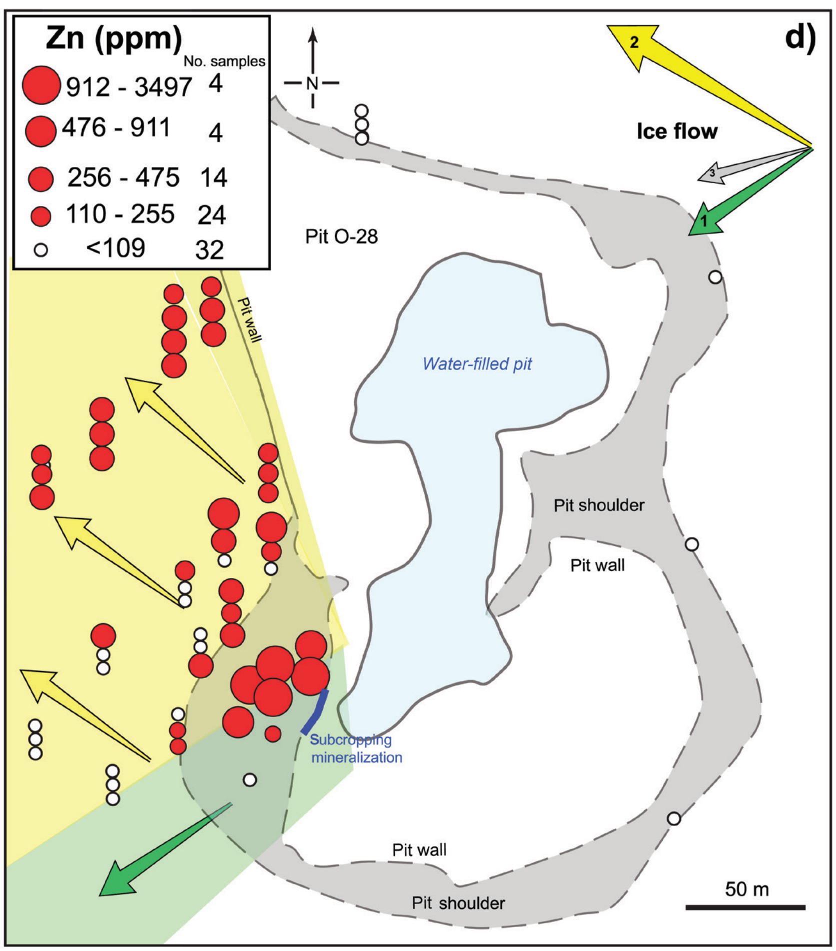


Figure 19. (cont.) Distribution of Zn (ppm) in the fraction smaller than 0.063 mm of till in the area **c)** west and southwest of deposit; and **d)** immediately west of the open pit. At sites where more than one till sample was collected at different depths, the data are plotted as vertically stacked 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).

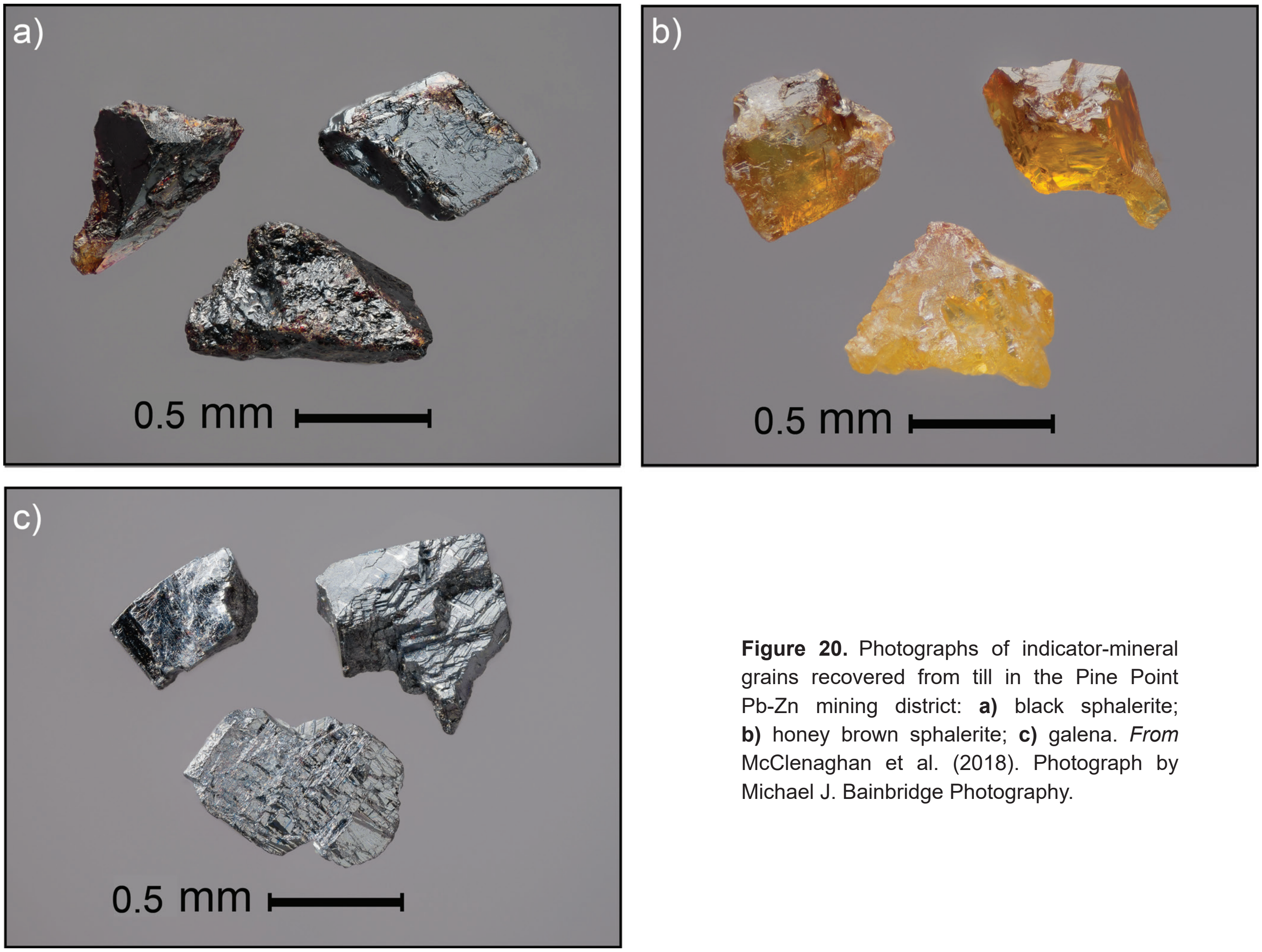


Figure 20. Photographs of indicator-mineral grains recovered from till in the Pine Point Pb-Zn mining district: **a)** black sphalerite; **b)** honey brown sphalerite; **c)** galena. *From* McClenaghan et al. (2018). Photograph by Michael J. Bainbridge Photography.

