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NEW FRONTIERS FOR EXPLORATION IN GLACIATED TERRAIN

FOREWORD

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This publication is a compilation of short papers that describe relatively new drift prospecting methods and concepts for mineral exploration for a broad range of commodities in glaciated terrain. These extended abstracts were originally prepared to accompany the *"New Frontiers for Exploration in Glaciated Terrain"* workshop that was held March 1st, 2013 for the Prospectors and Developers Association of Canada (PDAC) in conjunction with the PDAC 2013 International Convention, Trade Show & Investors Exchange – Mining Investment Show (March 3-6, 2013). This workshop was organized by the Geological Survey of Canada (GSC) and funded by the GSC's Geomapping for Energy and Minerals Program (GEM 2008-2013) through the Tri-Territorial Indicator Mineral Project.

The short papers in this volume are grouped thematically, beginning with a historical review of drift prospecting in glaciated terrain and an overview of recent advances in our understanding of glacial processes. The introductory short papers are then followed by two papers that outline the glacial sediment sampling and protocols for indicator mineral methods and digital data management practices adopted by the GSC during the GEM Program. A paper integrating multivariate statistical methods with surficial sample data sets introduces the reader to powerful tools to help decipher complex relationships in surficial sediments. Successful application of the aforementioned concepts by forward-thinking exploration companies are presented for both gold and diamond properties discovered by drift prospecting in Canada. Successful use of surficial geochemical methods is shown to be applicable to various commodity types, specifically for volcanogenic massive sulphide deposits (VMS) across Canada and Pb-Zn deposits in the carbonate terrane of Canada's Arctic. Lastly, two short papers present the newest frontiers in drift prospecting in glaciated terrain. The first is the application of iron-oxide indicator minerals for mineral exploration, a heavy mineral fraction traditionally not investigated, to fingerprint a vast array of mineral deposit types. The second paper presents a comparative study of commercially available portable XRF (pXRF) instruments and a comparative study of a sample dataset between pXRF and conventional lab-based aqua regia/ICS-MS analysis.

The authors represent a wide range of specialties and are some of the most experienced researchers or practitioners in the field of drift prospecting and surficial geochemistry in glaciated terrain. They come from government, academia, and industry. The original extended abstracts have undergone review and editing by the Geological Survey of Canada. The editors would like to acknowledge all the reviewers, especially Dan Kerr who provided a final review of this entire volume. Elizabeth Ambrose is thanked for a thorough grammatical review and the digital page layout. We trust this collection of short papers will be of interest and use to active and future mineral exploration activities in glaciated terrain.

Recommended citation for individual papers within this volume:

Spirito, W.A., Adcock, S.W., and Paulen R.C., 2013. Managing geochemical data: challenges and best practices, *in* New Frontiers for Exploration in Glaciated Terrain, (ed.) R.C. Paulen and M.B. McClenaghan; Geological Survey of Canada, Open File 7374, p. 21-26.

HISTORY AND STATUS OF TILL GEOCHEMICAL AND INDICATOR MINERAL METHODS IN MINERAL EXPLORATION

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ABSTRACT

Mineral exploration methods ranging from boulder tracing to elemental and indicator mineral methods utilize clastic debris transported from mineralized bedrock sources. An understanding of glacial process and history, combined with sound survey design and interpretation, are essential to successful application of these methods in glacial terrain. In North America and Fennoscandia, mineral exploration and glacial geology advanced concurrently in the latter 20th century, coincident with a shift in exploration to overburden-covered regions. During this time, an understanding of sediment transport history was followed by recognition of the textural and mineralogical tendencies of glacial sediments. Development of logistics such as reverse circulation and rotasonic drilling followed, and in the 1990s, the discovery of diamonds in Canada resulted in much progress in application and awareness of drift prospecting methods. The discipline now centres on intricate indicator mineral and elemental methods based on concepts from glacial geology, mineral deposit geology, and mineral chemistry, in the search for a broad range of commodities.

KEYWORDS: glacial sediment, indicator mineral, mineral exploration, till geochemistry

INTRODUCTION

Mineral exploration may take advantage of clastic dispersal of mineralized boulders, indicator minerals, and fine detrital debris or their weathering products that may be detected by elemental analysis.

Whereas what might be regarded as purely geochemical methods rely on elements that have been dispersed from primary or secondary sources by aqueous or gaseous chemical processes, indicator mineral and till geochemical methods utilized in glaciated terrain are based on mineral grains transported by mechanical processes.

Elemental analyses of, for example, soils, may be used to detect a combination of chemical and clastic signals, although an exploration strategy usually is directed at either one or the other. For example, the B horizon might be sampled and appropriate analytical procedures applied to seek a dominantly chemical signal, while the C horizon might be sampled and analyzed to seek primarily a clastic signal residing in mineral grains or their weathering products. In the case of indicator mineral grains, however, the signal is attributable to mechanical dispersal processes alone.

In glaciated environments, labile minerals may be detected 100s of km from source (Fig. 1). Tracing of glacial indicators therefore requires assessment of indicator character and mapping of concentration gradients, supported by knowledge of ice flow history, processes of sediment transport, and factors such as glacial sediment thickness, bedrock topography, and bedrock erodibility.

The principle that underpins these methods holds that sediments bearing traceable clastic debris carried down the transport trend by glacial processes will be detected during exploration, mapping, or research, if sample spacing and signal to noise ratio are adequate.

Exploration surveys carried out by industry test for the presence of mineralization, to aid decisions regarding property acquisition and follow-up. Mapping surveys typically conducted by government agencies serve as a reference for exploration by defining trends in background, identifying problematic areas, and by providing examples of anomalies (Fig. 2). Research surveys are carried out to enhance methods, understand processes, and improve the effectiveness of both exploration and mapping, commonly as case studies around known mineral deposits.

The dispersed signal characteristically has a much larger aerial footprint than the source. Dispersal train size and contrast with background are governed by size of the source, concentration at source, dilution, background level, visual distinctiveness of the debris, and the nature of the processes of sediment transport (Averill, 2001). Detection method also affects signal to noise ratio in relation to sample size, the degree to which the textural, density, and/or magnetic fraction in which the target preferentially resides is concentrated, and analytical methods.

Indicator minerals recovered for morphological and mineralogical analyses include those from kimberlite and lamproite, gold grains, sulphides, and other minerals indicative of mineral deposits and associated alteration. In addition to visual and mineralogical analysis of mineral grains, and to reduce cost or seek a signal not recoverable as mineral grains, elemental methods may also be used to detect elements diagnostic of specific mineral grains or their weathering products, typi-

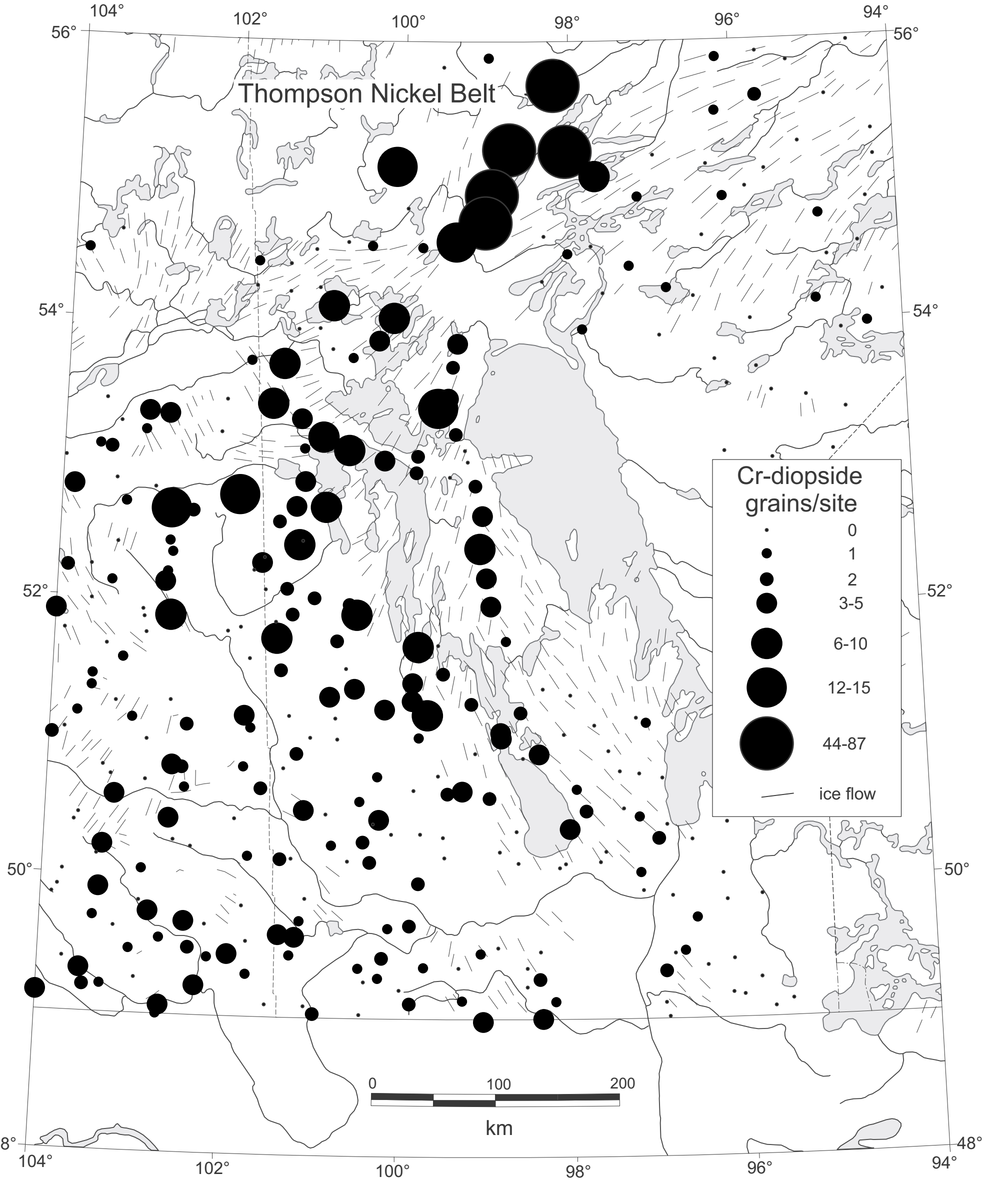

Figure 1. An indicator mineral plume consisting of Cr-diopsides glacially dispersed from the Thompson Nickel Belt in Manitoba, Canada, detected in ~20 litre till samples at a 30-km spacing (Thorleifson et al. 1994; Thorleifson and Matile 1997).

cally in a fraction defined by texture, density, and/or magnetic susceptibility. To avoid mixing clastic and chemical signals, C-horizon or deeper sediments in soil profiles are sampled. The gravel, sand, and finer fractions may also be analyzed to trace provenance, in order to assist interpretation.

Several syntheses, including the Prospecting in Areas of Glaciated Terrain series, have reviewed the application of till geochemical and indicator mineral methods to mineral exploration in glaciated terrain (Bølviken and Gleeson, 1979; Coker and DiLabio, 1989; DiLabio and Coker, 1989; Kujansuu and Saarnisto, 1990; Kauranne et al., 1992; Bobrowsky et al., 1995; Shilts, 1996; McClenaghan et al., 1997, 2001; Thorleifson and McClenaghan, 2003; McClenaghan, 2005; Paulen and McMartin, 2009; Gent et al., 2011; McClenaghan and Hall, 2011; McClenaghan et al., 2011).

HISTORY

Pre-20th century literature includes reference to glacially transported boulders and mineral grains being recognized as indicators of mineral potential, and early 20th century literature confirms that glacial transport of mineral deposit indicators was understood (e.g. Prest, 1911).

In the latter 20th century, there was rapid progress in glacial geology, and concurrent progress in its application to mineral exploration (e.g. Dreimanis et al., 1957). Progress was stimulated by publication of case studies that recognized glacially transported kimberlite indicator minerals (Lee, 1968), and development of logistics such as reverse circulation drilling that are well suited to glaciated terrain (Averill, 1978; Skinner, 1972).

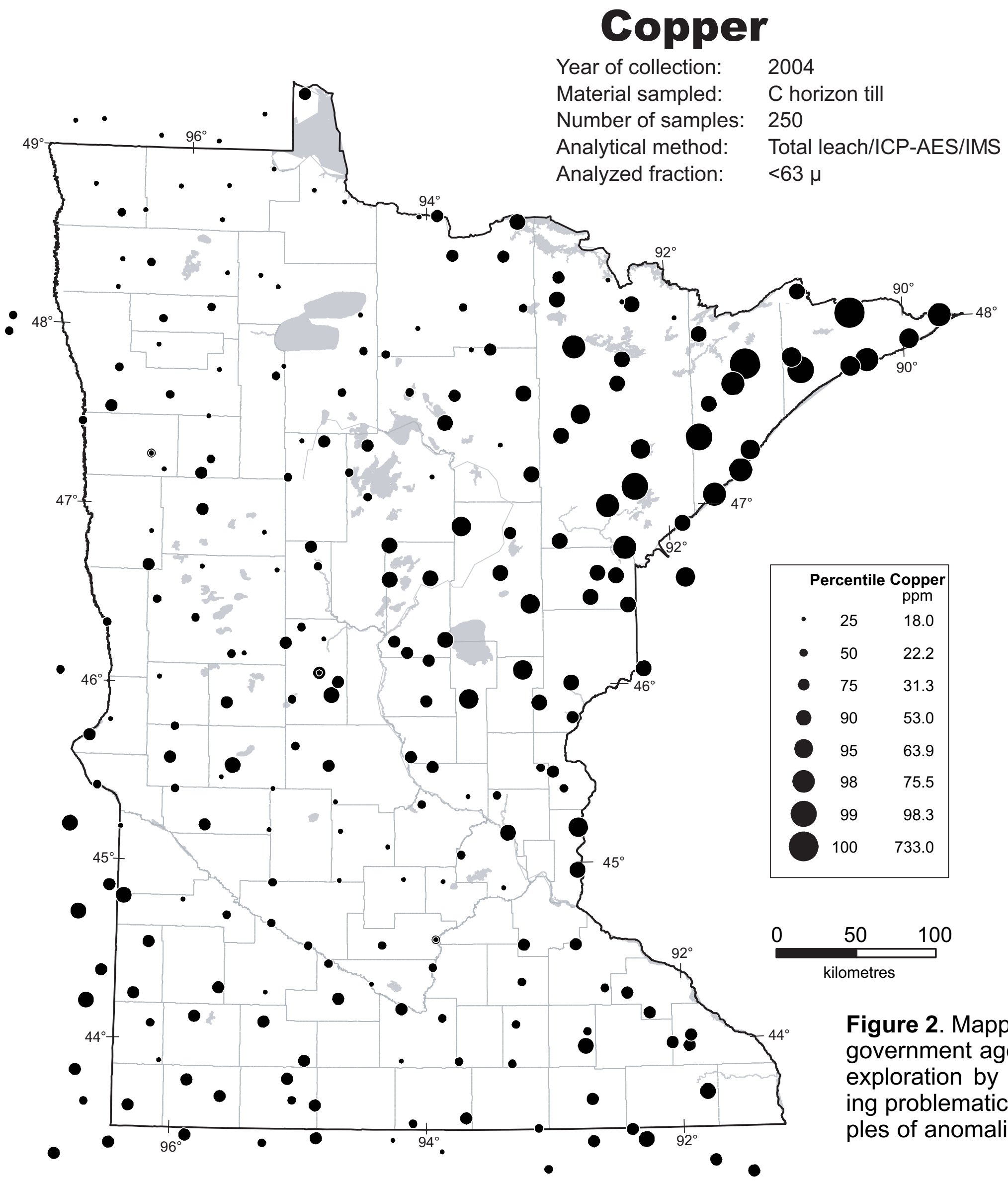

Figure 2. Mapping of sediment composition by government agencies provides a reference for exploration by mapping background, identifying problematic areas, and by providing examples of anomalies (Thorleifson et al., 2007).

