Overview of surficial geochemistry and indicator mineral surveys and case studies from the Geological Survey of Canada’s GEM Program


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Abstract: The Geological Survey of Canada carried out reconnaissance-scale to deposit-scale geochemical and indicator-mineral surveys and case studies across northern Canada between 2008 and 2020 as part of its Geo-mapping for Energy and Minerals (GEM) program. In these studies, surficial geochemistry was used to determine the concentrations of up to 65 elements in various sample media including lake sediment, lake water, stream sediment, stream water, or till samples across approximately 1 000 000 km² of northern Canada. As part of these surficial geochemistry surveys, indicator mineral methods were also used in regional-scale and deposit-scale stream sediment and till surveys. Through this program, 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 geoscience knowledge was transferred to northern communities. Regional- and deposit-scale studies demonstrated how transport data (till geochemistry, indicator mineral abundance) 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 Zn–Cu–Pb–Ag VMS, Nunavut, the Pine Point carbonate-hosted Pb–Zn in the Northwest Territories, the Strange Lake REE deposit in Quebec and Labrador as well as U–Cu–Fe–F and Cu–Ag–Au–Au IOCG deposits in the Great Bear magmatic zone, Northwest Territories demonstrate new suites of indicator minerals that can now be used in future reconnaissance- and regional-scale stream sediment and till surveys across Canada.

Keywords: exploration geochemistry; stream sediments; lake sediment geochemistry; indicator minerals

Received 4 October 2021; revised 29 November 2021; accepted 30 November 2021

Numerous reconnaissance-scale to deposit-scale geochemical and indicator mineral surveys have been carried out in targeted areas across northern Canada (Fig. 1) as part of the Geological Survey of Canada’s (GSC) Geo-mapping for Energy and Minerals (GEM) program between 2008 and 2020. The purposes of this ongoing program are to advance geological knowledge, support increased exploration of Canada’s natural resources, and to inform decisions on land use that balance conservation of resources with responsible resource development. The specific purpose of the GEM regional geochemical surveys is to expand the existing systematic coast to coast to coast surficial geochemical mapping and database for Canada that was started in the 1970s as the National Geochemical Reconnaissance (NGR). These NGR surveys used established methods and specifications for the collection, preparation, analysis and public cation of data (Friske and Hornbrook 1991; Cook and McConnell 2001; Davenport et al. 2007) and were used to stimulate mineral exploration and determine environmental geochemical baselines.

The aims of this paper are to provide a brief overview of surficial sampling media that are suitable for regional geochemical and mineralogical surveys across Canada, provide an overview of the surveys and case studies carried out between 2008 and 2020, and to highlight the results of selected surveys/studies.

Outcomes of the GEM program thus far include:

(a) identification of areas that contain elevated concentrations of elements and/or abundances of indicator minerals that are indicative of economic bedrock mineralization for a broad range of commodities including precious, base and rare metals, uranium and diamonds;

(b) development and refinement of exploration models and protocols to improve the search for base, precious and rare metals, and diamonds using surficial methods;

(c) training of a new generation of professional personnel through collaborative research partnerships with research organizations and academia, courses taught at universities, short courses, and publication of journal papers and special volumes;

(d) geological knowledge transfer to northern communities through consultations, presentations, and activity wrap-up meetings, summaries and discussions.

A list of all publications that report GEM geochemical and mineralogical data is included in McClenaghan et al. (in press). Readers are encouraged to refer to the original GSC reports for complete descriptions of how the samples were collected and analysed, how quality control and quality assurance were evaluated, and how the data were plotted and interpreted. Metadata for all GEM datasets that have been published to date are reported in the Canadian Database of Geochemical Surveys website (https://geochem.nrcan.gc.ca).

Surficial sample media used in GEM surveys

Five main types of surficial media were collected, as appropriate, as part of GEM geochemical and mineralogical surveys: lake sediment, lake water, stream sediment, stream water, or till. A few esker samples were also collected as part of three till sampling surveys. These various sample media were collected in order to characterize regional elemental concentrations and mineralogical
abundances and to delineate anomalies for exploration targeting at the broad scale of geological provinces down to individual mineral deposits.

Centre-lake sediments

Lake sediments 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; Cook and McConnell 2001). Samples are collected from the centres of lakes or the centres of bays in large lakes, away from inflows and outflow channels. 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); Jonassen (1976); Coker and Nichol (1975); Coker et al. (1979, 1980), and Friske (1991):

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

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

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

GSC reconnaissance lake sediment (95% of which are organic lake centre gels) surveys were conducted using protocols established by the GSC in the mid 1970s (Friske 1991; Friske and Hornbrook 1991; McCurdy et al. 2014) during the NGR Program. The sampling and analytical protocols have largely remained the same but analytical techniques and the number of elements determined have progressed with advances in instrumentation technology. The GSC’s consistent use of these protocols over the past 40+ years allows comparison of new GEM datasets with older NGR datasets that are often separated by large distances or time. NGR samples were air dried, disaggregated and sieved to recover the ~80 mesh (~0.177 mm) fraction in a commercial laboratory after collection during the original survey. All new (GEM) samples or archived NGR that were reanalysed during the GEM program were analysed using a modified aqua regia digestion (HCl:HNO₃:H₂O 1:1:1) combined with ICP-ES and ICP-MS. The new samples were also analysed using instrumental activation analysis (INAA).