Great Bear magmatic zone IOCG 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 (area 21 in Fig. 1) in the Great Bear magmatic zone (GBMZ) in the Northwest Territories (Lypaczewski et al., 2013; Normandeau and McMartin, 2013; Normandeau, 2018; Normandeau et al., 2018). This research was funded, in part, by the GEM program.

Gold-grain abundance, size, and shape, as well as magnetite and hematite compositions, reflected 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, as well as 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 varied depending on till cover, the 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 indicated 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 fraction smaller than 0.063 mm and Cu (Fig. 23a, b), Mo, and Bi (aqua regia/ICP-MS) in the fraction smaller than 0.002 mm of till were the most useful pathfinders to mineralization.

REVIEWS OF KEY CONCEPTS AND METHODS

Indicator minerals and till geochemical methods for exploration

The GEM-program contributions to surficial geochemistry and mineralogy include timely reviews of key concepts and methods. The overview of glacial dispersal processes and the application of drift prospecting to mineral exploration in

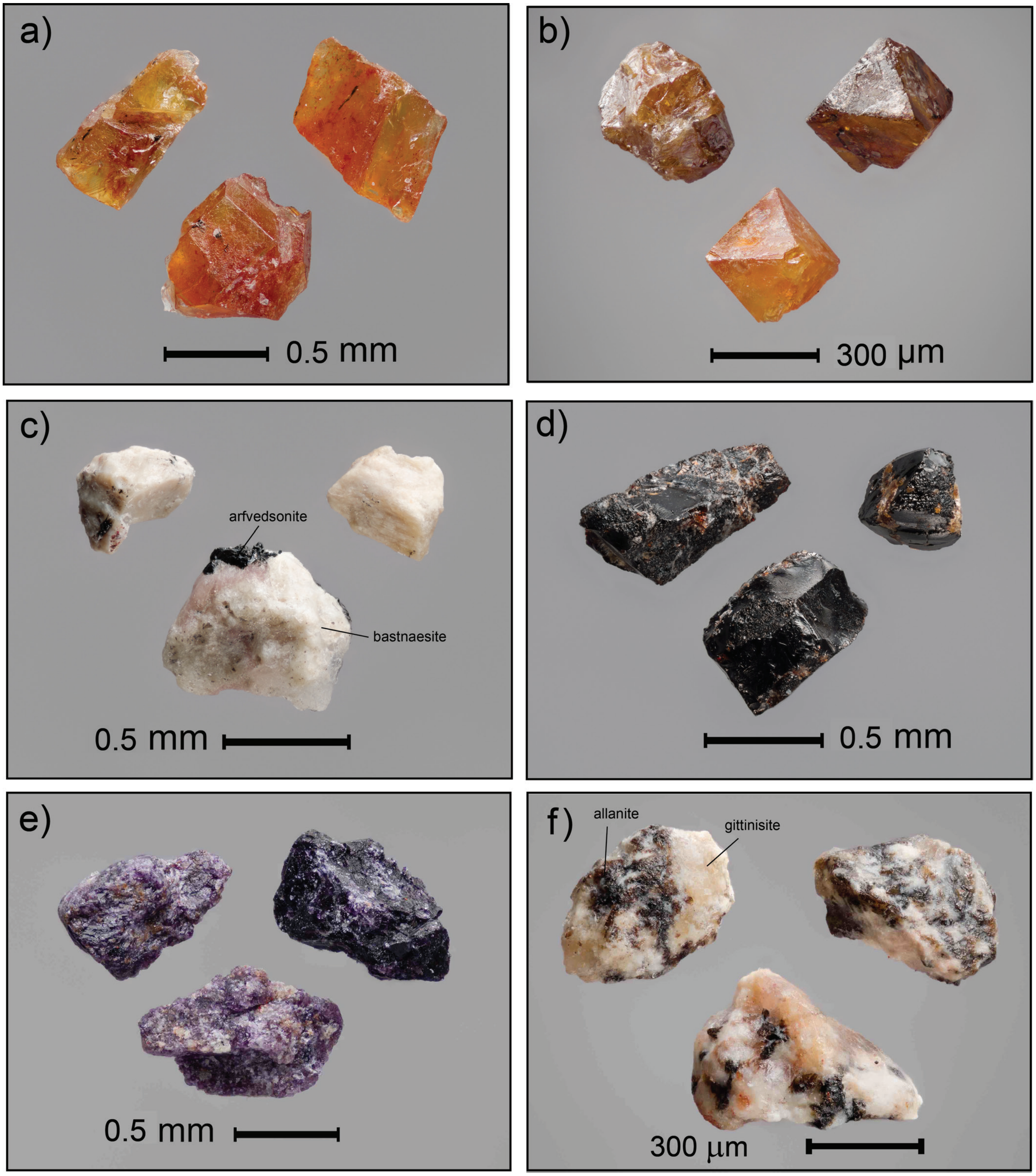


Figure 21. Photographs of selected indicator minerals from bedrock or from till samples overlying and down ice of the Strange Lake rare-earth element deposit: **a)** orange monazite; **b)** orange-brown octahedral pyrochlore; **c)** white bastnaesite; **d)** black chevkinite; **e)** dark purple fluorite;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