Much further effort was required, however, to establish the textural and mineralogical tendencies of glacial sediments, and to clarify how survey design and interpretation requires a comprehension of these tendencies. Dreimanis and Vagners (1971), for example, demonstrated how varying rocks tend toward differing size fractions during glacial comminution, such as carbonate preferentially producing silt, and granite preferentially producing sand.

Shilts (1971) demonstrated the striking compositional differences between the clay, silt, and sand fractions of till, thus indicating the great significance of textural partitioning with respect to till geochemistry. Similarly, a comprehension of the controls on sulphide preservation in glacial sediments, with sulphides virtually absent above the water table due to aeration while being well preserved in deeper sediments, was fundamental to facilitation of progress in the discipline (Shilts, 1975).

With these principles in place, and with improved insights into glacial processes, the boom in gold exploration in the 1980s resulted in broader application and awareness of drift prospecting, and the ensuing explosion of diamond exploration in the 1990s brought advanced methods in mineral chemistry to the discipline.

STATUS

Current developments in till geochemical and indicator mineral methods in mineral exploration largely relate to more intricate and confident survey design and interpretation that take into account an enhanced comprehension of glacial process and history. Concurrently, developments in field and laboratory, elemental and isotopic analytical technology are progressing, as is the integration of knowledge from the fields of glacial geology, mineral deposit geology, and mineral chemistry. As a result, the range of targets being sought has broadened to encompass all commodities, for example with the development of indicator mineral methods suitable for the search for base metals.

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A REVISED LOOK AT CANADA'S LANDSCAPE: GLACIAL PROCESSES AND DYNAMICS

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ABSTRACT

Our understanding of the Laurentide Ice Sheet has been significantly improved by recent developments in theoretical models of ice sheets and ice dynamics, understanding of mechanisms of glacial erosion, transport and deposition, and mapping of glacial deposits and drift composition. Theoretical models have increasingly accommodated diverse glaciological, physiographic and geological factors that can affect ice flow, and have been used to reinterpret the geological record in terms of glacial processes.

The glacial system of North America is described at scales from continental (thousands of square kilometres), to regional (hundreds of square kilometres), local (kilometres to tens of kilometres), and site-specific (hundreds of metres to kilometres). Drift prospecting is based on an understanding that indicators of economic mineralization recovered from glacial deposits can be traced back to their original bedrock source. Geochemical, mineralogical and lithological methods employed in the exploration for mineral deposits in glaciated terrain requires knowledge of past glacial flow direction(s), means of entrainment, and variations in the nature of glacial dispersal such as glacial sediment thickness, bedrock topography, bedrock erodibility, and basal glacial flow velocity gradient. Combined, this knowledge is used to determine the distance to the up-ice bedrock source from the identified down-ice dispersal train location. Over the last two decades, drift prospecting in northern Canada has significantly improved through the continued development of ice sheets models, and the acquisition of empirical evidence for ice-flow patterns, drift composition and glacial history. Increased attention to the dynamic nature of glacial dispersal centers and related ice-flow complexes has thus become increasingly important for mineral exploration in northern Canada.

INTRODUCTION

Reconstruction of past ice-flow trajectories is fundamental for successful drift prospecting mineral exploration, as it provides knowledge of former flow directions and dispersal characteristics of former Pleistocene glaciers. Ice-flow directions are indicated by a variety of erosional and depositional landforms and features (cf., Aylsworth and Shilts, 1989; Boulton and Clark, 1990; McMartin and Henderson, 2004).

Glacial history and paleoflow models for northern Canada (Prest et al., 1968; Shilts, 1985; Dyke and Prest, 1987a,b; Dyke and Dredge, 1989; Dyke, 2004; Shaw et al., 2010) have been published (Fig. 1). However, applications of these continental and regional-scale ice sheet models to property-scale mineral exploration in any given prospective region are often not realistic. Indeed there are many documented examples of how localized glacial flow at a given location can be highly complex with multiple trajectories and ages, which can vary considerably from regional-scale ice-flow models (e.g. Shilts, 1984; Veillette, 1995; Parent et al., 1996; McMartin and Henderson, 2004; Ferbey and Levson, 2009; Stea et al., 2009; Trommelen and Ross, 2010; Plouffe et al., 2011; Tremblay and Paulen, 2012).

The intent of this paper is to succinctly highlight processes and features specific to glacial materials derived, transported and deposited within northern Canada. Examples highlight the detailed scale of mapping required to illustrate the differences between regional and local scale glacial dispersal models and how to apply both for successful mineral exploration. The message for exploration is that relations among bedrock, drift composition and ice-flow history must be assessed in the wider context of ice sheet and glacial history through recognition of the distinct character of local and site-specific erosional and depositional records.

GLACIAL DYNAMICS

Recognition of relict ice-flow trajectories puts in perspective the complexity of the former Laurentide Ice Sheet (Tyrrell, 1898; Flint, 1943; Shilts et al., 1979; Dyke and Prest, 1987a; Kleman et al., 1994; Dyke, 2004), and has important implications for the interpretation of compositional data generated by regional till and stream sediment geochemistry surveys and mineral exploration. It is imperative to understand that dispersal trains are the net effect of glacial erosion of mineralized bedrock sources, glacial transport and subglacial deposition, all of which can be complexed by possible multiple cycles of till re-entrainment and deposition, as glacial dynamics changed over time. Developments in Quaternary geology and ice sheet modeling have provided an important set of tools for tailoring drift prospecting methods to suit regional variations in ice-flow dynamics and glacial dispersal.

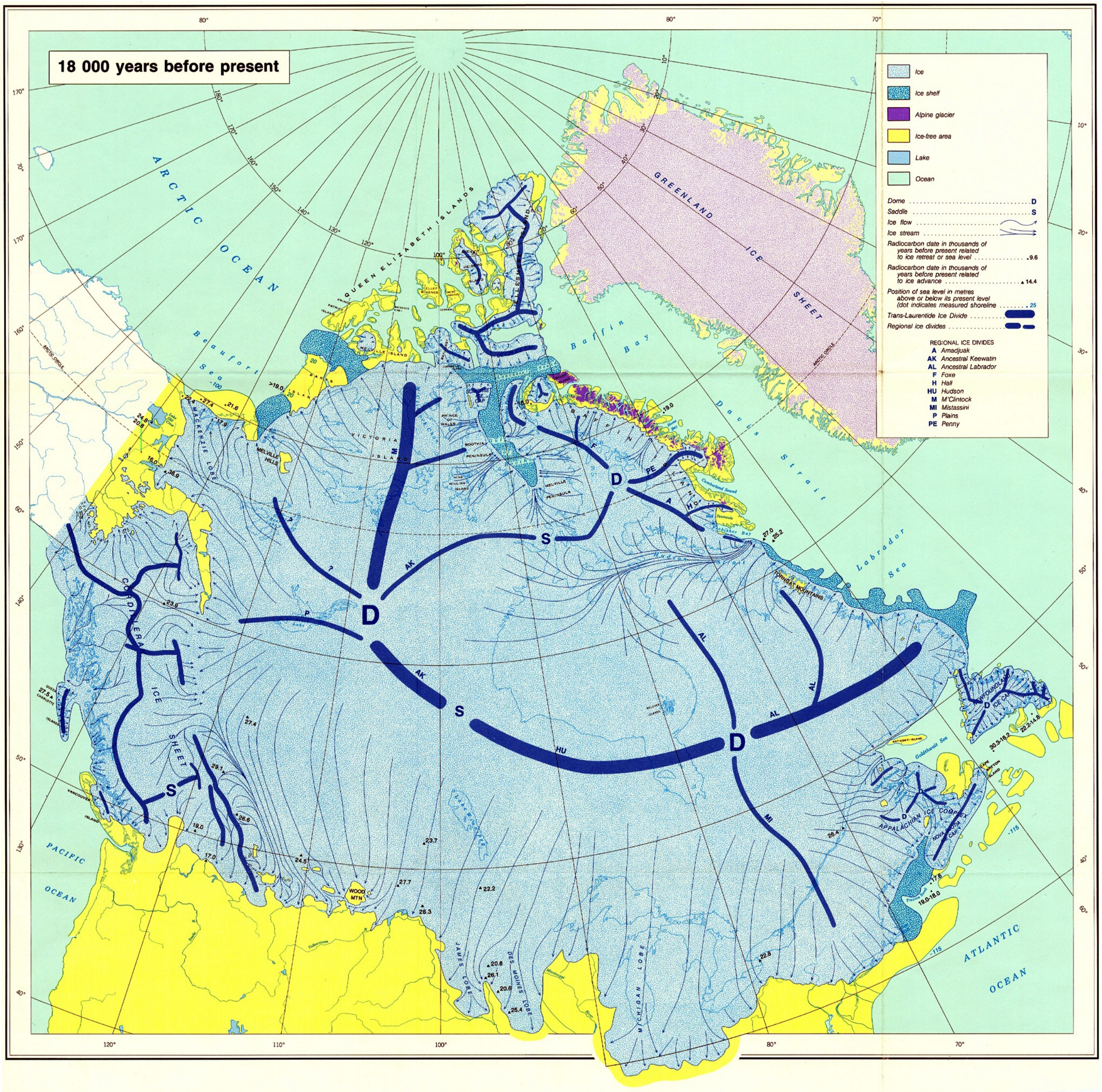


Figure 1. Extent of glaciated areas in North America during the last glacial event, showing approximate regions of ice divides and basic ice-flow trajectories (from Dyke and Prest, 1987b).

Ice streams are now recognized as prominent features of continental ice sheets, playing a vital role in flow dynamics and mass balance, (Fig. 2) (e.g. Marshall et al., 1996; Stokes and Clarke, 2003; Evans et al., 2008; Ross et al., 2009; Evans et al., 2012). Major shifts in ice flow locally and regionally also affected the basal thermal regime of the Laurentide Ice Sheet, which impacted the nature of erosion, down-ice transport and deposition of sediments. Glacial flow was a time transgressive event, and mineral deposits could quickly change from undergoing intense glacial erosion and directly contributing to dispersal trains to being buried by newly formed till deposits and thus no longer directly contributing to dispersal trains. Yet, the dispersion of mineralized detritus can continue through comminution and entrainment by ongoing ice flow (Fig. 3). As ice-flow trajectories shift, mineral-rich debris can be further reworked and diluted by non-mineralized debris, shifting the dispersal train geometry to reflect later ice-flow directions. Resultant dispersal trains can either be lobate, fan or amoeboid shape (e.g., Stea, 1994; Parent et al., 1996). A fan-shaped dispersal train can be created

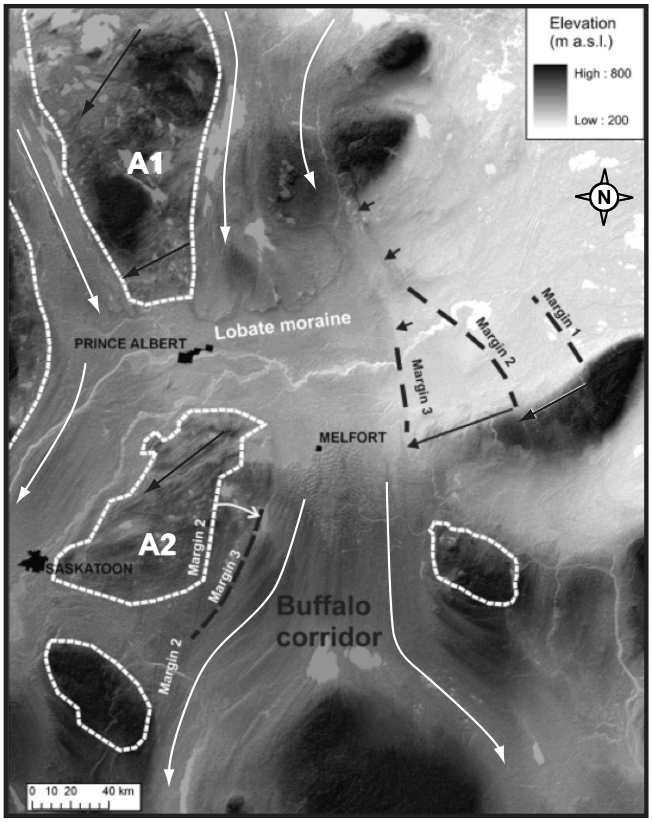


Figure 2. Shuttle Radar Topographic Mission (SRTM) hill-shade digital elevation model (DEM) from central Saskatchewan, illustrating former ice stream corridors (long white arrows), with mega-scale glacial lineations, and associated sediment-landform assemblages. A1 – A2 uplands, bounded by ice stream margins, (shown by white dashed lines) contain older ice-flow lineations (black arrows) and tracts of hummocky terrain (modified from Ross et al., 2009).

from multiple ice-flow events, or from shifting/rotating ice flow during a single glaciation (Parent et al., 1996). Palimpsest dispersal trains recorded in eastern Hudson Bay (Parent et al., 1995) suggest either re-orientation of an Early Wisconsin train or creation of a second Late Wisconsin train in a new direction. In contrast, palimpsest dispersal trains documented in Nunavut suggest that while all ice-flow directions were capable of creating a dispersal train, flow was often stronger/faster in particular directions versus others (Stea et al., 2009; Paulen et al., submitted).