Under the GEM program, archived lake sediment samples from 30 previous GSC NGR surveys were reanalysed (Fig. 1). Reanalysis has allowed for the determination of a broader range of elements: 65 elements in 2018 v. 31 in the 1990s, and 12 in the 1970s. The reanalysis benefited from use of analytical methods with lower analytical detection limits and increased data precision. One new set of lake sediment samples was collected in the Abitau Lake area of SE 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 km² were generated for 26 865 samples.

Stream sediment and water

Stream sediment and water sampling are an 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 Hombrook 1991). In mountainous to hilly terrains, stream sediments are derived from erosion of bedrock as well as local glacial and colluvial sediments. In lower relief terrain of the Canadian Shield, stream sediments are derived primarily from the fluvial erosion of glacial sediments. GEM stream sediment and water surveys were conducted using NGR protocols established by the GSC in the mid 1970s (Ballantyne 1991; Friske and Hombrook 1991; McCurdy et al. 2014) and, as with lake sediments, the consistent use of these protocols over the past 40+ years, allows comparison and integration of new GEM datasets with older GSC datasets. The sampling and preparation protocols have largely remained the same but analytical techniques and the number of elements determined have progressed and increased with advances in instrumentation.

Three types of samples were collected from GEM program stream sample sites:

(i) Stream waters were sampled in mid-channel from flowing water where possible and prior to or upstream of any sediment sampling. Each sample was filtered on site through a 0.45 μm single-use disposable filter unit. Two water samples were collected at each site: (a) filtered and acidified (FA), and (b) filtered and unacidified (FU). Samples were preserved by acidifying to 0.4% with ultrapure 8 M HNO₃ either in the field or at GSC Ottawa. The FA water samples were analysed for trace and major elements by inductively coupled plasma emission spectrometry and mass spectrometry (ICP-ES and MS). The FU samples were analysed for anions and pH, conductivity, alkalinity and dissolved organic carbon (DOC) were determined.

(ii) A small (c. 2 kg) sample of clay to fine sand-sized material was collected from various points in an active stream channel while moving upstream over a distance of 5 to 15 m. Each sample was air dried and sieved in the GSC-Ottawa Sedimentology Laboratory to recover the ~80 mesh (<0.177 mm) fraction. This fraction was geochemically analysed using a modified aqua regia digestion (HCl:HNO₃:H₂O, 1:1:1) combined with ICP-ES and ICP-MS and by using INAA.

(iii) A large (c. 8–14 kg) sediment sample was collected using a shovel from high-energy gravel-rich streams in large gravel bars, boulder traps, or tiny pools of sediment in rocky narrow streambeds. Samples were wet sieved onsite to remove the >2 mm fragments and to allow the maximum volume of <2 mm material to be collected and hence reduce the nugget effect. In a commercial lab, the samples were processed using a combination of shaking table and heavy liquid separation methods to produce a heavy mineral concentrate (HMC) (>3.2 specific gravity) for examination of indicator minerals (McClennenahen 2011; Plouffe et al. 2013; McClennenahen et al. 2020).

Under the GEM program, reconnaissance-, regional- and local-scale till surveys covering about 500 000 km² and including the collection of about 3900 till samples were conducted across northern Canada (Fig. 1). These surveys include six detailed till studies around known mineral deposits (Fig. 1 - yellow dots) to test methods and to document for the first time the indicator mineral signature of different deposit types: the Izok Lake volcanogenic massive sulfide (VMS) Zn–Cu–Pb–Ag deposit, in Nunavut, the Kiggavik U deposit, the Pine Point carbonate-hosted Pb–Zn deposits, the NICO Co–Au–Bi, Fab U–Cu–Fe–F and the Sue Dianne Cu–Ag–U–Au iron oxide copper gold (IOCG) deposits – all in the Northwest Territories, the Amaruq Au deposit in Nunavut, and the Strange Lake rare earth element (REE) deposit in Quebec and Labrador.

GEM digital data
All GEM geochemical and mineralogical data are freely available as individual reports/data releases via GEOSCAN (https://geoscan.nrcan.gc.ca/geoscan-index.html) and the Government of Canada’s Canadian Database of Geochemical Surveys (CDoGS) (Adcock et al. 2013). The public interface to CDoGS can be found at https://geochern.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 291 surveys have data available for download in a standardized format. Currently, there are metadata for 1391 GEM, older NGR and other program surveys stored in the database and links to produced GEM surficial geochemical and indicator mineral reports are available from the website. Addtion of the most recent surveys and standardizing of the raw data for viewing in Google Earth™ is on-going. More detailed information about the CDoGS website is reported in Spirito and Adcock (2010).