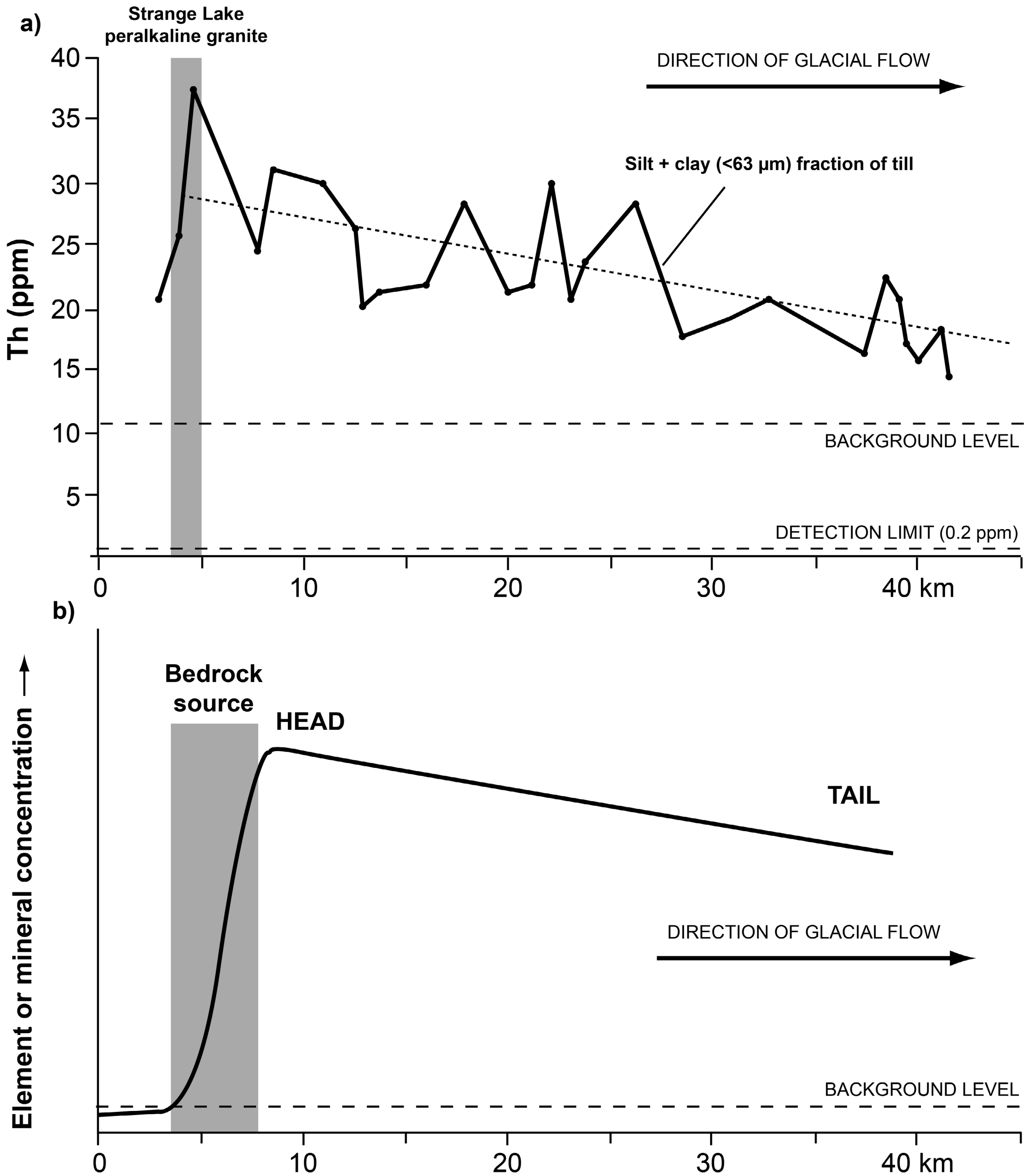


Figure 22. **a)** Line plot of thorium (Th) concentration in the fraction smaller than 0.063 mm of surface till, down ice of the Strange Lake rare-earth element deposit in northern Quebec and Labrador, with the best-fit data curve shown as a dashed line. Data *from* Batterson and Taylor (2009). **b)** 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. *Modified from* Paulen et al. (2017).

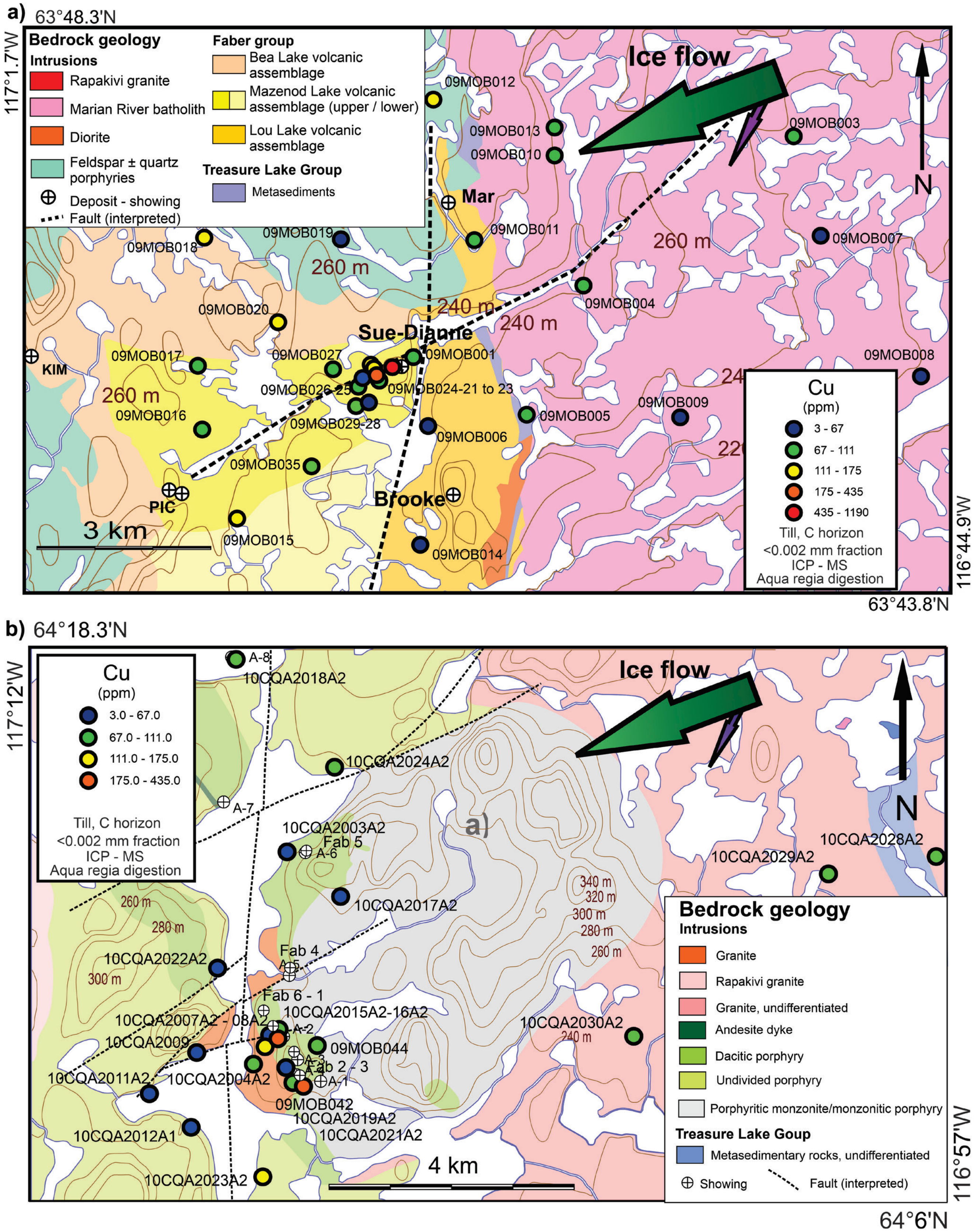


Figure 23. Dot map of copper (Cu) concentrations in the fraction smaller than 0.002 mm of surface till determined by aqua regia digestion followed by inductively coupled plasma mass spectrometry (ICP-MS) around the **a)** Sue-Dianne Cu-Ag-Au deposit. **b)** Fab Cu-U occurrence in the Great Bear magmatic zone, Northwest Territories. *After* Normandeau (2018).

the glaciated terrains of Canada by McClenaghan and Paulen (2018) is the most comprehensive paper. These authors reviewed 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 became 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 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) reported examples of till geochemical and indicator-mineral signatures for a broad suite of mineral-deposit types that included key GEM results.