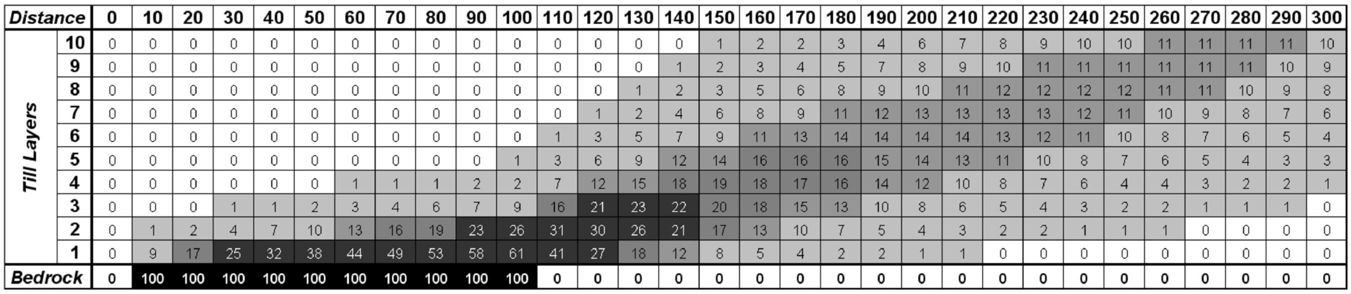
McARTHUR RIVER

Background

The McArthur River uranium boulder trains occur in the eastern side of the Athabasca Basin of northern Saskatchewan at approximately 57°45'N; 105°00'W. The Athabasca Basin consists of shallow quartz sandstones and conglomerates of the Athabasca Group, which have been subdivided into several formations based on their depositional history (Ramaekers, 1990), and fill an oval-shaped basin up to 1500 m thick in its centre. Large high-grade uranium deposits such as Key Lake, Cigar Lake, Cluff Lake, Rabbit Lake and McArthur River are situated at the unconformity between the Proterozoic Manitou Falls Formation (Athabasca Group), and the underlying Aphebian and Archean gneisses and schists (Tremblay, 1982; Langford, 1986; McGill et al., 1993). Basement-rock structural and lithological features, such as reverse faulting and graphite-bearing pelitic rocks, are typically associated with the mineralization, and that the alteration haloes can extend upward from the deposits to the present bedrock surface (Golightly et al., 1983; Hoeve, 1984). In the McArthur River area, a number of mineralized boulder trains are known, probably derived from alteration halos occurring from unconformity mineralization at depths of 200 to 400 m (Ramaekers et al., 1982).

Glacial History and Dispersion

More than one glaciation has affected northern Saskatchewan (Klassen, 1989), and during the last interstadial (Middle Wisconsin), the Laurentide Ice Sheet margin is considered to have occupied northernmost Saskatchewan (Dyke et al., 2002), potentially resulting in a substantial thickness of glacial sediment being deposited over the Athabasca Basin over a pro-



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Bedrock		0	100	100	100	100	100	100	100	100	100	100	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Figure 3. A predictive glacial aggradational-constant debris entrainment and depositional decay model, assuming the mineral source is at 100% concentration at the bedrock surface (from Stanley, 2009). As each till 'cell' entrains material from the bedrock or till layer below it, it provides source material to the overlying till layer, which is displaced one cell down-ice. The result is a dispersal train that: a) climbs at an angle relative to the bedrock surface, b) exhibits dilution down-ice, and c) becomes more diffuse as it passes upward through the entire thickness of the till.

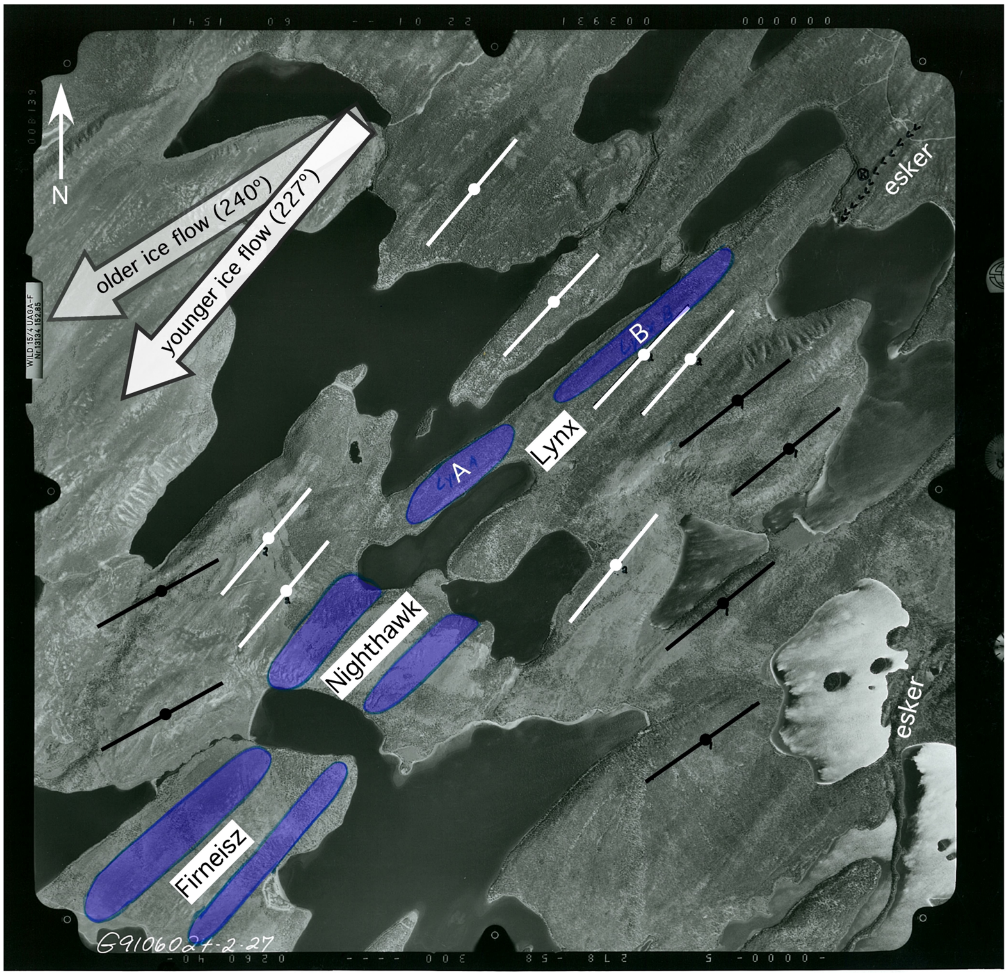

Figure 4. Aerial photograph showing (from north to south) the Lynx Lake, Nighthawk and Firneisz Lake dispersal trains in drumlinoid terrain (Saskatchewan Mineral Deposit Index 2006). Aerial photo analysis shows two phases of ice flow; an older flow to the west-southwest (black drumlinoid symbols) and a younger flow to the southwest (white drumlinoid symbols). Ice flowing west-southwest created boulder trains on the large drumlinoid landform occupied by the Lynx Lake B and A trains. A subsequent southwest ice flow created the Nighthawk Lake and Firneisz trains by dispersing the head of the Lynx Lake B train, obliterating and redistributing the tail of the Lynx Lake A train, creating two offset, parallel dispersal trains. A small esker occurs up-ice of the Lynx Lake B, but no uraniferous boulders were ever reported on the esker ridge, probably indicating a barren, northern glaciofluvial source (aerial photograph G9106024-2-27, 1:20,000, National Airphoto Library).

tracted period of time. Ice flowing from the Keewatin Sector of the Laurentide Ice Sheet generally advanced southwestward from a dispersal centre in Nunavut (Prest, 1984; McMartin and Henderson, 2004). During deglaciation, flow dynamics was affected by thinning ice and ice-flow trajectories may have varied up to 60 degrees or more (Campbell, 2007; Dyke, 2004).

Regional mapping of erosional and depositional ice-flow indicators (Campbell, 2007) record that multiple, distinct phases of glacial flow affected the region. Two dominant ice flow directions were consistently observed on aerial photographs.

1) An older, strong west-southwestward ice flow, ranging from 240º to 260º, occurred during the onset through to glacial maximum of the Late Wisconsin Laurentide Ice Sheet. The thickest sediment deposits of a Canadian Shield clast-rich till, and the largest drumlins across the southern part of the study reflect this earlier phase of ice flow (Campbell, 2009), the effect of which can be seen today in some of the orientation of lakes that occupy the low regions between drumlins.
2) A younger, strong southwestward ice flow, ranging from 220º to 230º. Most of the drumlins formed by the earlier phase of flow were reshaped to reflect this southwestward direction. The majority of mineralized boulder dispersal trains found in the field parallel this southwest flow direction (Fig. 4).

Although the extensive druminloid landscape does infer a dominant dispersal direction to the southwest, observations of erosional ice flow indicators provide insight into a more complex history of dispersion. Extensive dispersion and glacial erosion of mineralized bedrock resulted from the oldest phase of west-southwestward flowing ice. The three boulder trains (Saskatchewan Mineral Deposit Index 2006) shown in Figure 4 are considered to be part of a composite glacial dispersal from a single source. The parallel trains identified for Nighthawk and Firneisz are probably palimpsest phenomena (Parent et al., 1996; Stea et al., 2009). That is, ice flowing west-southwest created boulder trains in the older, larger drumlinoid landform occupied by the Lynx Lake trains. Till generated from this older ice flow probably buried the mineralized source, ensuring that subsequent younger ice flow could not produce a second primary-sourced train. Younger southwestward ice flow created the Nighthawk Lake and Firneisz trains by entrainment and dispersal of the head of the Lynx Lake B train, and obliterated and redistributed the tail of the Lynx Lake A train, and created two offset, parallel Nighthawk and Firneisz dispersal trains. Rather than considering these parallel trains as being derived from separate sources, it is considered more likely that the radioactive boulders were transported first west-southwestward and subsequently southwestward and, as these flow directions are prominent in the area. The intervening barren zone can be explained as a result of mixing (dilution) of previous tills with inert up-ice debris, referred to as overprinting (Stea and Finck, 2001).

IZOK LAKE

Background

The Izok Lake deposit (65° 38' 00" N, 112° 47' 45" W) is in Nunavut, at its western border with the Northwest Territories, in the Point Lake map sheet (NTS 86H), approximately 400 km north of Yellowknife. The Izok Lake deposit and surrounding regions are located in the central Slave Structural Province, a granitic-greenstone terrain of folded, faulted and metamorphosed Archean rocks containing belts of 2.67 to 2.70 billion year old metasedimentary and metavolcanic rocks of the Yellowknife Supergroup (Padgham and Fyson, 1992; Bleeker and Hall, 2007). The Izok Lake deposit is a significant mineral deposit, with total indicated and inferred resources of 14.8 Mt grading 2.5% Cu, 12.8% Zn, 1.3% Pb, and 71 g/t Ag enclosed within a group of five near-surface sulphide lenses (Costello et al., 2012). The three western most zones subcrop under Izok Lake. The deposit consists mainly of galena, sphalerite, and chalcopyrite, with a variety of other lesser ore minerals (Money and Heslop, 1976; Morrison, 2004). The presence of sulphide–rich boulders on the west shore of Izok Lake led to the deposit's discovery in 1975 (Money and Heslop, 1976).

Glacial History and Dispersion

Regional mapping of the surficial geology and ice-flow indicators document a general systematic, clockwise rotation of ice flow in the study area from southwest to northwest, occurring as a series of discrete ice-flow phases, rather than a progressive, continuous change in flow (Dredge et al., 1996a; Kerr et al., 1995, 2000; Stea et al., 2009). These ice-flow phases can be defined as regionally mappable patterns at a number of sites, distinguished by relative ages and the presence or absence of striations and trends of landforms. The oldest known phase of ice flow across the Point Lake map sheet has been documented as a generally southwest direction (Kerr et al., 1995; Dredge et al., 1996b). This earliest flow was followed by a strong northwestward trending ice flow, as indicated by landforms and striae (Paulen et al., submitted). The final ice-flow phase is documented as ice-marginal flow in several directions, at local scales, from west-southwest to north in the Point Lake map sheet (Kerr et al., 1995). Surficial maps indicate a strong relationship between the latest phase of ice flow and the trend of glaciofluvial landforms (Dredge et al., 1996b).

The discovery of high grade massive sulphide boulders and gossanous frost boils on the south, southwest and western shorelines of Izok Lake in 1974 (Money and Heslop, 1976) indicated that mineralized rocks were dispersed in a broad fan spread of almost 90 degrees. At the reconnaissance survey scale, McClenaghan et al. (2012a) demonstrated that indicator minerals from the Izok Lake VMS deposit were detected in 10 kg till samples at least some 40 km northwest of the deposit, generally down-ice from the later, dominant ice-flow trajectory.

At the property scale, strong dispersal from the older southwest ice flow is apparent by the presence of massive sulphide boulders and gossanous rusty-orange frost boils along the southern shore of Izok Lake. Recent detailed till sampling down-ice of the Izok Lake VMS deposit (Hicken et al., 2012; McClenaghan et al., 2012b) also documents a strong southwest dispersal with elevated indicator mineral counts southwest of the deposit. This older dispersal train was reworked by subsequent northwest ice flows, resulting in a palimpsest dispersal fan west of the Izok Lake deposit (Fig. 5). Distal elements of the main Late Wisconsin dispersal train show a west-northwest dispersal trend, but are slightly offset to the southwest.