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: (i) plastic containers of 800 g of unprocessed material; (ii) vials of at least 60 g of <0.063 mm material; and (iii) vials of heavy and mid-density mineral
concentrate fractions and picked mineral grains. Stream sediment sample material that was archived includes vials of: (i) at least 60 g of <0.177 mm material; and (ii) heavy mineral concentrate fractions and picked mineral grains. Archived lake sediment sample material consists of vials of at least 60 g of <0.177 mm material. Sample fractions are stored in bar-coded containers within cardboard boxes with lids to prevent sunlight from degrading the plastic sample containers and vials.

Reconnaissance- and regional-scale surveys

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, Saskatchewan, Quebec and western Labrador. Approximately 35 600 new and archived samples (lake sediment, lake water, stream sediment, stream water, till, and esker) were analysed. Some survey areas had not previously been sampled, whereas 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 (Fig. 1 – area #1) (McClenaghan et al. 2014a; McCurdy et al. 2018). These new maps are remarkable because of the large area they cover (295 000 km²) and the obstacles that were overcome to produce them. Challenges included the need to merge geochemical datasets from two government agencies (Quebec and Canada), the long time span over which the samples were collected, and the slight differences in analytical digestions and methods. In order to merge datasets from the two different agencies, approximately 5000 GSC archived lake sediment samples collected in Labrador (Fig. 1 – area #2) were reanalysed in 2015 (McCurdy 2016; McCurdy et al. 2016b) using similar methods that had been used for the Quebec dataset (Maurice and Labbé 2009). These new GEM data were then combined with geochemical data for more than 16 000 lake sediment samples from adjacent northeastern Quebec, previously published by the Ministère de l’Énergie et des Ressources naturelles du Québec. Data treatment and merging methods are described in detail in Amor (2015) and Amor et al. (2016, 2019). Single element maps were produced using a ‘moving median’ smoothing algorithm in which the value plotted at each sample point is the median value of all the samples that plot within a fixed (10 km) radius of the sample. This method smoothed the data and at the same time preserved the original sample locations in the resulting maps (Amor et al. 2019).

The combined lake sediment dataset and maps contribute new information for the bedrock mapping of this large region as well as indicating new targets for future mineral exploration (McCurdy et al. 2018; Amor et al. 2019). The data reveal a new geochemical province that coincides with the bedrock feature known as the Labrador Trough and is characterized by the highest concentrations of Sb, As, Bi, Re (Cd, Hg along the Trough’s 600 km length and the highest concentrations of 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 dataset include the highest 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. Some of the highest rare earth element (REE) values outline some Mesoproterozoic intrusions and may indicate their potential to host REE mineralization.

In addition to reanalysis of regional lake sediment samples, Core Zone regional surficial activities included regional-scale till sampling for geochemistry (McClenaghan et al. 2016a, 2019; Rice et al. 2017a, 2020; Hagedorn et al. 2018) and examination of indicator minerals (McClenaghan et al. 2016b; Rice et al. 2017b; in press) for the Schefferville-Smallwood reservoir region (Fig. 1 – area #3). Highlights for these new data include elevated Cu, Zn, Au, Pt, Pd, and Sb concentrations in till overlying the laporte terrane metasedimentary rocks, Labrador Trough (Knob Lake Group), and Doublet zone mafic volcanic rocks (Rice et al. in press). Elevated Au (up to 23 ppb) and Ag (up to 693 ppb) values in till matrix overlying the Doublet zone coincide with the elevated gold grain content in till samples (>6 grains/10 kg) indicating the potential for gold mineralization. The presence of chalcopyrite and platinum group minerals (sperrylite, mocheite) in till overlying the Doublet zone, and ultramafic rocks further east, suggests that there is potential for Cu-Ni-PGE mineralization (McClenaghan et al. 2017a; Rice et al. in press).

West-central Baffin Island, Nunavut

In 2018, archived GSC lake sediment samples from west-central Baffin Island (Fig. 1 – area #4) were reanalysed using funding provided by the Government of Nunavut and GEM (McNeil et al. 2019).
Bonham-Carter et al. (2019) provide an interpretation of the new lake sediment dataset and describe multi-element geochemical anomalies using principal component analysis and weighted sum modelling of various types of mineral deposits.

Principal component analysis of a large suite of metallic elements shows some clear patterns. The dominant axis, PC1, separates Piling Group sedimentary rock units from igneous Archean and Paleoproterozoic units. Weighted sum modelling, in which the...
weights were based on prior knowledge of the geochemical signatures of selected mineral deposits types, was applied for 16 different mineral deposit types including magmatic Ni–Cu, Au, VMS, carbonate-hosted Pb–Zn (Fig. 3), sediment-hosted Cu, and pegmatites. In most of the models used in the analysis, the anomaly south of Flint Lake is the most obvious. Other highly metalliferous areas of interest include the area east of Flint Lake, further east along the Astarte River and Flint Lake formations at the north edge of the Paleoproterozoic basin, west of Nadluardjuk Lake overlying the Bravo Lake Formation, discrete clusters of samples further east along the Bravo Lake Formation, and a cluster of lake sediment samples overlying the Longstaff Bluff Formation. This research provides new insights and understanding of this large geochemical dataset in the modern metallogenic framework described by Wodicka et al. (2014).