The GEM program contributions to surficial geochemistry and mineralogy also include two sets of conference workshop 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 used in the exploration of a broad range of deposit types were reviewed, including orogenic gold, diamond, volcanogenic massive sulphide, porphyry copper, rare metal, and intrusion-hosted tungsten deposits. Topics also included heavy-mineral sample processing methods and microanalytical techniques for indicator minerals.

The GEM program also supported the publication of conference workshop notes that 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. Campbell, 2009; Paulen, 2009a, b; Stea et al., 2009) provided the impetus for GEM research on the use of indicator minerals at the Izok Lake, Pine Point, and Kiggavik deposits.

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 of glacial dispersal, as well as those of 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 data sets 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- and clay-sized fragments. Chromium-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.

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; the map was synthesized from published literature and included 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

The GEM-funded 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 handheld 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., 2014b). 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 and to unsieved versus sieved till and making determinations through plastic sandwich bags if nothing else is available (Peter et al., 2010; Hall and McClenaghan, 2017; Plourde et al., 2013; Kjarsgaard et al., 2014a, b; Sarala et al., 2015; Hall et al., 2016; Sarala, 2016). Knight et al. (2013b) and Rukhlov (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 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 1 000 000 km^2 in northern Canada to assess the potential for hosting not only precious, base, rare, and strategic metals, but also uranium and diamonds.
- Indicator-mineral and till geochemical data are essential components of all GEM surficial mapping projects (Kerr et al., this volume). 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, focusing 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 results will also help direct the GSC's future regional bedrock and metallogenic mapping activities to areas in which they can be most productive.
- The GSC's archive 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 reanalyzed 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 at the Izok Lake VMS deposit also demonstrated the robustness of gahnite as an indicator mineral. Studies at deposits in the 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. The GEM geochemical and indicator-mineral surveys covered about 1 000 000 km^2 of northern Canada. This new coverage, combined with earlier GSC and territorial geochemical surveys, leaves about one third of Canada's north still to be assessed 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 laboratory geochemical methods such as pXRF, laser-induced breakdown spectrometry, and portable Fourier transform infrared spectrometry can assist in 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, Campbell et al., this volume), 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 its impact on surface exploration methods remain poorly known. The interpretation of newly mapped glacial land systems and new ages determined for surface materials (using terrestrial cosmogenic nuclides, infrared stimulated luminescence, ^{14}C) will help evaluate the significance of inheritance with regard to glacial erosion. The net effect of complex ice-flow dynamics and changing basal-ice thermal regimes will lead to a better understanding of sediment provenance in key regions of the Canadian Shield covered by glacial sediments (McMartin, Campbell et al., this volume; Parent, this volume; Rice et al., this volume; Tremblay and Lamothe, this volume).
- The GSC protocols for collection and analysis of lake and stream sediments, as well as till, will continue to evolve, including improved analytical methods, lower analytical detection limits, and faster more efficient data capture in the field, such as used in Australia (e.g. Noble et al., 2020).
- The GEM and older GSC geochemical and indicator-mineral data sets present new opportunities for mineral exploration using artificial intelligence–deep learning initiatives. Combining lake- and stream-sediment and till data as part of the interpretation will be particularly insightful to data mining and analytics.

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Appendix A

Listing of government publications that report Geo-mapping for Energy and Minerals (GEM) program geochemical data for lake-sediment, lake-water, stream-sediment, stream-water, and till samples

Active individual web links to metadata for each data set (those associated to projects are highlighted in yellow) in the Canadian Database of Geochemical Surveys (CDoGS) are listed in a separate column in Table A1.

Contents

Table A1.

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived samples	Publication	CDoGS survey or project metadata	Authors	Year published	Title
Nunavut	Melville Peninsula	Regional	Lake sediment, lake water	Yes	OF 6269	210152	Day et al.	2009	Regional lake sediment and water geochemical data, Melville Peninsula, Nunavut (parts of NTS 046N, O, P, 047A and B)
Nunavut	Melville Peninsula	Regional	Till	Yes	OF 6285	210014	Dredge	2009	Till geochemistry, and results of lithological, carbonate and textural analyses, northern Melville Peninsula, Nunavut (NTS 47A, B, C, D)
Northwest Territories	Victoria Island	Regional	Stream sediment, stream water	Yes	OF 6622	210241	McCurdy et al.	2010a	Regional stream sediment and water geochemical data, Victoria Island, Northwest Territories and Nunavut (NTS 77G, 78B, 87E, 87H, 88A)
Manitoba	NE Manitoba	Regional	Lake sediment	Yes	OF 6671	210152	McCurdy et al.	2010b	Regional lake sediment geochemical data, Great Island–Seal River area, Manitoba (NTS 54L, 54M, 64I, 64P)
Northwest Territories	NICO IOCG deposit	Deposit	Till	No	OF 6723	210368	McMartin et al.	2011a	Results from an orientation study of the heavy mineral and till geochemical signatures of the NICO Au-Co-Bi deposit, Great Bear magmatic zone, Northwest Territories, Canada
Nunavut	Baffin Island	Regional	Till	No	OF 6763	210356	Gammon et al.	2011	Geochemistry and physical properties of till samples collected in 2009 from Cumberland Peninsula, Nunavut
Northwest Territories	Mackenzie Mountains	Regional	Stream sediment, stream water	No	OF 6721	270007	Day et al.	2012	Regional stream sediment and water geochemical data, Cranswick River area, Northwest Territories (parts of NTS 106F and G)
Manitoba	NE Manitoba	Regional	Till	No	OF 6967	210367	Campbell et al.	2012	Till composition and ice-flow indicator data, Great Island–Caribou Lake area (parts of NTS 54L, 54M, 64I and 64P), northeast Manitoba
Nunavut	Baker Lake	Regional	Lake sediment, lake water	Yes	OF 6985	210152	McCurdy et al.	2012c	Regional lake sediment and water geochemical data, Baker Lake area, Nunavut (NTS 55M and 65P)
Nunavut	Nueltin Lake	Regional	Lake sediment, lake water	Yes	OF 6986	210152	McCurdy et al.	2012b	Regional lake sediment and water geochemical data, Nueltin Lake area, Nunavut (NTS 65A, 65B and 65C)
Nunavut	Izok Lake VMS deposit	Deposit	Till	No	OF 7046	210366	Hicken et al.	2012	Till geochemical signatures of the Izok Lake Zn-Cu-Pb-Ag volcanogenic massive sulphide deposit, Nunavut
Nunavut	Melville Peninsula	Regional	Till	No	OF 7115	310005	Tremblay and Paulen	2012	Glacial geomorphology and till geochemistry of central Melville Peninsula, Nunavut
Northwest Territories	Victoria Island	Regional	Stream sediment, stream water	No	OF 7198	210365	McCurdy et al.	2012a	Geochemical, mineralogical and kimberlite indicator mineral data for silts, heavy mineral concentrates and waters from two geochemical surveys (2010 and 2011) on Victoria Island, Northwest Territories (NTS 87G, 87H, 88A and 88B)