CONCLUSION

The geometry of the mineral dispersal patterns shown are the result of the juxtaposition of different flow regimes as the Keewatin Ice Divide evolved and shifted during the last glaciation (McMartin and Henderson, 2004). Clearly, the predominant regional ice flow, southwestward at McArthur River and northwestward at Izok Lake, had a major effect on the landscape and the shape of the fans, but significant offsets and fan relics are left from the precursor older ice flows. As ice-flow trajectories shifted, debris from the earlier dispersal trains was reworked by several processes which include comminution, re-entrainment and transport of mineralized debris from previously deposited till and the mineralized source (inheritance) and overprinting (Stea and Finck, 2001). The evolution of dispersal fans over time may be modeled using vectors with both scalar (duration/intensity) and directional components (ice-flow trends).

Through mapping ice-flow indicators and knowledge of regional glacial history, it is possible to recognize when a palimpsest glacial dispersal train may be expected in a field area. If not recognized ahead of

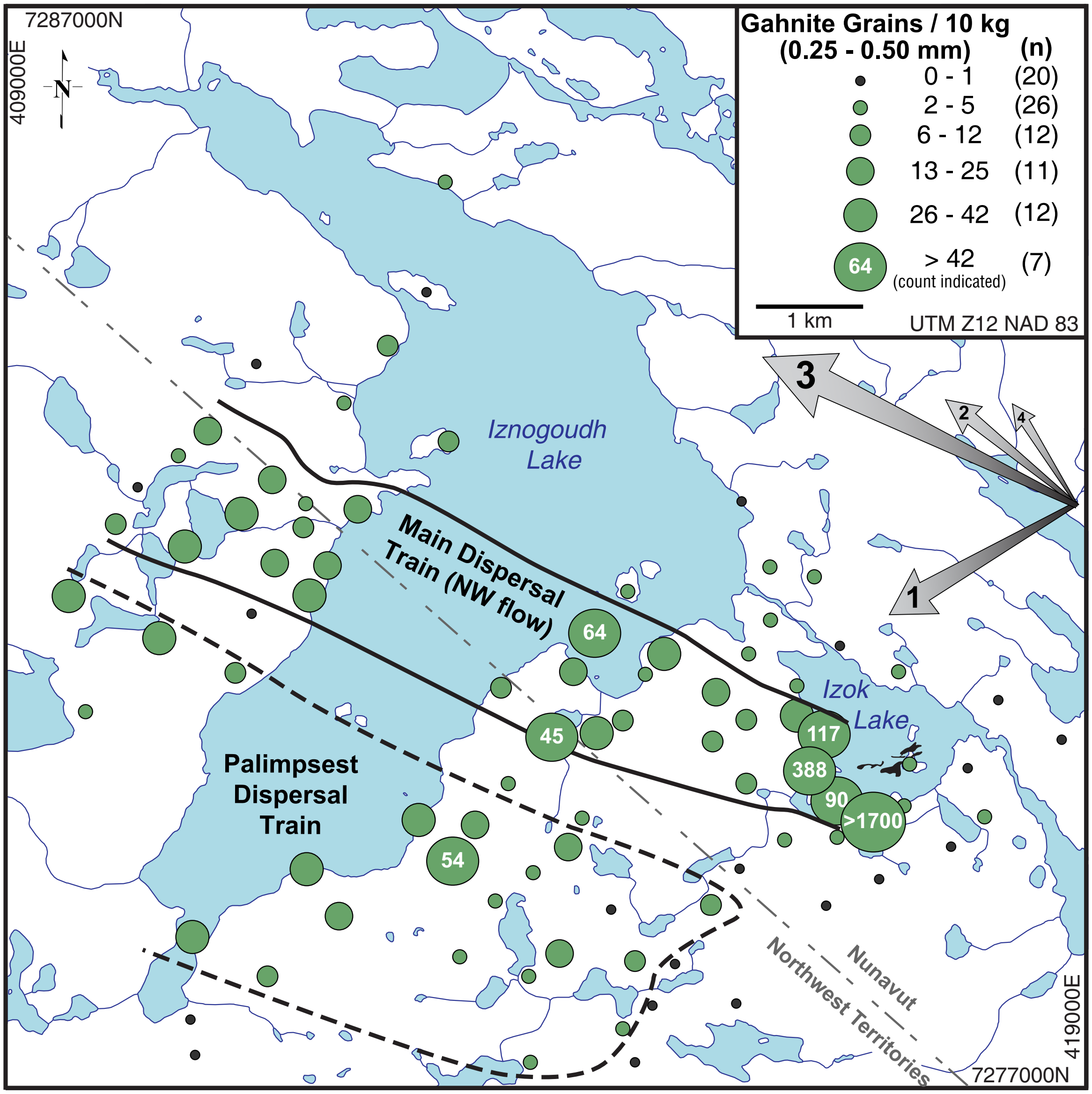

Figure 5. Gahnite grain abundances in the 0.25-0.50 mm fraction of till (normalized to 10 kg sample weight) up-ice, proximal to, and down-ice from, the Izok Lake VMS deposit (McClenaghan et al., 2012b; unpublished data MMG), which subcrops (indicated as black polygons) under Izok Lake (Morrison and Balint, 1993). The Late Wisconsin (main) dispersal train is defined by solid lines; the dashed lines indicate a palimpsest dispersal train. Arrows indicate relative chronology (1 = oldest) and strength (arrow size) of glacial events (from Paulen et al. submitted).

time, the possibility exists that only part of a dispersal train/fan may be sampled or that detected trains/fans may be traced up-ice in the wrong direction. Stea et al. (2009) have demonstrated that searches for multiple bedrock sources may be unnecessary in areas of palimpsest trains. Understanding the relative strength of each glacial trajectory, and the nature of the complete fan may help narrow down potential target areas, as the dispersal train source is usually located up-ice of the fan apex (Shilts, 1976; Parent et al., 1996; Stea et al., 2009; Plouffe et al., 2011). That said, it is plausible, that the minerals that define palimpsest dispersal fans could also be derived from undiscovered, and unknown local mineral deposits.

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QUALITY ASSURANCE AND QUALITY CONTROL MEASURES APPLIED TO INDICATOR MINERAL STUDIES AT THE GEOLOGICAL SURVEY OF CANADA

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INTRODUCTION

A number of research projects are conducted at the Geological Survey of Canada (GSC) with the objective of identifying new indicator minerals hosted within, or associated with, a variety of mineral deposit types. These minerals can be recovered from glacial sediments and traced back to their bedrock source as an effective mineral exploration method in glaciated terrain. These projects are currently carried out as part of the Geo-mapping for Energy and Minerals (GEM 2008-2013) and the Targeted Geoscience Initiative-4 (TGI-4 2010-2015) programs. As research on indicator minerals evolves, quality assurance and quality control (QA/QC) measures must be implemented to ensure that 1) in the field, samples are not contaminated from external sources or from other samples; 2) during sample processing and indicator mineral picking, loss of indicator mineral grains are minimized (close to zero), cross-contamination before and among sample batches does not occur, and minerals are correctly identified; and 3) all reported indicator mineral data include adequate metadata for future reference and comparison. To fulfill these needs, protocols have been developed for ongoing and future research projects at the GSC to ensure indicator mineral data of the highest quality. These protocols satisfy the requirements of National Instrument 43-101 (2005), which specifies that technical information reported by exploration and mining companies (such as indicator mineral data) must include an indication that a quality assurance program is in place and is being implemented. This extended abstract contains a summary and the key points addressed in Plouffe et al. (in press) and Spirito et al. (2011).

FIELD PROCEDURES

Detailed field procedures to accurately locate sample sites, record field notes, and identify the type of glacial sediments being sampled are addressed by Spirito et al. (2011). Metallic tools (shovels, picks, hammers, etc.) are generally used for the sampling of glacial sediments. Tools should be examined and thoroughly cleaned in order to reduce their role as potential sources of contamination at the onset of a field program. Paint, varnish, and other types of surface coatings should be removed as they represent a potential source of contamination to heavy mineral concentrates. Sampling tools do wear with usage (Fig. 1), and produce metal shavings of various unnatural forms, which should be expected and recognized in heavy mineral concentrates (Fig. 2). Glacial sediment samples collected from diamond-drill core can be contaminated with industrial diamonds from the drill-bit (Fig. 3). Tools should also be cleaned properly between collection of samples to avoid cross-contamination (Fig. 4a,b). As much as possible, samples should not be manipulated by hand or with dirty gloves, which also represent a source of contamination (Fig. 4c). Finally, those collecting the samples should not wear hand jewellery because rings are known sources of contamination (Kontas, 1991) and could impact geochemical analyses of heavy mineral concentrates.

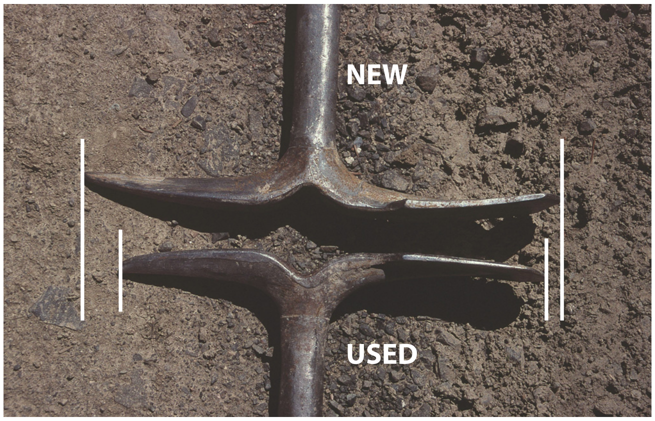

Figure 1. Two hoe-picks of the same brand. The top one is nearly new and the bottom one has served for three field seasons. Note that the older one has visibly lost metallic mass (distance between the white lines), which has, in part, ended up in samples collected over the years.

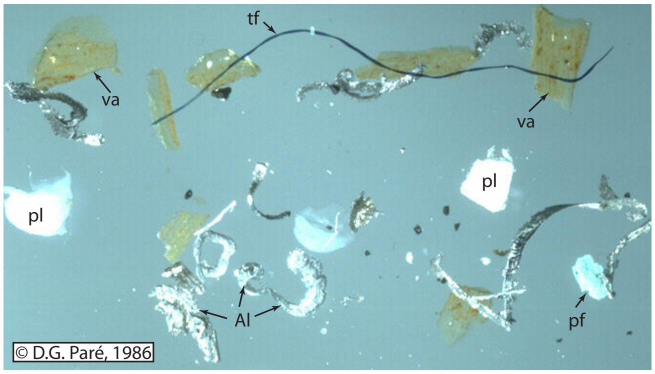

Figure 2. Examples of contamination in heavy mineral concentrates including plastic from vial cover (pl), textile fibre (tf), aluminum shavings (Al), varnish flakes with traces of wood fibre (va), and paint flakes (pf); photographs from D.G. Paré, Consorminex Inc., Gatineau, QC (consorminex.com).

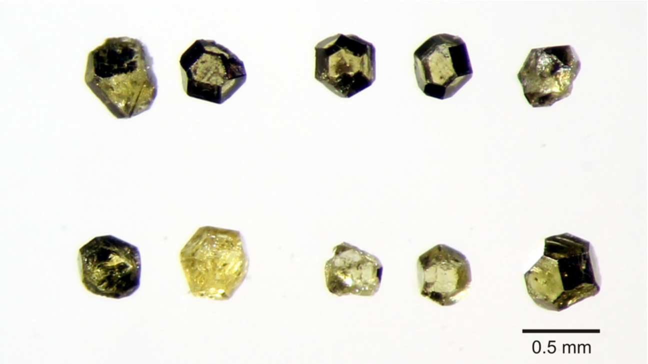

Figure 3. Industrial diamonds recovered from a till sample that was collected from diamond drill core.

Anthropogenic contamination of glacial sediments may also affect the indicator mineral component and should be expected in areas proximal to present and past-producing mines and related infrastructure (Bajc and Hall, 2000; McMartin et al., 2002; Hozjan and Averill, 2009; Michaud and Averill, 2009). For example, gold spheres can be expected in samples collected close to gold mines with assay facilities (DiLabio et al. 1988). Although smelter particles can be small (e.g. 5-100 mm in Knight and Henderson, 2006), larger particles (0.25-0.5 µm) can be expected near smelter sites (Fig. 5 and examples in Henderson et al., 1998; McClenaghan et al., in press-a). In at least one instance, airborne particles have been suspected to have been introduced in the sample at the time of collection (McClenaghan et al., in press-a). Therefore, near anthropogenic sites, sample bags should be kept closed until the last moment of sample collection and samples should be collected at a minimum depth of 0.5 m (where possible) even if fresh unoxidized and undisturbed till is exposed at surface (Fig. 6). All sites where anthropogenic contamination is suspected should be sampled with extreme caution and noted accordingly. Near-surface till that appears to be undisturbed can actually be highly contaminated in these areas. Knowledge of the sedimentological properties of till (cf. Evans et al., 2006) is essential to identify sediment genesis properly near anthropogenic deposits.

Samples should be collected in new plastic bags (>6 mil), plastic pails, or in metal pails lined with large plastic bags. Rice or cloth bags should not be used for till or glaciofluvial sediment sampling as they are slightly porous and allow loss of fine-grained material and/or contamination. Care must be taken when transporting samples from the field sites to the laboratory to avoid puncturing the bags and contaminating samples. Chain of custody of those samples must be monitored and documented to prevent other potential sources of contamination or tampering.

Figures 4. Potential sources of carry-over contamination: **(a)** a dirty pick with sediment stuck to it after the collection of a sample, and therefore unsuitable for the collection of the next sample; **(b)** a cleaned pick ready for the collection of a sample; and **(c)** dirty gloves also represent a potential source of contamination if the subsequent sample is manipulated by hand.