Archived GSC lake sediment samples collected from the central part of the Melville Peninsula in 1977 (Fig. 1 – area #5) were reanalysed under GEM (Dredge 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, 2019). Patterns for Au, Cr, Ni, Cu, and Zn in lake sediments reflect the underlying bedrock geology. For example high residual Zn values, estimated from a linear regression against the dominant principal components, are associated with the Paleoproterozoic Penrhyn Group supracrustal rocks in southern Melville and appear to be associated, in part, with known Zn sulfide mineral occurrences.

Regional till geochemistry surveys were carried out in the mid 1980s on northern and central Melville Peninsula to assist in evaluating the mineral potential of the region. Under the GEM Program, archived till samples from that study were reanalysed (Dredge 2009) (Fig. 1 – area #6) and combined with data for new till samples collected by Tremblay and Paulen (2012) (Fig. 1 – area #7A). This region is characterized by carbonate-rich till derived from Paleozoic carbonate rocks in the Foxe Basin (Tremblay and Lamothe in press). During deglaciation, this carbonate till was dispersed across the northern part of the peninsula by streaming ice, overprinting the local till matrix, and masking the geochemical signal from local Precambrian bedrock. As a result, till geochemistry in the northern part of the peninsula reflects the composition of Paleozoic carbonate rocks to the east. In contrast, indicator mineralogical and geochemical analysis of till heavy mineral concentrates in the same area reflects the composition of local bedrock.

Across the southern Melville Peninsula (Fig. 1 – area #7B), the highest concentrations of Au (Fig. 4), Cu, Ni, and Zn plus pathfinder elements (Rose et al. 1979) (As, W, Ag, Sb, Bi, Se, Sb and Hg) and high abundances of indicator minerals (gold, sulfides, sperrylite) in till overlie Penrhyn Group metasedimentary rocks. Comparisons of till matrix geochemistry data with regional lake sediment data for the region reveal similar patterns of high metal values. For example, the highest Au values in till (124 ppb, 44 gold grains) coincide with the highest Au values (18 ppb) in regional lake sediment data (Fig. 4) and these areas of high Au concentrations appear to be most prospective (Tremblay et al. 2016).
Southeastern Northwest Territories and northern Saskatchewan

As part of the GEM South Rae project, archived GSC lake sediments collected between 1977 and 1993 (NTS map areas 74N, O, P, 64L, M) in northern Saskatchewan (Fig. 1 – area #8A) were reanalysed (McCurdy et al. 2015). In addition to the reanalysis, new lake sediment samples were collected in the Abitau Lake (NTS 75B) area (Fig. 1 – area #8B), immediately to the north (McCurdy et al. 2016a). Copper data for these surveys were combined with those for the GEM reanalysis data for archived samples in NTS map areas 75C, F and K (Fig. 1 – area #8C), immediately to the north (McCurdy et al. 2016a). Copper data for these surveys were combined with those for the GEM reanalysis data for archived samples in NTS map areas 75C, F and K (Fig. 1 – area #8C) (McCurdy et al. 2016c) and 65A, B and C (McCurdy et al. 2012; Hayward et al. 2013; Harris and Grunsky 2015) (Fig. 1 – area #8D). All these combined data are plotted together in Figure 5. The high Cu concentrations NE of the east end of Lake Athabasca occur in an area of known Cu and Ni sulfide showings and may be of interest for Ni-Cu exploration (Acosta-Góngora et al. 2017). Southeastern Northwest Territories

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Southwestern Northwest Territories

As part of the GEM Mackenzie project, regional-scale stream sediment and water sampling and till sampling were carried out across the SW Northwest Territories (Fig. 1 – area #9) (Paulen et al. 2019). Prior to these new GEM activities, the surficial geology of the region had not been mapped and only limited surficial sampling had ever been conducted there. Despite the presence of the past-producing world-class Mississippi Valley-type (MVT) Pine Point Pb–Zn district on the southern shore of Great Slave Lake and Hannigan’s (2006) positive assessment of its Pb–Zn potential, almost no other mineral showings have been reported in the region.

Stream sediments from low energy streams and tills contain significant numbers of sphalerite, galena (Fig. 6) and chalcopyrite grains in samples collected far to the west (down ice) of the Pine Point District (Day et al. 2018; Paulen et al. 2018). Sulfur and Pb-isotopic compositions of galena grains indicate that their source(s) is MVT-type mineralization, but not the Pine Point District (King et al. 2018, 2019). The low hardness of galena (2.5) and its brittle nature combined with GSC dispersal studies already conducted at Pine Point (McClenaghan et al. 2018) suggest that undiscovered buried bedrock sources for the galena are possibly no more than 1 km away from highly anomalous sample sites. Chalcopyrite grains may have been sourced from sediment-hosted Cu mineralization, as indicated by their significant variations in δ34S values (King et al. 2018). Arsenopyrite grains have δ34S values similar to orogenic Au deposits near Yellowknife, 400 km to the NE, indicating that grains may have been dispersed from similar style Au deposits in the study area (King et al. 2018). Additional GEM stream sediment and till indicator and geochemical data for SW Northwest Territories will be published and these will help to further refine exploration targets for follow up.