Table A1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived samples	Publication	CDoGS survey or project metadata	Authors	Year published	Title
Manitoba	NW Manitoba	Regional	Till	No	Manitoba GP2013-1	060041	Trommelen et al.	2013	Till composition and ice-flow indicator data, Snyder Lake area, northwestern Manitoba
Nunavut	Wager Bay north	Regional	Till	No	OF 7288	210387	McMartin et al.	2013a	Till composition and ice-flow indicators west of Repulse Bay: 2010 and 2011 results from the GEM Wager Bay Surficial Geology Activity
Northwest Territories	Great Bear magmatic zone	Regional	Till	No	OF 7307	210388	Normandeau and McMartin	2013	Composition of till and bedrock across the Great Bear magmatic zone: Quaternary field database and analytical results from the GEM IOCG-Great Bear project
Manitoba	Kasmere Lake–Nueltin Lake	Regional	Lake sediment	Yes	OF 7309	210152	McCurdy et al.	2013c	Regional lake sediment geochemical data, Kasmere Lake–Nueltin Lake area, Manitoba (NTS 64-K, 64-N, 64-O)
Northwest Territories	Pine Point mining district	Deposit	Till	No	OF 7320	210337	Oviatt et al.	2013b	Till geochemical signatures of the Pine Point Pb-Zn Mississippi Valley-type district, Northwest Territories
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7351*	210386	Kjarsgaard et al.	2013c	Geochemistry of till samples, NTS 75-I, 75-J, 75-O, 75-P (Mary Frances Lake – Whitefish Lake – Thelon River area, Northwest Territories)
Northwest Territories	Victoria Island	Regional	Stream sediment, stream water	No	OF 7374	210365	McCurdy et al.	2013a	Exploring for Pb and Zn using indicator minerals with stream silt and water geochemistry in the Canadian arctic islands: an example from Victoria Island, NWT
Northwest Territories	East Arm, Great Slave Lake	Regional	Till, esker sediment	No	OF 7408*	210386	Plourde et al.	2013	Portable XRF spectrometry of surficial sediments, NTS 75-I, 75-J, 75-O, 75-P (Mary Frances Lake – Whitefish Lake – Thelon River area), Northwest Territories
Nunavut	Tehery–Wager Bay south	Regional	Till	No	OF 7417	210389	McMartin et al.	2013b	Till composition across the Rae Craton south of Wager Bay, Nunavut: results from the Geo-mapping Frontiers' Tehery–Cape Dobbs project
Nunavut	Central Nunavut	Regional	Till	No	OF 7418	210390	McMartin et al.	2013c	Till composition of a transect across the Thelon tectonic zone, Queen Maud Block, and adjacent Rae Craton: results from the Geo-mapping Frontiers' Chantrey project
Nunavut	Lorillard River	Regional	Stream sediment, stream water	No	OF 7428	210385	Day et al.	2013	Preliminary geochemical, mineralogical and indicator mineral data for stream silts, heavy mineral concentrates and waters, Lorillard River area, Nunavut (parts of NTS 56-A, -B, and -G)
Nunavut	Duggan Lake	Regional	Stream sediment, stream water	No	OF 7471	210384	McCurdy et al.	2013b	Geochemical, mineralogical and kimberlite indicator mineral data for silts, heavy mineral concentrates and waters, Duggan Lake area (NTS 76-H and 76-I South)
Nunavut	Kiggavik U deposit	Deposit	Till	No	OF 7550	210394	Robinson et al.	2014	Till geochemical signatures of the Kiggavik uranium deposit, Nunavut

Contents

Table A1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived samples	Publication	CDoGS survey or project metadata	Authors	Year published	Title
Northwest Territories	Pine Point mining district	Regional	Stream sediment, stream water	No	OF 7577	210337	McCurdy and McNeil	2014	Geochemical data from stream silts and surface waters in the Pine Point mining district, Northwest Territories (NTS 85-B)
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7649*	210407	Kjarsgaard et al.	2014a	Geochemistry of regional surficial sediment samples from the Thelon River to the East Arm of Great Slave Lake, Northwest Territories, Canada
Northwest Territories	Flat River area	Regional	Stream sediment, stream water	No	NWT Open Report 2015-002	270008	Falck et al.	2015	Geochemical, mineralogical and indicator mineral data for stream silt sediment, heavy mineral concentrates and waters, Flat River area, Northwest Territories, (part of NTS 95E, 105H and 105I).
Saskatchewan	Northern Saskatchewan	Regional	Lake sediment, lake water	Yes	OF 7746	210152	McCurdy et al.,	2015	Regional lake sediment and water geochemical data, northern Saskatchewan, (NTS 64-L, 64-P, 74-N, 74-O and 74-P)
Nunavut	Wager Bay north	Regional	Till	No	OF 7748	210387	McMartin et al.	2015	Quaternary geology and till composition north of Wager Bay, Nunavut: results from the GEM Wager Bay Surficial Geology project
Nunavut	Izok Lake VMS deposit	Deposit	Till	No	OF 7770	210376	Paulen et al.	2015	Till geochemistry data for till samples from the Izok Lake Zn-Cu-Pb-Ag volcanogenic massive sulphide deposit, Nunavut: till samples collected in 2012
Nunavut	Ellice River	Regional	Till	No	OF 7910	210410	McMartin and Berman	2015	Till composition across the MacAlpine moraine system: results from the GEM-2 Thelon tectonic zone project, Nunavut (NTS 76-H and NTS 76-I)
Nunavut	Sylvia Grinnell Lake area, Baffin Island	Regional	Till	No	CNGO GDS 2016-001	310008	Tremblay et al.	2016b	Data tables accompanying geochemical, mineralogical and sedimentology results on till, stream and lake sediment and water samples in the Sylvia Grinnell Lake area, Baffin Island, Nunavut
Nunavut	Melville Peninsula	Regional	Till	No	OF 7494	310007	Tremblay et al.	2016a	Glacial geomorphology and till geochemistry and mineralogy of southern Melville Peninsula, Nunavut
Northwest Territories	Abitau Lake	Regional	Lake sediment, lake water	No	OF 8082	210431	McCurdy et al.	2016a	Geochemical data for lake sediments and surface waters, Abitau Lake area, Northwest Territories (NTS 75-B)
Nunavut	Ellice River	Regional	Stream sediment	No	OF 7887	210429	McCurdy et al.	2016c	Geochemical and mineralogical data for stream silts, stream waters and heavy mineral concentrates, Ellice River area, Nunavut (parts of NTS 76-H and NTS 76-I)
Quebec; Newfoundland and Labrador	Northern Quebec–Labrador	Regional	Till	No	OF 7967	220012	McClenaghan et al.	2016a	Till geochemical data for the south Core Zone, Quebec and Labrador (NTS 23-P and 23-I): till samples collected in 2014