Sample size suitable for recovery of indicator minerals is largely dependent on glacial sediment texture. To obtain an adequate number of indicator mineral grains, a sample must contain an average of 5 to 10 kg of sand-sized material (0.063-2 mm) (Clifton et al., 1969; Averill, 2001). Sample size may also be dictated

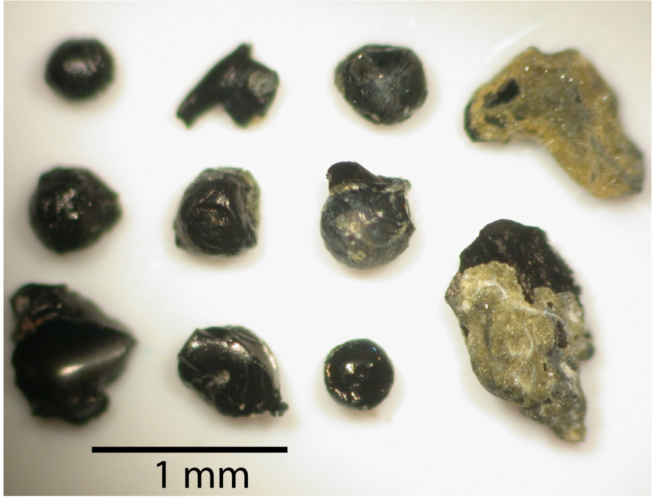

Figure 5. Smelter particles recovered from till samples collected proximal to the Thompson Mine site (McClenaghan et al., in press-a).

by the range and type of analyses to be performed. In the field, a consistent sample size is collected based on volume, for example a full pail or full sample bag, knowing that a full pail or bag represents an approximate weight of material. The weight of the sediment will vary according to moisture content, sediment compaction, and composition. As a general guide, 10 to 20 kg of sandy-silty till, 20 to 40 kg of clayey till, and 12 to 25 kg of glaciofluvial sediment is required to obtain a representative heavy mineral sand-sized concentrate. At the GSC, samples are often not screened in the field because silt and clay adhering to larger clasts would be lost from the sample (in other words, there is the potential of losing silt-sized indicator minerals such as gold and platinum group minerals) and sieves may represent an additional source of cross-contamination.

Field duplicate samples can be collected to estimate site variability due to sediment heterogeneity, and to assess the precision of the laboratory separation and mineral identification procedures. Typically, a duplicate sample is collected about 5 to 10 m from the original sample site within the same sedimentary unit and at about the same depth from surface (Fig. 7).

PREPARING SAMPLES PRIOR TO INDICATOR MINERAL PROCESSING

Blank and spiked samples should be introduced into a sample batch prior to being shipped to an indicator mineral processing laboratory. Blank samples should consist of unconsolidated earth materials devoid of indicator minerals of interest. Currently, the GSC utilizes as a blank a weathered granite (grus) collected from a Silurian-Devonian intrusion of the South Nepisiguit River Plutonic Suite (Wilson, 2007; McClenaghan et al., 2012) located approximately 66 km west of Bathurst, New Brunswick (Fig. 8). A blank is introduced as the first sample in a batch to

Figure 6. Till sample site in a region heavily disturbed by anthropogenic activity at the old Pine Point Pb-Zn Mississippi Valley-Type mining district, Northwest Territories. Till samples were collected in a former open pit mine, below the original natural land surface (Rice et al., in press) and away from mine waste piles, which consisted of till excavated from the former open pit, mixed with other mine debris.

Figure 7. Example of a sampling site from which a routine sample (black arrow) and a field duplicate sample (white arrow) have been collected in the same sedimentary unit and at approximately the same depth.

Figure 8. a) Sample site of the unconsolidated weathered Silurian-Devonian granite (grus) used for GSC blank heavy mineral samples; **b)** close-up view of the blank sample material; and **c)** close-up view of the 2 to 4 mm fraction of the blank material.

monitor cross-contamination potentially derived from previously processed samples. A blank sample should also be introduced immediately after a sample known to contain large abundances of indicator minerals of interest (e.g. collected near known mineralization). In a large sample batch (N>200), a blank sample can be introduced randomly every 50 samples. Blank samples serve to detect cross-contamination, but cannot necessarily prevent it.

Spiked samples consist of base material into which spiking grains were voluntarily introduced. They are used to quantitatively monitor the effectiveness of a processing laboratory at recovering and identifying specific indicator minerals (Michaud and Averill, 2009). These spiked samples are the equivalent of the secondary standards with known elemental concentrations used to monitor accuracy of geochemical analyses (McClenaghan et al., in press-b). The base material should be similar in texture to the rest of the routine samples. Its mineralogy should be known following repetitive indicator mineral separations and analyses. Currently, the GSC is using till recovered from a borrow pit near Almonte, Ontario that is texturally typical of till derived from the southern Canadian Shield and has an established average mineralogical composition based on repetitive indicator minerals analyses (Plouffe et al., in press). The spiking grains should be mineral grains of interest that have been either laser etched (Whiteford, 2003) or photographed so that they can be recognized. These grains should be carefully selected to ensure that they are not fractured or well cleaved as they could break into smaller particles during the sample processing (Hozjan and Averill, 2009; Michaud and Averill, 2009). If possible, spiking grains should be grains that have been recovered from other sediment samples as grains recovered from crushed bedrock will differ in morphology and could bias the assessment of processing and picking recovery rates. Artificial density markers with specific size range and density are commercially available and also can be used for spiking (Gent et al., 2011) with some limitations as outlined in Plouffe et al. (in press). As part of the protocols implemented at the GSC, it is recommended that 2% of a sample batch be spiked samples.

Blank, spiked, and duplicate samples should have numbers similar to the routine samples so that they cannot be easily recognized by the processing laboratory and a processing order should be communicated to the laboratory. For instance, to avoid cross-contamination, samples known to potentially contain large amounts of indicator minerals (e.g. collected near known mineralization) should be processed last.

LABORATORY PROCEDURES FOR THE RECOVERY OF INDICATOR MINERALS

Towie and Seet (1995), Gent et al. (2011), and McClenaghan (2011) provide an account of several processing methods available for the recovery of indicator minerals from unconsolidated sediments. It should be emphasized that different processing methods will produce concentrates of varying mineral species and weights. Therefore, it is important to ensure that the method used in the laboratory is appropriate for the recovery of the target minerals. Furthermore, as part of the laboratory selection, Doherty (2009) recommends visiting the facility to identify potential steps in the processing where contamination might occur or mineral grains may be lost.

Plouffe et al. (in press) describe the heavy mineral processing methods adopted by the GSC. These methods have been utilized by the GSC in various geological settings with glacial sediments of varying textures with satisfactory results. These methods include 1) a pre-concentration of the <2 mm size fraction of the bulk sediment sample using a shaking table (material >2 mm is retained for the identification of clast lithologies); 2) micro-panning of the table concentrates for the identification of small mineral grains with high density (e.g. gold grains, platinum group minerals, uranium, and sulphide minerals); 3) further density concentration of the table concentrate with heavy liquids (typically with a specific gravity of 3.2 but 2.8 and 3.0 can also be used depending on the minerals of interest); 4) extraction of the ferromagnetic fraction from the heavy mineral concentrates using a hand magnet; and 5) examination and identification of indicator minerals in three different size fractions: 1.0-2.0 mm, 0.5-1.0 mm, and 0.25-0.50 mm. Electromagnetic separations at precise amperages are used to further separate minerals in the 0.25-0.50 mm fraction as per their magnetic properties and to facilitate mineral identification (e.g. McClenaghan, 2011). The ferromagnetic fraction can also be examined for the presence of specific indicator minerals such as pyrrhotite and the recovery of magnetite (e.g. McMartin et al., 2011). Sample weights should be recorded at each step of the processing. Visual identification of potential indicator minerals is carried out using a binocular microscope and is aided by using a scanning electron microscope (SEM) and ultraviolet light.

AFTER RECEIVING DATA AND INDICATOR MINERALS FROM A PROCESSING LABORATORY

Once data are received from the mineral processing and identification laboratory, all QA/QC results should be examined and evaluated. The QA/QC results should then be communicated to the laboratory. Satisfactory results indicate to the laboratory that their procedures are adequate for the recovery and identification of the reported minerals. In the case of perceived errors, laboratory procedures may need to be adjusted.

To verify the precision of the indicator mineral identification, approximately 10% of the mineral concentrates should be re-submitted (Doherty, 2009; McClenaghan, 2011). Those samples should be relabelled so that they can not be identified by the laboratory personnel.

The chemical composition of indicator minerals provides key information about the genesis of the mineralization, alteration, or bedrock lithology, and, in some cases, the mineral fertility of a potential deposit (e.g. diamond from kimberlite). A number of analytical methods and instruments are available to assess and/or determine the composition of mineral grains including scanning electron microscope equipped with an energy dispersive X-ray spectrometer (SEM-EDS), electron microprobe (EMP), laser ablation-inductively coupled plasma mass spectrometry (LA ICP-MS) (Jackson, 2009), and secondary ion mass spectrometry (SIMS). Regardless of the selected analytical method, certified mineral reference standards and duplicate grain analyses should be used to monitor analytical accuracy and precision (de Souza, 2006; Doherty, 2009).

At the GSC, all indicator mineral data including original laboratory reports and mineral chemistry, as well as sample heavy mineral concentrates, unmounted picked grains, and grain mounts are permanently archived for future reference using specific guidelines (Spirito et al., 2011).

REPORTING INDICATOR MINERAL DATA

As a minimum, all GSC published reports with indicator mineral data include the following:

- Sample medium: till, glaciofluvial sediments, stream sediments, etc.;
- Name of processing laboratory;
- Name of mineral identification laboratory (if different from the processing laboratory);
- Weights of material processed for recovery of indicator minerals (original sample weight, weight of table feed, <2 mm);
- Pre-concentration method (e.g. panning, hydroseparator, shaking table, dense media separator, Knelson concentrator, jig, rotary spinal concentrator, other);
- Heavy liquid separation: name of liquid, and density;
- Magnetic separation: type of magnet used (e.g. hand magnet, Frantz, roll magnet, or other methods) and amperages if an electromagnet is used;
- List of all size and density fractions prepared and their individual weights;
- Weight and size range of fraction(s) examined for indicator minerals and the percentage of concentrate examined for each sample if the complete concentrate was not examined;
- Mineral identification or characterization method: visual scan under the binocular microscope, MLA, quantitative evaluation of material by scanning electron microscopy (QEMSCAN), SEM-EDS, cathodoluminescence (CL), or other methods;
- Mineral chemistry determination method, machine operating conditions, and laboratory name used for: EMP, SEM-EDS, LA ICP-MS, other;
- Raw indicator mineral count data as reported by the picking laboratory;
- Indicator mineral count data as confirmed by EMP, SEM-EDS or other methods;
- Indicator mineral count data as values normalized to total sediment weight processed (e.g. number of grains per 10 kg table feed, <2 mm);

Note: the total indicator mineral grain counts are never combined; they are reported separately for each size fraction.

CONCLUSIONS

Indicator mineral surveys represent a significant investment, as such, implementation of proper QA/QC measures at all stages of surveys, from field to archival, will ensure that the data generated is of the highest possible quality. The GSC protocols presented in these short course notes will continue to be improved over time as more samples are processed, and as mineral separation and identification procedures at commercial laboratories evolve and improve.

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MANAGING GEOCHEMICAL DATA: CHALLENGES AND BEST PRACTICES

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INTRODUCTION

Geochemical data are complex and pose many challenges for data management systems. Indictor mineral data can be even more challenging, with problems arising principally from the complex and varied sample processing procedures involved in recovering and identifying indicator minerals. Indicator mineral data from Geological Survey of Canada (GSC) projects are stored in a sophisticated general-purpose geochemical database, together with other more traditional types of geochemical data. This extended abstract will focus on the benefits of a good data management plan, and look at some of the issues that need to be addressed, using the GSC database as an example.

DATA MANAGEMENT PLAN

Managing data effectively makes the information easier to use and understand. A comprehensive database enables easy dissemination of the data and ensures its long-term preservation. A well thought-out plan to organize, store, share, and archive data (Data Information Literacy Project, 2011) is efficient and allows easy succession planning with long-term data management. An effective data management plan can mitigate common issues, such as cryptic column names.

Quality assurance (QA) and quality control (QC) of the data are integral parts of a good data management plan. Spirito et al. (2011) discuss in detail protocols being used at the GSC. It is good practice to have an effective analytical QA/QC program in place and that all geochemical data are checked for completeness, precision, and accuracy before interpreting the data.

The most effective way to organize geochemical data varies on the nature of the data, how it is to be used, and what is logical for the organization. Geochemical data, for example, logically fit into a database designed using surveys, sites, and samples as the main "entities" for ordering the data. One of the most important considerations is to document the data with as much detail as possible to ensure its long-term usefulness.

The two most common formats for storing data are databases and spreadsheets. Relational databases are excellent at managing complex data sets, but it is very difficult to design an effective database for the long term as the data are continually evolving with greater complexity. For example, storing indicator mineral data, such as grain abundance and electron microprobe (EMP) compositional data, along with all the other associated details, including size fractions, weights of magnetic and non-magnetic fractions, and processing information, can be very complicated. It is often more practical to use a simpler architecture; for example, data in a Microsoft Excel® spreadsheet, with associated metadata in an accompanying Microsoft Word® document. This simple architecture is enough to ensure that the data will maintain their value in the long term, but it is not conducive to sophisticated merging and analyzing of multiple data sets. Although tables in a database are much like tables in a spreadsheet, with columns and rows, tables in a database are more powerful because the data between tables are related and can be manipulated. A robust database can be easily queried and the relevant data extracted for an end-user. Some of the advantages and challenges encountered when using databases and spreadsheets are listed in Table 1.

It is important to note that even the simplest relational database cannot be designed without a basic knowledge of concepts such as primary and foreign keys, one-to-many and many-to-many relationships, and normalization (Adcock et al., in press). There are many good textbooks and websites describing these concepts, including Wikipedia, which is a good starting point.

Legacy data must be considered in any data management plan as there can be challenges with storage media as well as hardware and software. For example, old media, such as 5¼" diskettes, may no longer be readable because the diskette itself may have deterio-

Table 1. Advantages and challenges of using databases and spreadsheets.