East-central Manitoba

In east-central Manitoba, GEM reconnaissance-scale surface till sampling was carried out in the Great Island-Caribou Lake area (Fig. 1 – area #10) in combination with ice-flow indicator mapping to assist in evaluating the mineral potential of the region (Campbell Fig. 6. 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 SW NWT. The large black rectangle is the Pine Point mining district. From Paulen et al. (2018).
The till geochemical results provide estimates of background and threshold values characteristic of the region, and partly fill in part of a gap in regional coverage (Dredge and Pehrsson 2006; Dredge and McMartin 2007).

Further south in the Gods Lake area of east central Manitoba (Fig. 1 – area #11), archived GSC NGR lake sediments collected in 1986 were re-analysed under the GEM program. Areas of potential interest for mineral exploration are summarized below from McCurdy et al. (2017). Clusters of samples with Au concentrations >97th percentile in lake sediments occur near known gold occurrences and as well as near Joint, Bigstone, Knee lakes, and north of Island Lake. Silver concentrations >97th percentile in lake sediments occur NE of known Ag-bearing showings on Island Lake and around Beaver Hill Lake, west and south of Oxford Lake and SE of Knee Lake. Values for Ni (Fig. 7) and Cu that are >97th percentile occur in areas of known Ni mineralization around Island Lake, as well as around Beaver Hill Lake, Cinder Lake, Oxford Lake, Knee Lake, Bigstone Lake, and Atik Lake. Concentrations of Li and REE in lake sediments that are >97th percentile were identified around known pegmatites and carbonatites as well as in areas of unknown mineralization.

Deposit-scale surveys
In addition to GEM regional-scale till sampling surveys, detailed till sampling studies were conducted around the following mineral
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, a Zn-spinel (Spry and Scott 1986a, b; Heimann et al. 2005; Ghosh and Praveen 2008; O’Brien et al. 2014) that is visually distinctive (Fig. 8) and physically robust. Glacial dispersal of gahnite from the deposit forms a complex, fan-shaped pattern that was produced by two main ice-flow phases, an older SW ice flow and younger NW ice flow (Fig. 9) (McClennen et al. 2012a, b, 2013b, 2014b, 2015; Hicken et al. 2013a, b; Paulen et al. 2015). Archived GSC till heavy mineral concentrates collected as part of a regional-scale sampling program in the 1990s were re-examined for gahnite as part of this GEM study. The results indicate that the Izok Lake gahnite dispersal fan extends at least 40 km down ice (Fig. 10).

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. It also highlights the value of heavy mineral concentrate archives when conducting regional till surveys or exploration programs. The GEM program also supported Makvandi et al. (2015, 2016a, b) in their investigation of the utility of magnette as an indicator mineral for detecting VMS mineralization down ice of the Izok Lake deposit.

Glacial dispersal of metal-rich till from the Izok Lake VMS deposit was detected up to 6 km down ice using till geochemistry of closely spaced (500 m) till samples (Hicken et al. 2012; McClennen 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 Ti.

The Izok Lake case study confirms that till sampling is a viable VMS exploration method in the region and demonstrates that indicator mineral identification and till geochemistry (transport data) combined with detailed ice-flow mapping, define a palimpsest pattern of glacial dispersal in the region. The reconnaissance-scale sample spacing was suitable for detecting glacial dispersal of the unusual and physically robust mineral gahnite, from the alteration of the Izok Lake deposit (McClennen et al. 2012b), clearly demonstrating the benefit of using indicator minerals to explore for metamorphosed VMS deposits in this remote region. This study also demonstrates the value of returning to archived HMC samples when new indicator mineral suites become available.

Results from this case study suggest that the 5 to 10 km sample spacing from the GSC’s 1994 reconnaissance-scale till geochemistry survey (Dredge et al. 1996) was too large to detect geochemical dispersal patterns from the Izok Lake deposit.

Pine Point MVT Pb–Zn deposits

A GEM indicator mineral case study was also conducted in the former producing Pine Point Mississippi Valley-type (MVT) Pb–Zn district in the southern Northwest Territories (Fig. 1). This study was undertaken to understand the dispersal of Pb and Zn sulfides in a carbonate-rich till (McClennen et al. 2012c, 2018; Oviatt et al. 2013a, b, 2015) and in local streams (Mccurdy and McNeil 2014). Ice-flow history in this region was found to be much more complicated than previously reported by Prest et al. (1968) and Lemmen (1990, 1998a, b). Evidence for multiple ice-flow phases, each with an erosional and depositional record across the district, includes cross-striated bedrock surfaces, streamlined landforms, and till clast fabrics (Rice 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 SW and NW, producing a fan-shaped palimpsest dispersal train defined best by sphalerite (Fig. 11a, b), galena, Zn (Fig. 11c, d) and Pb concentrations. The last ice-flow phase during deglaciation had a minimal effect on the dispersal train geometry (McClennen et al. 2018).