Table A1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived samples	Publication	CDoGS survey or project metadata	Authors	Year published	Title
Northwest Territories	East Arm, Great Slave Lake	Regional	Lake sediment	Yes	OF 8010	210152	McCurdy et al.	2016d	Regional lake sediment geochemical data, Nonacho Basin – East Arm of Great Slave Lake region, Northwest Territories (NTS 75-C, NTS 75-F and NTS 75-K)
Newfoundland and Labrador	Labrador	Regional	Lake sediment	Yes	OF 8017	210216	McCurdy	2016	Regional lake sediment and water geochemical data, Labrador, Newfoundland and Labrador (NTS 13-L, 14-C, 14-E, 14-F, 14-L, 23-J, 23-O, 24-A, 24-H and 24-I)
Newfoundland and Labrador	Labrador	Regional	Lake sediment	Yes	OF 8026	210216	McCurdy et al.	2016b	Regional lake sediment and water geochemical data, western and central Labrador (NTS 13-L, 13-M, 14-D, 23-I, and 23-J)
Nunavut	Ellice River	Regional	Till	No	Current Research 2017-1	210410	McMartin	2017	Till provenance aross the terminus of the Dubawnt Lake ice stream, central Nunavut
Manitoba	NE Manitoba	Regional	Lake sediment	Yes	OF 8179	210190	McCurdy et al.	2017	Geochemical data for lake sediments in the Superior Province of Manitoba (NTS 53-E, 53-L and 53-M)
Quebec; Newfoundland and Labrador	Northern Quebec–Labrador	Regional	Till	Yes	OF 8219	210421	Rice et al.	2017a	Till geochemical data for the southern Core Zone, Quebec and Newfoundland and Labrador (NTS 23-P and 23-I): samples collected in 2015 and 2016
Nunavut	Ellice River	Regional	Stream sediment, till	No	OF 8302	210430	McCurdy and McMartin	2017	Geochemical and mineralogical data for stream sediment and proximal till sites, Ellice River area, Nunavut (parts of NTS 76-H and NTS 76-I)
Nunavut	Baffin Island	Regional	Lake sediment	Yes	CNGO GDS2018-001	210152	McNeil et al.	2018b	Data tables accompanying geochemical reanalysis of archived regional lake sediment samples, central Baffin Island, Nunavut
Nunavut	Baffin Island	Regional	Lake sediment	Yes	CNGO Summary of Activities 2018	210152	McNeil et al.	2018a	Geochemical reanalysis of archived regional lake sediment samples, central Baffin Island, Nunavut
Quebec; Newfoundland and Labrador	Northern Quebec–Labrador	Regional	Lake sediment	Yes	OF 8348	210216	McCurdy et al.	2018	Geochemical atlas of northeastern Quebec and adjacent areas in Labrador
Quebec; Newfoundland and Labrador	Northern Quebec–Labrador	Regional	Till	No	OF 8337	210421	Hagedorn et al.	2018	Radiometric domains and the integration of multiple gamma-ray data sources for a remote area of northern Quebec
Nunavut	Baffin Island	Regional	Lake sediment, lake water	Yes	OF 8590	210152	Bonham-Carter et al.	2019	Lake sediment geochemical evaluation of the mineral potential of west-central Baffin Island, Nunavut

Contents

Table A1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived samples	Publication	CDoGS survey or project metadata	Authors	Year published	Title
Nunavut	Tehery–Wager Bay south	Regional	Till	No	OF 8563	210436	McMartin et al.	2019a	Till composition across the Keewatin Ice Divide in the Tehery–Wager GEM-2 Rae project area, Nunavut
Nunavut	Axel Heiberg Island	Regional	Stream sediment	No	OF 8719	210432	McNeil et al.	2020	Geochemical, mineralogical, and indicator-mineral data for stream silt sediment, water, and heavy-mineral concentrates, East Fiord area, western Axel Heiberg Island, Nunavut (part of NTS 59-G)
Northwest Territories	South Rae, NWT	Regional	Till	No	OF 8714	210220	Campbell et al.	2020	Field data, till composition, and ice-flow history, South Rae Craton, Northwest Territories: results from the GEM2 South Rae project–Surficial Mapping activity
Nunavut; Northwest Territories	Central Nunavut and eastern NWT	Regional	Till	No	OF 8808	210221	Campbell et al.	2021	Field data and till composition in the GEM-2 Rae Glacial Synthesis activity field areas, Nunavut and Northwest Territories
Nunavut	Boothia Peninsula	Regional	Till	Yes	CNGO GDS2021-002	310011	Tremblay	2021	Geochemistry of glacial sediments, Boothia Peninsula and Melville Peninsula
Nunavut	Tehery–Wager Bay south	Regional	Stream sediment, stream water	No	Not available yet	210435	Day et al.		Stream sedment and water samples collected in 2015 and 2016 predominantly from the headwaters of the Borden and Lorillard rivers
Northwest Territories	Southern Mackenzie	Regional	Till	No	Not available yet	210434	Paulen et al.		Till geochemistry data for till samples from southern Mackenzie region (NTS 85B, 85C, 85D, 85E, 85F, 85G and 95B, 95G, 95H)
Northwest Territories	Southern Mackenzie	Regional	Stream sediment	No	Not available yet	210217	Day et al.		Stream sediment heavy mineral sampling program, geochemistry (waters) for southern NWT, in 2017, 2018 and 2019 (NTS 85B, 85C, 85D, 85E, 85F, 85G and 95B, 95G, 95H)
*** Additional context for OF 7351, 7408, 7649, but not funded by GEM**									
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7196	210407	Kjarsgaard et al.	2013a	Chapter 10: Till geochemistry studies of the Thaidene Nene MERA study area
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7196		Wright et al.	2013	Mineral and energy resource assessment of the proposed Thaidene Nene National Park Reserve in the area of the East Arm of Great Slave Lake, Northwest Territories
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7607	210407	Kjarsgaard et al.	2014b	Portable XRF spectrometry of surficial sediment samples in the region of East Arm, Great Slave Lake, Northwest Territories

Appendix B

Listing of government publications that report Geo-mapping for Energy and Minerals (GEM) program indicator-mineral data for stream-sediment and till samples

Active individual web links to metadata for each data set (those associated with projects are highlighted in yellow) in the Canadian Database of Geochemical Surveys (CDoGS) are listed in a separate column in Table B1.

Table B1.