	Databases	Spreadsheets
Advantages	- Better organized - Better controls for data integrity - Easier to manipulate data	- Users comfortable with tabular format - Easier to use
Challenges	- Design needs time up-front - Interface is not user-friendly (MS-Access® is the exception)	- Storing data consistently across multiple spreadsheets, e.g., SampleID 2013-MPB-001 vs. 2013_MPB_001 - Easily corrupted by copy/paste errors or incorrect data sorting

rated or the drives to read the diskettes may no longer be available. In addition, some file formats (e.g. Lotus® 123) may no longer easily be read by current software. There is no one-solution to store data for future use. The solution will depend on the organization, its resources and the people managing the data.

Digital data can easily be corrupted or altered, either intentionally or unintentionally (Hodge, 2004). A robust data management plan includes backup and archival procedures and accommodates changes in technology.

METADATA

Metadata are structured information that describe or explain the data and make it easier to retrieve, use, and manage the data. Metadata are often referred to as "data about data" or "information about information" (Hodge, 2004) and do not vary from sample to sample in a survey.

Metadata are essential to ensuring that the data survive and continue to be accessible into the future (Hodge, 2004). For example, with metadata, the data will continue to have value years after the samples were originally collected, especially if the person who collected the data has left the organization. Metadata are also used for data discovery, either to facilitate searching over the internet or to discover relevant data within an organization.

It is important to store metadata with the data because metadata give context to the data and increase the confidence others have in it. If the data and metadata are not stored together, they will become disconnected and there is a chance the metadata will be lost. Without metadata, meaningful analysis of the raw data may be difficult. For example, consider a set of Zn analyses for sediment samples for which it is unknown if the analyses were by partial or total digestions, what size fraction was analysed, or even if the sediment is till or stream sediment. The data can be plotted and it may be possible to see patterns but the magnitude of the numbers will have no real meaning. It is therefore a good idea to have the metadata embedded with the data in a database, or to have the raw data in a spreadsheet and the related metadata in the same spreadsheet file or in a text file.

Categories of Metadata

For most geochemical surveys, the minimum classes of metadata that should be recorded can be grouped into five categories, as shown in Table 2. Metadata specific to indicator minerals will be discussed in a later section.

Balance and Metadata Standards

Ideally, it would be useful to have every single aspect of the data documented by cataloguing extensive metadata, but in reality there must be a balance between the utility of the metadata and the time it takes to collect and record it. Therefore, there are usually minimum metadata requirements that should be established when the project is being designed. Other categories of metadata, or levels of detail within those categories, while useful to have, are optional. For example, documenting

Table 2. Minimum metadata to be recorded for a geochemical survey.

Metadata Category	Information to Record
Field Operations	- Date, location, geologist's name, NTS map sheet, sample medium, etc.
Sample Preparation	- Laboratory name - Methodology – describe in as much detail as possible - Number of samples prepared (i.e. was every collected sample prepared?) - Include a published reference to the techniques, if possible
Analytical	- Laboratory name - Date the samples were analysed - Size fraction analysed - Aliquot weight - Digestion (if applicable) – be specific about ratio and type of acid(s) - Analytical method - Upper and lower detection limits - Laboratory package name- use the package name the laboratory advertises in its catalogue - Laboratory package description – reproduce the description from the catalogue in the database (old catalogues may disappear from the web)
Project	- Funding source - Context of the project or program the work lies within
Publication	- Citation of publication, if applicable - Clearly identify if the data are published in places other than the current publication or if there is a reference to background work reported in other publications; includes online/digital publications

analytical digestions and techniques is recommended, but it is not necessary to describe every minute detail of the methodology, only to ensure that there is sufficient detail recorded to understand and interpret the data. If time and resources permit, recording excessive metadata does not create problems and recording as much metadata as possible is encouraged (Adcock et al., in press).

Currently there is no standard for cataloguing geochemical metadata. There is, however, a standard for recording geospatial data that can be extended for use with geochemical data. It is helpful to include keywords as a category of metadata, but at this time there is no generally recognized controlled vocabulary or thesaurus for geochemical data. Use of established keywords, like those found in the GeoRef thesaurus (Goodman, 2008), for example, is advantageous. If established keywords are not used, it is important to standardize keywords within the organization.

MERGING DATA SETS

Merging multiple overlapping data sets in a given area, or merging geographically adjacent data sets to create a regional compilation, allows for more detailed analyses. Regional patterns become apparent, the larger number of samples improves statistical estimates, and when there is more overlap with other data sets it permits more sophisticated data interpretation.

However, merging data sets can be dangerous, especially if the processing procedures, digestion methods, and analytical techniques are not known. In the case of indicator minerals, the data should not be merged unless the sample weight is known and the criteria used to identify the minerals from the EMP data are the same. Adequate metadata will help determine whether or not the data sets can be merged simply or if some leveling must be applied before the data can be safely merged. For indicator minerals, it is possible to go back to the original EMP data and change the mineral identification if one decides to reclassify the EMP data using different criteria.

In practice, most data sets cannot be safely merged without a sophisticated geospatial statistical investigation. The GSC's National Geochemical Reconnaissance (NGR) data are an exception to this rule — the samples were collected over three decades, but always using the same protocols for collection, preparation, and analysis. Even with the NGR data, there can still be problems when merging data sets (cf. Daneshfar and Cameron, 1998). There are many strategies for levelling data sets (cf. Darnley et al., 2005) but in all cases caution should be used.

THE CANADIAN DATABASE OF GEOCHEMICAL SURVEYS (CDoGS)

The Canadian Database of Geochemical Surveys (CDoGS) is a robust database that holds geochemical data for a variety of geological sample media. It has seen a continuous evolution, both in software and hardware, from the 1980s to the present. It is a sophisticated relational database designed from a corporate perspective, storing geochemical data from all types of sample media, from all GSC offices across Canada, and is designed to survive staff departures.

The CDoGS database is published periodically as GSC Open Files, which are systematically archived by Library and Archives Canada (LAC). The Open Files are created in formats that can survive hardware, software, and institutional changes, which will ensure that if CDoGS' web presence does not survive, the database and its contents will. Organizations that do not have a corporate governance system in place or that do not have a publication system must develop their own strategies for preserving their data.

CDoGS Successes

1. The data model can evolve to accommodate new features (e.g. indicator mineral data);
2. The data model can handle complex data sets without being modified, e.g., the model can accommodate data generated as a result of one sample being split into multiple size fractions with each fraction analyzed by multiple analytical techniques by more than one laboratory;
3. The system is fully automated to get data to the end user; and
4. The database has been successfully migrated as technology has advanced so that the data are always accessible.

CDoGS Challenges

1. Geochemical and indicator mineral data are complicated to store and require adequate metadata;
2. Accommodating changes in hardware and software; and
3. Corporate governance.

It is important to note that without corporate governance to guide data flow automatically from the analytical laboratories to the database, data are only able to be imported into CDoGS after they are published. It would be preferable to import data directly from the original laboratory files in order to avoid possible data loss or corruption.

CDoGS is designed so that if QA/QC procedures indicate that there are problems with the data, any new data received from reanalyzing the samples are stored in the database along with the original incorrect data. Each data set has "qualifiers" associated with it so that the incorrect data are never exported to the end-user but are stored as a digital record of the analytical history.

Indicator Minerals

Indicator mineral data can be even more complicated to store in a database than geochemical data due to the complex processing history, picking, and identification of the indicator minerals. Adding to the complexity is the possibility that one field sample can be subdivided into hundreds of laboratory samples (individual indicator mineral grains that have been analyzed using EMP) that all have to be tracked in the database.

Indicator mineral data interpretation is critically dependent on understanding how the data were obtained. Some important factors to consider are the following:

1. What material was sampled; how was it sampled; how much was sampled?
2. What size fractions were obtained and what is the weight of the fraction(s) to be processed?
3. What preconcentration method was used and what is its specific gravity threshold, i.e., what minerals could be recovered?
4. What final concentration method was used? What was the density of the heavy liquid, if used? Were magnetic separations carried out?
5. What criteria were used in the initial visual inspection to identify the indicator mineral?
6. Were the visual mineral identifications verified? For example, are EMP data available?
7. What definitions were used when assigning mineral species names? For example, how much Cr must be present for a diopside to be classified as a Cr-diopside (likewise for Mg content in Mg-ilmenite) or how are garnet solid solutions classified?

All of these metadata need to be preserved alongside the actual laboratory data if the data are to have long-term value. Therefore, in addition to the general metadata for a geochemical survey outlined above, the GSC recommends recording the metadata shown in Table 3 when samples have been processed for indicator minerals (from Spirito et al., 2011).

Adequately recording metadata for samples processed to recover indicator minerals is only one of the challenges in working with these kinds of data. It can be complicated to read and extract data from the laboratory reports themselves. Commonly, the format of the reports varies between laboratories and can even vary between work orders from the same laboratory. Different laboratories may provide different content, they may not report all of the required metadata, or the information may be difficult to find in the report. It is important to become very familiar with the report and to communicate with the laboratory about project requirements.

GSC Web Application

A simplified view of the contents of the CDoGS database is available online at http://geochem.nrcan.gc.ca. The online catalogue contains metadata from over a thousand geochemical surveys across Canada. Several hundreds of these are indicator mineral surveys, primarily obtained from Northwest Territories and Nunavut assessment reports filed with Aboriginal Affairs and Northern Development Canada. The catalogue also

Table 3. Metadata to be recorded for samples processed for indicator minerals.

Metadata	Details
Sample medium	- till, glaciofluvial sediments, stream sediments, other
Name of processing laboratory	- also include name of picking laboratory if different
Weight of material processed for recovery of indicator minerals	- e.g. weight of <2.0 mm table feed
Preconcentration method	- e.g. panning, hydro-separator, shaking table, dense media separator, Knelson concentrator, jig, rotary spinal concentrator, other
Method used for disaggregation and name of laboratory	- crusher, electric pulse disaggregator (EPD), other
Heavy liquid separation	- name of liquid and density
Ferro-magnetic separation	- name of method used, i.e., hand magnet, Frantz, roll magnet, other
Size fraction and weight	- list all size fractions prepared and their weights
Weight and size range of fraction(s) picked	- also list % of concentrate examined for each sample
Mineral identification method	- binocular microscope, mineral liberation analysis (MLA), SEM, or other
Mineral chemistry determination method and lab name	- electron microprobe (EMP), SEM, LA-ICP-MS, other
Raw mineral abundance	- as reported by the picking laboratory
Mineral abundance data	- as confirmed by EMP, SEM or other methods
Mineral grain abundance data as values normalized to total sediment weight processed (e.g. GSC normalizes to 10 kg)	- e.g. number of grains per 10 kg table feed

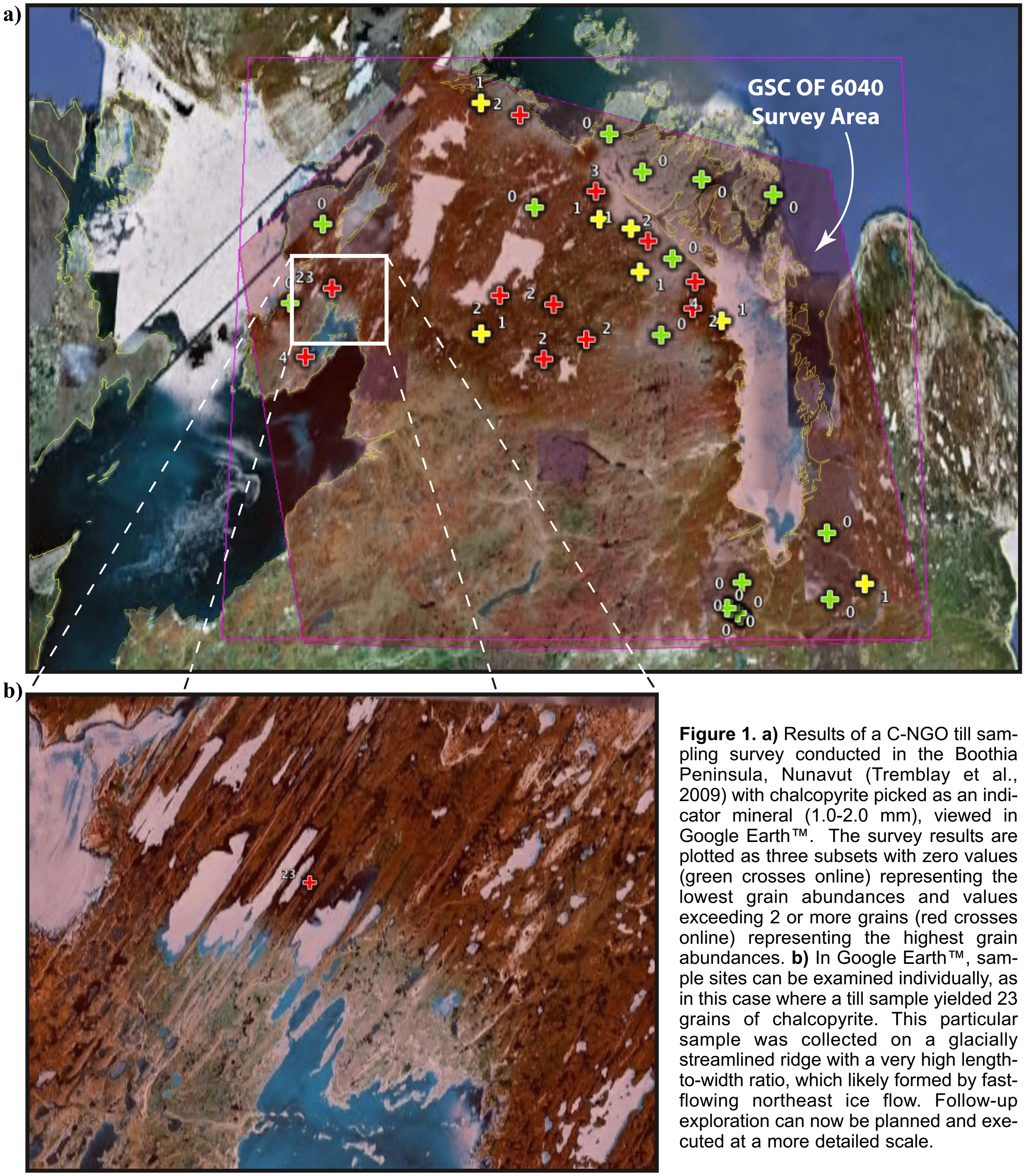

Figure 1. a) Results of a C-NGO till sampling survey conducted in the Boothia Peninsula, Nunavut (Tremblay et al., 2009) with chalcopyrite picked as an indicator mineral (1.0-2.0 mm), viewed in Google Earth™. The survey results are plotted as three subsets with zero values (green crosses online) representing the lowest grain abundances and values exceeding 2 or more grains (red crosses online) representing the highest grain abundances. **b)** In Google Earth™, sample sites can be examined individually, as in this case where a till sample yielded 23 grains of chalcopyrite. This particular sample was collected on a glacially streamlined ridge with a very high length-to-width ratio, which likely formed by fast-flowing northeast ice flow. Follow-up exploration can now be planned and executed at a more detailed scale.

provides raw data for 85 surveys, including a few indicator mineral surveys carried out by the GSC and C-NGO staff. Currently, considerable effort is going into increasing the volume of raw data stored in the system. The raw data that have been stored are accessible via the website as standardized Microsoft Excel® spreadsheets as well as KML files that can be viewed online using Google Earth™.