The Ca-carbonate rich (c. 25% CaO) till matrix in the Pine Point region acts as a buffer during surficial weathering and soil formation, maintaining a high soil pH and limiting the oxidation of detrital sulfide minerals in the till. As a result, surface till (up to 4 m depth) in the district contains large numbers of fresh sulfide grains (Fig. 12). In contrast, carbonate and sulfide minerals in till are easily destroyed by post-glacial weathering and soil formation in areas of naturally carbonate-poor till (e.g. Canadian Shield, Appalachians, Cordillera; cf., Shilts 1975, 1976, 1996; McMartin and McClennen 2001; Averill 2014). Pathfinder elements in the till matrix that also help define dispersal from the MVT deposits in the District include Zn, Pb, Cd, Ti and S.

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

The Pine Point study confirms that till sampling is a viable exploration method in the carbonate platform of the Western Canada Sedimentary Basin and was the impetus for the subsequent GEM Mackenzie regional survey in SW Northwest Territories (Paulen et al. 2019). In the eastern part of the Pine Point district where the till is generally thin (<5 m), surface till sampling is cost effective; further west where extensive peatlands and thick till cover can exceed 30 m, overburden drilling methods will be needed to collect till samples at depth (Smith et al. 2019). Indicator mineral abundances and till geochemistry (transport data) combined with the ice-flow data define a palimpsest pattern of glacial transport in
the region that should be considered when following up anomalies in till or stream sediments. This study and that of Paulen et al. (2011) demonstrate that a benefit of using indicator minerals for MVT exploration is that the isotopic analysis of individual grains provides insights into the style of Pb mineralization up ice and the potential deep seated Pb sources of the mineralization (Oviatt et al. 2015).

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

The heavy mineral (>3.2 SG) and mid-density (3.0–3.2 SG) non-ferromagnetic mineral fractions of mineralized bedrock from the deposit and till to a maximum of 50 km down ice of the deposit were examined to determine the potential of using REE and high field strength element (Hf, Zr, Nb and Ta) indicator minerals for exploration (McClenaghan et al. 2017b, c, 2019). The deposit contains oxide, silicate, phosphate, and carbonate indicator minerals, some of which (cerianite, uraninite, fluorapatite, rhabdophane, thorianite, danburite, and aeschynite) have not been reported in previous bedrock studies of Strange Lake. Indicator minerals that could be useful in the exploration for similar deposits include: Zr-silicates (zircon, secondary gittinsite and other hydrated Zr ± Y ± Ca-silicates), pyrochlore, thorite, REE-bearing minerals monazite, chevkinite, parisite, bastnaesite, kainosite, and allanite. Other minerals that can be useful indicators when combined with the minerals listed above include fluorite, titanite, arfvedsonite, and aegirine (McClenaghan et al. 2017c, 2019). Colour photographs of some of these minerals are shown in Figure 13. The results indicate that indicator minerals can be used in regional- to reconnaissance-scale exploration programs to detect REE mineralization in peralkaline granites.

The Strange Lake dispersal train has a remarkable ribbon-shape that extends more than 50 km down ice to the ENE. It is defined by high REE element concentrations in till and equivalent thorium

Fig. 9. Proportional dot map of gahnite abundance in surface till normalized to a 10 kg sample mass around the Izok Lake VMS deposit showing the proximal part of the 40 km long dispersal fan formed by older SW (blue polygon) and then modified by younger NW (yellow polygon) ice flow across the Izok Lake VMS deposit. Arrows indicate relative ice-flow chronology (1 = oldest) and vigour (arrow size) of flow events. Modified from Paulen et al. (2013) and McClenaghan et al. (2015). Locations of gahnite-bearing rocks at surface indicated by green stars and location of massive sulfide indicated by solid red polygons (unpublished data, MMG Ltd.).

Table 1. No. of grains gahnite/10 kg

<table>
<thead>
<tr>
<th>Range</th>
<th>No. of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>51-1739</td>
<td>(9)</td>
</tr>
<tr>
<td>21-50</td>
<td>(19)</td>
</tr>
<tr>
<td>6-20</td>
<td>(22)</td>
</tr>
<tr>
<td>2-5</td>
<td>(32)</td>
</tr>
<tr>
<td>1</td>
<td>(18)</td>
</tr>
<tr>
<td>0</td>
<td>(3)</td>
</tr>
</tbody>
</table>
(cTh) values in airborne gamma-ray spectrometry data (Geological Survey of Canada 1980; Batterson 1989; Batterson and Taylor 2009; Zajac 2015; Paulen et al. 2017). The train was originally attributed to a consistent regional ice flow regime of the Laurentide Ice Sheet (Batterson and Taylor 2009). Recent reconstruction of the Laurentide Ice Sheet history places the Strange Lake train directly within the trunk of the Kogaluk River ice stream (KRIS), one of 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 (stream-lined landforms) up to 5 km long, with length to width ratios exceeding 12 within the train.