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived HMC samples	Publication	CDoGS survey or project* metadata	Authors	Year published	Title
Northwest Territories	NICO IOCG deposit	Deposit	Till	No	OF 6723	210368	McMartin et al.	2011a	Results from an orientation study of the heavy mineral and till geochemical signatures of the NICO Au-Co-Bi deposit, Great Bear magmatic zone, Northwest Territories, Canada
Northwest Territories; Manitoba	Sue-Dianne IOCG, Pipe Ni-Cu deposits	Deposit	Till	No	OF 7310	210388	Dupuis et al.	2012	Iron oxide compositions in till samples from the Sue-Dianne IOCG deposit, Northwest Territories and the Pipe Ni-Cu deposit, Manitoba
Nunavut	'Izok lake' (unofficial name) region	Deposit	Till	Yes	OF 7029	210013	McClenaghan et al.	2012b	Indicator mineral counts for regional till samples around the Izok Lake Zn-Cu-Pb-Ag VMS deposit, Nunavut
Nunavut	Izok Lake VMS deposit	Deposit	Till	No	OF 7075	210366	McClenaghan et al.	2012a	Indicator mineral abundance data for bedrock and till samples from the Izok Lake Zn-Cu-Pb-Ag volcanogenic massive sulphide deposit, Nunavut
Nunavut	Melville Peninsula	Regional	Till	No	OF 7115	310005	Tremblay and Paulen	2012	Glacial geomorphology and till geochemistry of central Melville Peninsula, Nunavut
Northwest Territories	Victoria Island	Regional	Stream sediment	No	OF 7198	210365	McCurdy et al.	2012a	Geochemical, mineralogical and kimberlite indicator mineral data for silts, heavy mineral concentrates and waters from two geochemical surveys (2010 and 2011) on Victoria Island, NWT (NTS 87G, 87H, 88A, 88B)
Northwest Territories	Pine Point Pb-Zn district	Deposit	Till	No	OF 7267	210337	McClenaghan et al.	2012c	Indicator mineral abundance data for bedrock, till and stream sediment samples from the Pine Point Mississippi Valley-type Zn-Pb deposits, Northwest Territories
Nunavut	Izok Lake VMS deposit	Deposit	Till	No	OF 7173	210366	Hicken et al.	2013a	Indicator mineral signatures of the Izok Lake Zn-Cu-pb-Ag volcanogenic massive sulphide deposit, Nunavut: part 1 bedrock samples
Nunavut	Wager Bay north	Regional	Till	No	OF 7288	210387	McMartin et al.	2013a	Till composition and ice-flow indicators west of Repulse Bay: 2010 and 2011 results from the GEM Wager Bay Surficial Geology Activity
Northwest Territories	Great Bear magmatic zone	Regional	Till	No	OF 7307	210388	Normandeau and McMartin	2013	Composition of till and bedrock across the Great Bear magmatic zone: Quaternary field database and analytical results from the GEM IOCG-Great Bear project
Northwest Territories	Sue-Dianne, Brooke IOCG deposits	Deposit	Till	No	OF 7319	210388	Lypaczewski et al.	2013	Petrographic and cathodoluminescence characterization of apatite from the Sue-Dianne and Brooke IOCG mineralization systems, Great Bear magmatic zone, Northwest Territories

Table B1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived HMC samples	Publication	CDoGS survey or project* metadata	Authors	Year published	Title
Nunavut	Izok Lake VMS deposit	Deposit	Till	No	OF 7343	210366	Hicken et al.	2013b	Indicator mineral signatures of the Izok Lake Zn-Cu-Pb-Ag volcanogenic massive sulphide deposit, Nunavut: part 2 till
Northwest Territories	Victoria Island	Regional	Stream sediment	No	OF 7374	210365	McCurdy et al.	2013a	Exploring for Pb and Zn using indicator minerals with stream silt and water geochemistry in the Canadian Arctic Islands: an example from Victoria Island, NWT
Nunavut	Izok Lake VMS deposit	Deposit	Till	No	OF 7386	210376	McClenaghan et al.	2013b	Indicator mineral abundance data for till and bedrock samples from the Izok Lake Zn-Cu-Pb-Ag volcanogenic massive sulphide deposit, Nunavut: samples collected in 2012
Nunavut	Tehery–Wager Bay south	Regional	Till	No	OF 7417	210389	McMartin et al.	2013b	Till composition across the Rae Craton south of Wager Bay, Nunavut: results from the Geo-mapping Frontiers' Tehery–Cape Dobbs project
Nunavut	Central Nunavut	Regional	Till	No	OF 7418	210390	McMartin et al.	2013c	Till composition of a transect across the Thelon tectonic zone, Queen Maud Block, and adjacent Rae Craton: results from the Geo-mapping Frontiers' Chantrey project
Northwest Territories	Pine Point Pb-Zn mining district	Deposit	Till	No	OF 7423	210337	Oviatt et al.	2013a	Indicator minerals in till and bedrock samples from the Pine Point Mississippi Valley-type district, Northwest Territories
Nunavut	Lorillard River	Regional	Stream sediment	No	OF 7428	210385	Day et al.	2013	Preliminary geochemical, mineralogical and indicator mineral data for stream silts, heavy mineral concentrates and waters, Lorillard River area Nunavut (parts of NTS 56-A, -B, and -G)
Nunavut	Duggan Lake	Regional	Stream sediment	No	OF 7471	210384	McCurdy et al.	2013b	Geochemical, mineralogical and kimberlite indicator mineral data for silts, heavy mineral concentrates and waters, Duggan Lake area, Nunavut (NTS 76-H and 76-I south)
Northwest Territories	East Arm, Great Slave Lake	Regional	Till, esker sediments	No	OF 7540*	210386	Knight et al.	2013a	Significance of indicator minerals from till and esker samples, NTS 75I, 75J, 75O, 75P (Mary Frances Lake - Whitefish Lake - Thelon River area), Northwest Territories
Nunavut	Izok Lake VMS deposit	Deposit	Till	No	OF 7603	210204	McClenaghan et al.	2014a	Physical features indicating the glacial transport distance of gahnite from the Izok Lake Cu-Zn-Pb-Ag VMS deposit, Nunavut
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7649*	210407	Kjarsgaard et al.	2014a	Geochemistry of regional surficial sediment samples from the Thelon River to the East Arm of Great Slave Lake, Northwest Territories, Canada

Table B1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived HMC samples	Publication	CDoGS survey or project* metadata	Authors	Year published	Title
Northwest Territories	Flat River area	Regional	Stream sediment	No	NWT Open Report 2015-002	270008	Falck et al.	2015	Geochemical, mineralogical and indicator mineral data for stream silt sediment, heavy mineral concentrates and waters, Flat River area, Northwest Territories (part of NTS 95E, 105H and 105I)
Nunavut	Wager Bay north	Regional	Till	No	OF 7748	210387	McMartin et al.	2015	Quaternary geology and till composition north of Wager Bay, Nunavut: results from the GEM Wager Bay Surficial Geology project
Nunavut	Ellice River	Regional	Till	No	OF 7910	210410	McMartin and Berman	2015	Till composition across the MacAlpine moraine system: results from the GEM-2 Thelon tectonic zone project, Nunavut (NTS 76-H and NTS 76-I)
Nunavut	Sylvia Grinnell Lake area, Baffin Island	Regional	Till	No	CNGO GDS 2016-001	310008	Tremblay et al.	2016b	Data tables accompanying geochemical, mineralogical and sedimentology results on till, stream and lake sediment and water samples in the Sylvia Grinnell Lake area, Baffin Island, Nunavut
Nunavut	Melville Peninsula	Regional	Till	No	OF 7494	310007	Tremblay et al.	2016a	Glacial geomorphology and till geochemistry of southern Melville Peninsula, Nunavut
Nunavut	Kiggavik U deposit	Deposit	Till	No	OF 7771	210394	Robinson et al.	2016	Till and bedrock heavy mineral signatures of the Kiggavik uranium deposits, Nunavut
Nunavut	Ellice River	Regional	Stream sediment	No	OF 7887	210429	McCurdy et al.	2016c	Geochemical and mineralogical data for stream silts, stream waters and heavy mineral concentrates, Ellice River area, Nunavut (parts of NTS 76-H and NTS 76-I)
Quebec; Newfoundland and Labrador	East Quebec + west Labrador	Regional	Till	No	OF 7968	210421	McClenaghan et al.	2016b	Indicator mineral abundance data for till samples from the south Core Zone, Quebec and Labrador (NTS 23-P and 23-I): samples collected in 2014
Quebec; Newfoundland and Labrador	East Quebec + west Labrador	Regional	Till	No	OF 8187	210421	Rice et al.	2017b	Indicator mineral abundance data for till samples from the south Core Zone, Quebec and Labrador (NTS 23P and 23I): samples collected in 2015
Quebec; Newfoundland and Labrador	East Quebec + west Labrador	Regional	Till	No	OF 8222	210421	McClenaghan et al.	2017a	Gold grains in till samples from the southern Core Zone, Quebec and Newfoundland and Labrador (NTS 23-P and 23-I): potential for undiscovered mineralization
Quebec; Newfoundland and Labrador	Strange Lake REE deposit	Deposit	Till	No	OF 8240	210427	McClenaghan et al.	2017b	Indicator mineral signature of the Strange Lake rare-earth element deposit, Quebec and Newfoundland and Labrador