With mineral exploration camps in northern Canada able to access the internet through satellite links, the image of a prospector studying a hand-contoured map has become a distant memory. Current exploration teams can utilize a laptop or hand-held tablet and plot geochemistry or indicator minerals of choice on Google Earth™ or other satellite imagery. The results for various indicator minerals, based on sample type (e.g. esker, till, or stream sediment sample), size range (e.g. 0.25-0.50 mm or 1.0-2.0 mm), and even grain morphology (e.g. pristine, modified, or reshaped gold grains) can be displayed and instant linkages and interpretations can be made from seeing the data plotted in association with regional glacial ice-flow landforms (Fig. 1), allowing exploration sampling teams to predicatively select the next day's surficial material sample sites.

ACKNOWLEDGEMENTS

Beth McClenaghan, Bob Garrett and Elizabeth Ambrose are thanked for their constructive review and suggestions to improve this short paper. Recent support for the CDoGS database was funded by the GSC's Geo-Mapping for Energy & Minerals (GEM) Program (2008-2013) under the Tri-Territorial Indicator Mineral Project. ESS Contribution No. 20120419.

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AN INTEGRATED STUDY OF TILL GEOCHEMICAL, INDICATOR MINERAL, AND PEBBLE LITHOLOGICAL DATA FOR THE THOMPSON NICKEL BELT, MANITOBA, CANADA

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INTRODUCTION

The Geological Survey of Canada (GSC) collected till samples around the Thompson, Birchtree, and Pipe magmatic Ni-Cu deposits in the northern part of the Thompson Nickel Belt (TNB), Manitoba, Canada to characterize the geochemical and mineralogical signature of Ni-Cu mineralization in glacial till at the deposit- and camp-scale at varying distances down-ice from known mineralization, as well as to define background values in the area. The TNB is a 10 to 35 km wide belt of variably reworked Archean basement gneiss and Early Proterozoic cover rocks along the northwest margin of the Superior Craton (Zwanzig et al., 2007). It hosts several world-class magmatic Ni-Cu deposits that have been strongly structurally and metamorphically modified. Nickel-copper sulphide mineralization is associated with, or localized within, ultramafic bodies in the lower part of the Proterozoic rocks (Bleeker and Macek, 1996). Primary ores are dominated by pyrrhotite, pentlandite, pyrite, and millerite with ubiquitous minor phases of chalcopyrite, magnetite, and ferrochromite (Layton-Matthews et al., 2007).

The most recent glaciation, during the Wisconsin, resulted in ice that flowed southwest from an ice centre in Keewatin and then west from ice centred in Hudson Bay (Klassen, 1986). Both ice-flow events eroded and transported metal-rich debris from the Ni-Cu deposits. In general, till across the region is thin (<3 m thick) and has a silty sand matrix. As the Laurentide Ice Sheet melted back 7800 years BP, the region was inundated by glacial Lake Agassiz, which deposited glaciolacustrine clay and silt over bedrock and till, in places up to 40 m thick. As a result, the region is covered by a flat-lying clay plain with few bedrock outcrops.

Single element or mineral plots were generated using the till geochemical and mineral abundance data (McClenaghan et al., 2009, in press). Though these plots show the distribution of element and mineral anomalies in till that are related to Ni-Cu sulphide mineralization, the data were never combined and evaluated as an integrated data set. In fact few studies have ever been carried out in which till indicator mineral and pebble lithological data have been combined with both partial (aqua regia digestion) and near-total (Li-metaborate fusion) geochemical data. The new study reported here, describes the integration and evaluation of these data using a combination of multivariate statistical methods and presentation using a geographical information system (GIS).

METHODS

Till samples (~15 kg) were collected across the northern TNB, most closely spaced around the Thompson, Birchtree, and Pipe Ni-Cu deposits. Archived till samples collected by the GSC across the region in 1996 (Matile and Thorleifson, 1997) were re-analyzed/re-examined as part of this study (Fig. 1). Till samples were collected from sites at varying distances down-ice (southwest and west) of the Ni-Cu deposits. The <0.063 mm fraction of till was analyzed using (1) aqua regia and (2) lithium borate fusion/nitric acid digestions combined with inductively coupled plasma emission and mass spectrometry (ICP-ES/MS) techniques; gold, Pt, and Pd were determined by Pb fire assay/ICP-MS (McClenaghan et al., 2009, 2011).

Indicator minerals of magmatic Ni-Cu-PGE deposits (e.g. Averill, 2011) were counted in the till samples (Fig. 2) after the samples were processed using a combination of tabling and heavy liquid separation to produce ferro- and non-ferromagnetic heavy mineral concentrates (McClenaghan et al., in press). Electron microprobe analyses were completed for selected oxide and silicate indicator minerals to confirm their identity.

The 2.5-5 cm pebble fraction of the till samples, collected for indicator mineral study along the TNB (Fig. 3), was classified into lithological categories that reflect the major rock types in the region.

Indicator mineral counts were normalized to the equivalent count of a 10 kg sample weight. Pebble-lithology counts were reported as frequency % data and did not require further normalization. Fire assay results for Au, Pt, and Pd were integrated into both the partial (aqua regia) and total (Li-metaborate fusion) analytical data sets. The resulting integrated data sets were treated as compositional (Aitchison, 1986) and subjected to a log-centred transform for further statistical processing.

The data sets (indicator mineral counts, pebble-lithology counts, partial-digestion till geochemistry, total-digestion till geochemistry) were studied individually and in combination using principal component analysis (PCA). This exploratory procedure works well for identifying geochemical processes based on the interaction of elements, minerals, and lithologies

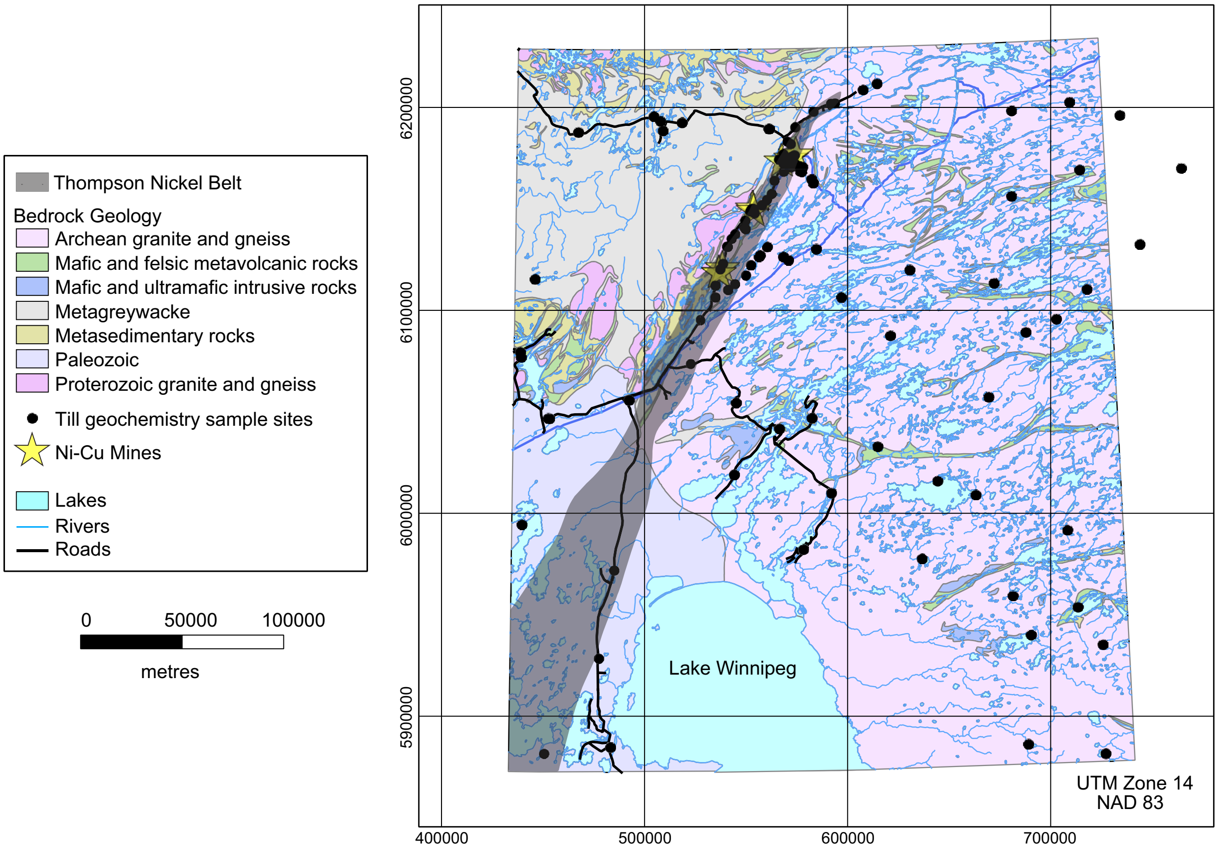

Figure 1. Map showing the location of the till samples collected for geochemical analyses.

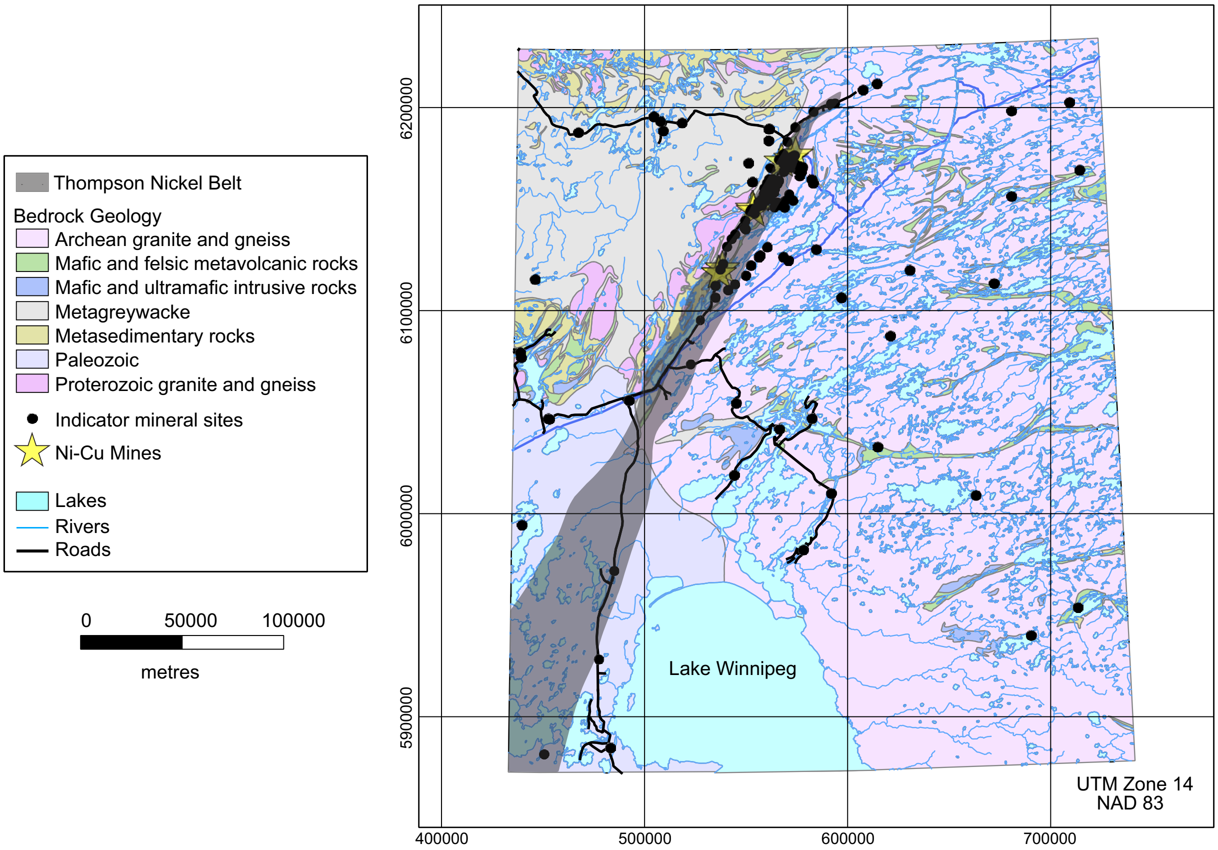

Figure 2. Map showing the location of the till samples that contained indicator minerals.