Ice streams are corridors within an ice sheet that flow more rapidly than the surrounding ice. They act as arteries to discharge large amounts of ice over large distances and are the source of well-defined trains of far-travelled glacial debris (e.g. Dredge 2000; Ross et al. 2009). Few studies have focused on the geochemical and mineralogical dispersal patterns formed or modified by ice streams, in part because former ice stream tracts were not previously recognized or identified in areas covered by the Laurentide Ice Sheet. Within KRIS, the concentration gradient of dispersed debris, as shown by total Th content in till, decreases linearly down ice (Fig. 14a) indicating that the rapid ice flow has transported high concentrations of debris far from source with little dilution, similar to the idealized linear distribution curve of Klassen (1997) (Fig. 14b). 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), show that the distributions of Hf, Sn and Zr (aqua regia ICP-MS) in lake sediments define a glacial dispersal train from Strange Lake that is much longer (150 km) than originally recognized. This study also demonstrates that lake sediment geochemical data can be used to identify glacial dispersal trains, including those formed by former by ice streams.

**Great Bear Magmatic Zone iron-oxide copper gold deposits**

The potential use of till geochemistry and indicator mineral methods to explore for iron oxide copper-gold (IOCG) deposits was evaluated in focused studies around the NICO Co–Au–Bi, Sue-Dianne Cu–Ag–U–Au and Fab U–Cu–Fe–F deposits (Fig. 1 – area #12) in the Great Bear magmatic zone (GBMZ) in the Northwest Territories (Lypaczewski et al. 2013; Normandeau and McMartin 2013; Normandeau 2018). This research was funded, in part, by the GEM program.

Gold grain abundance, size and shape as well as magnetite and hematite compositions reflect the presence of the NICO mineralization in till down ice (McMartin et al. 2011a, b; Dupuis et al. 2012; Sappin et al. 2014). Normandeau et al. (2018) documentedapatite texture, geochemistry, and cathodoluminescence response andapatite 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 potential of till geochemistry to help find mineralization in the GBMZ is variable depending on till cover, size fraction of till analysed (<0.063 mm v. <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 indicate their potential as pathfinder elements within the study area. At the Sue Dianne deposit, for example, Fe and Co (4-acid/ICP-ES/MS) in the <0.063 mm fraction and Cu (Fig. 15), Mo and Bi (aqua regia/ICP-MS) in the <0.002 mm fraction of till are the most useful pathfinders to mineralization.

Reviews of indicator mineral and till geochemical methods for exploration

The GEM program’s contributions to surficial geochemistry and mineralogy include timely reviews of key concepts and methods. The most comprehensive paper is McClenaghan and Paulen’s (2018) overview of glacial dispersal processes and the application of drift prospecting to mineral exploration in the glaciated terrain of Canada. They review the importance of using both ice-flow indicator data and transport data together to understand the complexity of continental ice-sheet dynamics and the resulting glacial dispersal patterns to successfully search for mineral deposits. Boulder tracing and till geochemistry are well established.
exploration tools that have been used in Canada for more than 60 years. Indicator mineral methods have become another important exploration tool, especially for the GSC during the past 12 years of regional bedrock and metallogenic mapping activities to where 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 large and irreplaceable resource. More than 26 000 archived NGR lake sediment samples covering all or part of 49 NTS map areas were reanalysed under the GEM program resulting in cost savings of at least $500 000 per NTS map area that would have been incurred to collect new samples. GEM geochemical surveys have significantly expanded NGR coverage of northern Canada.

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 Izok Lake also demonstrate the robustness of gahnite as an indicator mineral. Studies at Pine Point demonstrate that sulfide minerals are particularly useful indicators in carbonate-rich terrain and that isotopic fingerprinting of individual sphalerite and galena grains can help determine the style of bedrock

Methods development

The GEM-funded methods development research included the testing of portable X-ray fluorescence (pXRF) spectrometry to determine metal contents of till samples in the field and/or in the laboratory (Hall et al. 2016; Knight et al. 2021). 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 (e.g. 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 and avoid cross-contaminating background samples). 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. Hall and McClenaghan 2013; Plourde et al. 2013; McClenaghan et al. 2014a; Hall et al. 2016). 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).

Conclusions and implications for mineral exploration

Under the GEM program, modern geochemical methods were used to determine up to 65 elements for lake sediment, stream sediment, stream water, lake water and till surveys. Modern methods were used to examine the indicator mineral abundances 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 an area of about 1 million km2 in northern Canada to assess the potential for hosting precious, base, rare and strategic metals, uranium and diamonds. Indicator mineral and till geochemical data are essential components of all GEM surficial mapping projects (Kerr et al. in press). These data provide important insights into till provenance that are essential to understanding and deciphering the complex ice flow history of Canada’s north.

The most immediate impact of the GEM geochemical and mineralogical surveys has been the stimulation of mineral exploration in Canada’s north, 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. These results will help direct the GSC’s future regional bedrock and metallogenic mapping activities to where 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 large and irreplaceable resource. More than 26 000 archived NGR lake sediment samples covering all or part of 49 NTS map areas were reanalysed under the GEM program resulting in cost savings of at least $500 000 per NTS map area that would have been incurred to collect new samples. GEM geochemical surveys have significantly expanded NGR coverage of northern Canada.