Table B1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived HMC samples	Publication	CDoGS survey or project* metadata	Authors	Year published	Title
Nunavut	Ellice River	Regional	Till, stream sediment	No	OF 8302	210430	McCurdy and McMartin	2017	Geochemical and mineralogical data for stream sediment and proximal till sites, Ellice River area, Nunavut (parts of NTS 76-H and NTS 76-I)
Quebec; Newfoundland and Labrador	Strange Lake REE deposit	Deposit	Till	No	OF 8345	210427	McClenaghan et al.	2017c	Rare earth element indicator minerals: an example from the Strange Lake deposit, Quebec and Labrador, eastern Canada
Nunavut	Ellice River	Regional	Till	No	Current Research 2017-1	210410	McMartin	2017	Till provenance aross the terminus of the Dubawnt Lake ice stream, central Nunavut
Northwest Territories	Southern Mackenzie	Regional	Stream sediment	No	OF 8362	210426	Day et al.	2018	Heavy-mineral and indicator-mineral data from stream sediments of southwest Northwest Territories collected in 2017: new potential for undiscovered mineralization
Northwest Territories	Pine Point mining district	Regional	Till, stream sediment	No	OF 8449	270001	King et al.	2018	In situ, microanalytical sulphur and lead isotopic compositions of sulphide indicator minerals from surficial sediments in southwestern Northwest Territories
Newfoundland and Labrador	Hopedale Block, Labrador	Regional	Till	No	Nfld & Lab Open File LAB/1743	100044	Campbell and McClenaghan	2019a	Results of a 2017 indicator mineral pilot study in NTS map areas 13N and 13M, Hopedale Block, Labrador
Newfoundland and Labrador	Hopedale Block, Labrador	Regional	Till	No	Nfld & Lab Open File 013N_0156	100044	Campbell and McClenaghan	2019b	Data from a 2018 till indicator mineral sampling study in the NTS 13N map area, Hopedale Block, Labrador
Northwest Territories	Pine Point mining district	Regional	Till	No	OF 8547	270001	King et al.	2019	Major-, minor-, and trace-element geochemistry of sulphide indicator minerals from surficial sediments, southwestern Northwest Territories
Nunavut	Tehery–Wager Bay south	Regional	Till	No	OF 8563	210436	McMartin et al.	2019a	Till composition across the Keewatin Ice Divide in the Tehery–Wager GEM-2 Rae project area, Nunavut
Nunavut	Axel Heiberg Island	Regional	Stream sediment	No	OF 8719	210432	McNeil et al.	2020	Geochemical, mineralogical, and indicator mineral data for stream silt sediment, water, and heavy mineral concentrates, East Fiord area, Axel Heiberg Island, Nunavut (part of NTS 49-G, 59-H and 560-A)

Table B1. (cont.)

Territory	Location	Scale of survey	Sample medium	Reanalysis of archived HMC samples	Publication	CDoGS survey or project* metadata	Authors	Year published	Title
Northwest Territories	South Rae, NWT	Regional	Till	No	OF 8714	210220	Campbell et al.	2020	Field data, till composition and ice-flow history, south Rae Craton, Northwest Territories: results from the GEM-2 South Rae project–Surficial Mapping activity
Northwest Territories	Banks Island	Regional	Till, stream sediment	No	OF 8726	110005	Smith	2020	Kimberlite indicator mineral studies on Banks Island, Northwest Territories: assessing the potential for diamond-bearing kimberlite
Nunavut; Northwest Territories	Central Nunavut and eastern NWT	Regional	Till	No	OF 8808	210221	Campbell et al.	2021	Field data and till composition in the GEM-2 Rae Glacial Synthesis activity field areas, Nunavut and Northwest Territories
Northwest Territories	Southern Mackenzie	Regional	Till, stream sediment	No	OF 8799	210434	Smith et al.	2021	Chemical studies of kimberlite indicator minerals from stream sediment and till samples in the southern Mackenzie region (NTS 85-B, C, F, G), Northwest Territories
Nunavut	Tehery–Wager Bay south	Regional	Stream sediment, stream water	No	Not available yet	210435	Day et al.		Stream sediment and water samples collected in 2015 and 2016 predominantly from the headwaters of the Borden and Lorillard rivers
Northwest Territories	Southern Mackenzie	Regional	Till	No	Not available yet	210434	Paulen et al.	In press	Till indicator mineral data for till samples from southern Mackenzie region (NTS 85B, 85C, 85D, 85E, 85F, 85G and 95B, 95G, 95H)
Northwest Territories	Southern Mackenzie	Regional	Stream sediment	No	Not available yet	210433	Day et al.	In press	Stream sediment heavy mineral sampling program, samples collected in 2018–2019
*** Additional context for OF 7540 and 7649, but not funded by GEM**									
Northwest Territories	East Arm, Great Slave Lake	Regional	Till, esker sediments	No	OF 7196	210407	Kerr et al.	2013	Chapter 7: Gold grain counts from till and esker samples in the proposed national park reserve, East Arm of Great Slave Lake
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7196	210407	Kjarsgaard et al.	2013a	Chapter 10: Till geochemistry studies of the Thaidene Nene MERA study area
Northwest Territories	East Arm, Great Slave Lake	Regional	Till, esker sediments	No	OF 7196	210407	Kjarsgaard et al.	2013b	Chapter 9: Significance of indicator minerals from till and esker samples, Thaidene Nene MERA study area
Northwest Territories	East Arm, Great Slave Lake	Regional	Till	No	OF 7196		Wright et al.	2013	Mineral and energy resource assessment of the proposed Thaidene Nene National Park Reserve in the area of the East Arm of Great Slave Lake, Northwest Territories