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Fig. 12. Colour photographs of indicator mineral grains recovered from till in the Pine Point Mining District: (a) honey brown sphalerite; (b) dark brown Fe-rich sphalerite; (c) galena. Mineral photography by Michael J. Bainbridge Photography.
mineralization up ice and understand the deep seated sources of Pb that have led to deposit formation. At Strange Lake and the GBMZ, new suites of indicator minerals were identified for REE and IOCG deposits respectively, that can be applied across Canada as well as locally.

The indicator mineral suites described in the GEM deposit-scale studies can be added to the expanding list of indicator minerals that can be recovered from surficial sediments. This broad suite of indicator minerals can be used to evaluate a region’s potential to host a wide range of deposit types that also includes diamonds, precious and base metals. The main advantages of indicator mineral methods over conventional sediment geochemistry include: (1) the method is effective at reconnaissance- and regional-scales (5 to 15 km spacing) and requires fewer samples, in contrast to till geochemistry which requires a tighter sample spacing to detect dispersal of mineralized debris; (2) the ability to detect alteration zones of mineral deposits that may have muted or no geochemical signatures in surficial sediments; (3) the ability to estimate distance of glacial transport from a bedrock source; (4) the ability to provide information about the nature of the mineralized sources and its isotopic signature. The outcome of these successful case studies and regional indicator mineral surveys is that indicator mineral methods will be part of all future GSC reconnaissance and regional-scale till or stream sediment surveys.

**Future work**

Geochemical and indicator mineral mapping coverage of northern Canada is far from complete. GEM geochemical and indicator mineral surveys were carried out over about 1 million km² of
northern Canada. This new coverage, combined with the earlier GSC and territorial geochemical surveys, still leaves about 1/3 of Canada’s north to be assessed in future studies. Areas such as the Slave Craton, for example, 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 future sample medium in geochemical surveys is currently being assessed and improved by GSC.

Future geochemical research at the GSC should investigate how field and lab geochemical methods such as portable XRF (pXRF), laser-induced breakdown spectrometry (LIBS), and portable Fourier transform infrared spectrometry (pFTIR) can assist in generating regional geochemical survey results. Future indicator mineral research as part of case studies around known mineral deposits will continue to expand indicator mineral suites. The use of mineral chemistry as part of regional indicator mineral studies is rapidly expanding globally and at GSC. Studies will continue to broaden existing, and develop new, criteria for fertility assessments for a broad range of deposit types and allow, for the first time, the use minerals for which their spatial distribution alone is not indicative of mineralization. The use of automated mineralogy techniques such as mineral liberation analysis (MLA), TESCAN integrated mineral analyser (TIMA), and micro XRF for the rapid identification of minerals recovered from the mid to heavy density fractions of sediment samples will increase as these methods become more widely available and costs are reduced. Indicator mineral methods applied at reconnaissance and regional scales now allow for an assessment of an area to host a broad range of deposit types, not just one target commodity.

The GSC archive contains samples from several reconnaissance- and regional-scale lake, stream sediment and till geochemical surveys that have not yet been reanalysed using modern analytical methods. Reanalysis of these remaining sample sets are valuable to future GSC bedrock and mineral resource mapping. Some of these samples are currently undergoing reanalysis and will be reported in future publications.

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

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

GSC protocols for collection, preparation, and analysis of till, lake, and stream sediments will continue to evolve, including advancements in analytical methods, lower analytical detection limits, and more efficient data capture in the field such as those used in Australia (e.g. Noble et al. 2020). GEM and older NGR geochemical and indicator mineral datasets present new opportunities for the mineral exploration industry through the application of data-driven techniques.

Acknowledgements This overview of GEM surficial geochemical and indicator mineral surveys was written with the help of many colleagues, including R. Paullin, J. McMartin, J. Campbell, R. Smith, D. Kerr, T. Tremblay, and P. Normandeau who shared geological data, insights, and/or figures. R. Garrett is thanked for his help with interpretations and assessments of many of the GEM datasets that are summarized here. S. Madore and J. Plakholm helped to compile GEM geochemical and indicator mineral publications and survey coverage, and sample number totals. The GSC Sedimentology Lab staff S. Madore, M. Wygergangs, C. Moore, and A. Grenier, are thanked for their expert handling, preparation and archiving of GEM geochemistry samples, and assistance with proof reading. Thoughtful reviews of this manuscript were conducted by J. Bourdeau (GSC), S. Cook, and D. Arne.


Natural Resources Canada contribution number: 20210301

Author contributions MBM: conceptualization (lead), formal analysis (equal), supervision (lead), writing – original draft (lead), writing – review & editing (supporting), project administration (supporting), writing – review & editing (supporting); SWA: data curation (supporting), investigation (supporting), visualization (supporting), writing – original draft (supporting), writing – review & editing (supporting); RJM: data curation (supporting), formal analysis (supporting), investigation (supporting), writing – review & editing (supporting); WAS: conceptualization (supporting), data curation (supporting), visualization (supporting), writing – original draft (supporting), writing – review & editing (supporting).

Funding Funded by the Geological Survey of Canada’s Geo-mapping for Energy and Minerals Program (GEM).

Data availability All data referred to in this paper are publicly available at: https://geochem.nrcan.gc.ca

Scientific editing by Scott Wood

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