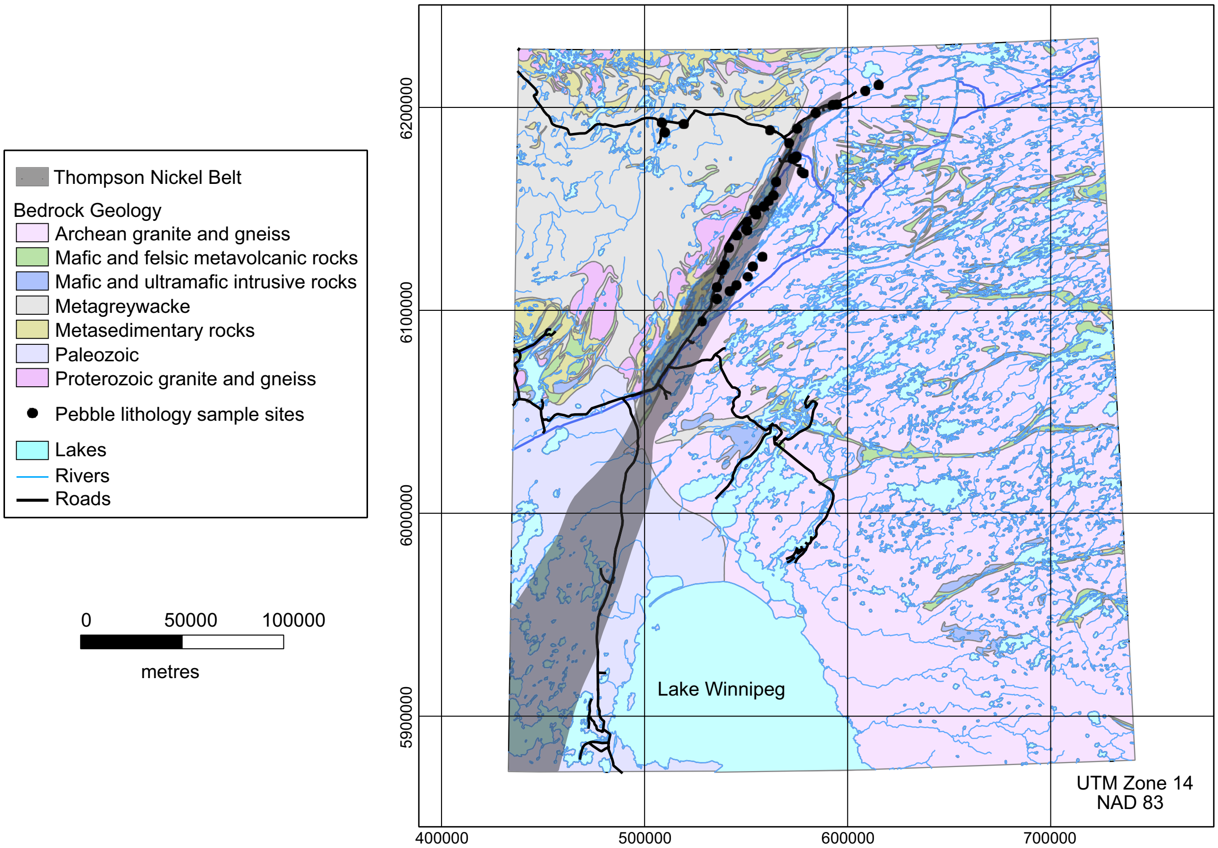

Figure 3. Map showing the location of the till samples that were used for determining pebble lithology.

(Grunsky, 2010). The resulting principal component scores are plotted on the regional geological map.

RESULTS

Indicator Mineral Results

A well developed indicator mineral signature (1000s to 10,000s of grains) occurs in till proximal (<1 km) to sulphide mineralization. Nickel-copper mineralization indicator minerals include pentlandite, pyrrhotite, sperrylite, chalcopyrite, pyrite, millerite, arsenopyrite, and loellingite. Of these minerals, chalcopyrite and sperrylite are the most likely to survive glacial transport and subsequent surficial weathering (Averill, 2007) and thus are the most useful for regional exploration.

Indicators of potentially fertile ultramafic intrusions include chromite, Cr-diopside, forsterite, enstatite, and Cr-corundum. Chromite and Cr-diopside (> ~1% wt.% Cr_2O_3) in till are most abundant in till samples collected proximal to mineralization. Mineral-abundance patterns for chromite, Cr-diopside, forsterite, and enstatite also indicate that some of these grains are derived from ultramafic rocks east of the TNB, some of which may warrant further investigation for their potential to host Ni-Cu mineralization.

The bedrock source of the till samples with 10s to 100s of Cr-diopside grains has not yet been found. In spite of the predominance of pyroxenite and peridotite in the TNB, remnants of primary Cr-diopside are scarce because most rocks have been metamorphically and metasomatically altered such that serpentine has replaced olivine, and orthopyroxene, and amphibole, chlorite, talc, and carbonate have replaced clinopyroxene.

A principal-component analysis of the 151 indicator mineral analyses indicate that the first principal component is dominated by a sulphide-mineral trend (chalcopyrite, pentlandite, pyrite, sperrylite, and chromite). The second principal component is dominated by an inverse association of mafic minerals (orthopyroxene, Cr-diopside, rutile, and forsterite) with a less mafic environment represented by Mn-epidote. A biplot of the first two components is shown in Figure 4 showing that these trends are evident and represent more than 45% of the overall variability in the data. A map plotting the scores of the first principal component (PC1) at the sample location is shown in Figure 5, which demonstrates that the dominant negative PC1 scores are associated with sulphide enrichment that has been identified along the TNB.

Combined Indicator Mineral and Pebble Lithological Results

Combining the indicator mineral data with the pebble lithology count data resulted in a small data set of 46

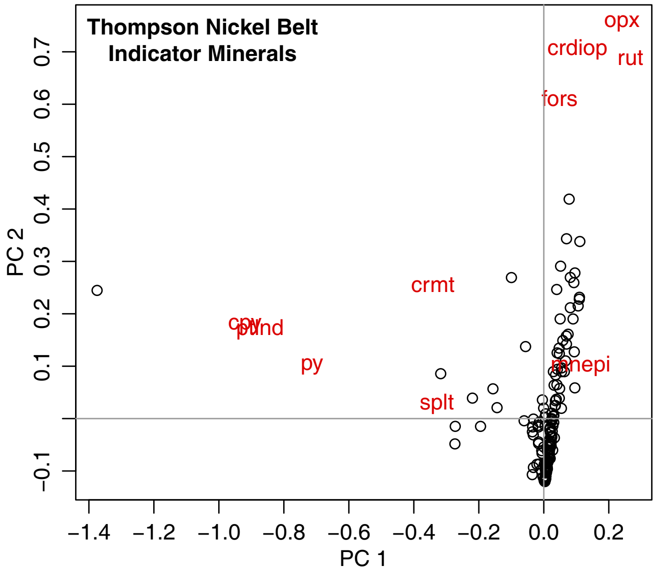

Figure 4. Biplot of the first two principal components (PC1 vs. PC2) of the indicator mineral data.

samples. The combined variables of the indicator minerals and pebble lithologies totalled 27. This is not an ideal population for a multivariate analysis; however, the results are consistent with the findings noted in the preceding section. The first two components account for approximately 29% of the overall data variability, with the first component accounting for the greatest variation in sulphide minerals and chromite. The second component shows an inverse association between felsic rocks (quartz-dominant) and mafic rocks (orthopyroxene-, Cr-diopside-, and forsterite-dominant). The relationships between the minerals and lithological PCA scores are shown in Figure 6 and a map of the first principal component scores is shown in Figure 7. The map clearly shows the sulphide/mineralization-enrichment trend mirroring the TNB trend.

Till Geochemical Results

Ni-Cu ores in the TNB are dominated by pentlandite, pyrrhotite, pyrite, and millerite (Layton-Matthews et al., 2007) and thus local metal-rich till has high Ni concentrations. Till samples that contain the highest Ni contents also contain up to 50,000 pentlandite grains/10 kg in the 0.25-0.5 mm fraction. Till with elevated Cu values at the Thompson and Pipe mines contain up to 2500 chalcopyrite grains/10 kg. TNB ore also contains Te-, As-, Sb-, Co-, Cd-, Se-, and Bi-bearing mineral species, which are likely the source of elevated concentrations of these elements in till proximal to the deposits.

A variety of PGE minerals occur in the ores, thus, it is likely that PGE minerals are the source of the ele-

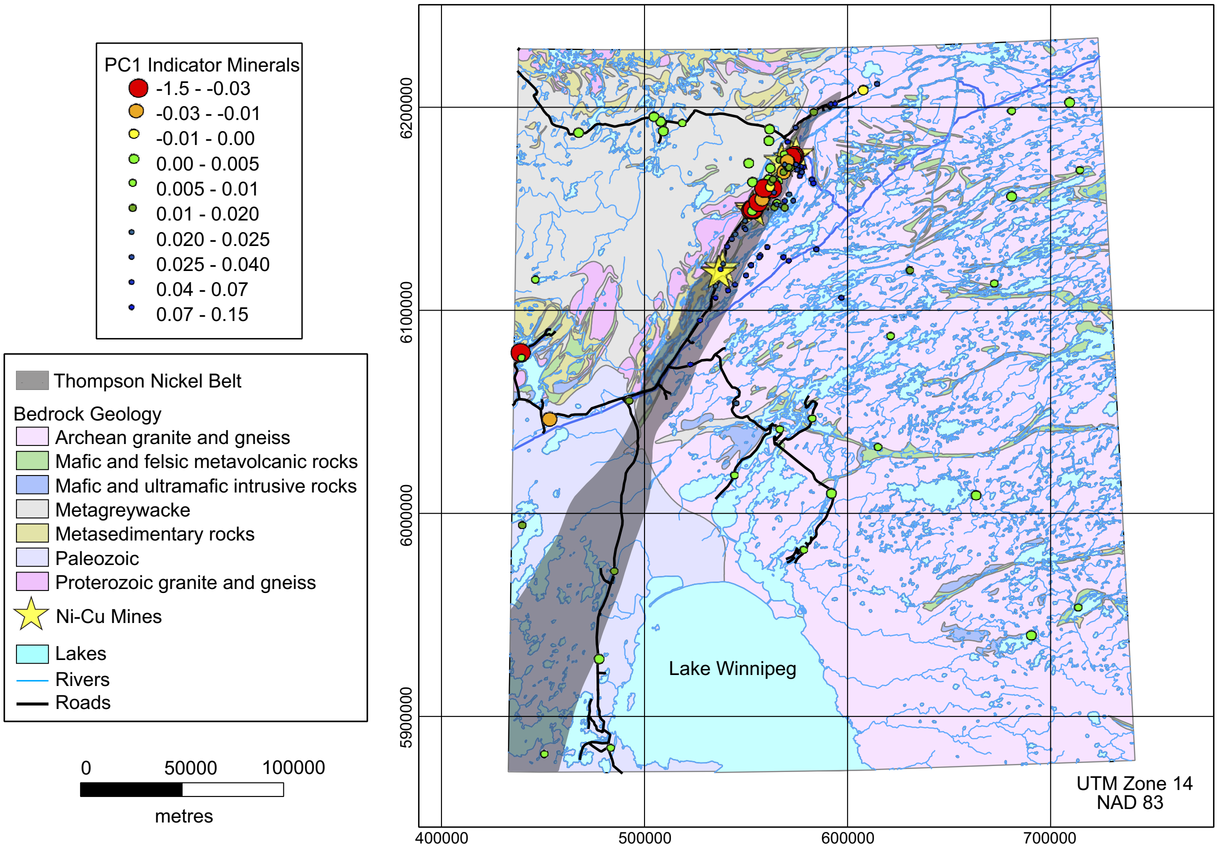

Figure 5. Map showing the distribution of the first principal component scores derived from the indicator mineral counts.

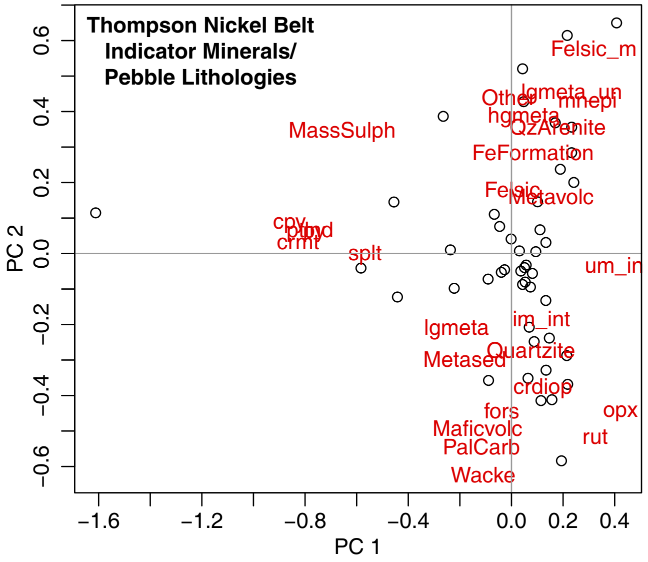

Figure 6. Biplot of the combined data of the indicator mineral analyses and the pebble lithology counts. The trend of sulphide enrichment along the first principal component is evident for both the indicator mineral analyses and the pebble lithologies.

vated Pd and Pt concentrations in the till. Sperrylite ($PtAs_2$) grains were recovered from 9 till samples collected near the Thompson and Pipe deposits. The full suite of till pathfinder elements for Ni-Cu deposits in the TNB include Ni, Cu, Pt, Pd, Co, As, Ag, Cd, Sb, Bi, S, Se, and Te (McClenaghan et al., 2009, 2011).

Total-Digestion Till Geochemical Results

Till geochemical data from 130 samples based on Li-metaborate fusion was evaluated using a log-centred transform and a principal component analysis applied to a suite of 50 elements, including Pt, Pd, and Au (by fire assay). The first component accounts for more than 40% of the overall data variability and the second component accounts for 12%. Figure 8 shows a biplot where the first principal component (PC1) is dominated by an inverse relationship of mineralized till (relative Pt-Pd-Ni-Cr-Co-Au enrichment) and till dominated by a felsic mineral association (relative REE-K-Al-P-U enrichment). The second principal component (PC2) shows relative enrichment of Mg-Ca-C-LOI along the positive PC2 axis, which likely represents the presence of Paleozoic carbonate debris in the till. The negative PC2 axis shows relative enrichment in Fe-Sc-V-Cr-Co, reflecting a mafic-enrichment trend that is not associated with the mineralized trend of PC1. Figure 9 shows a map of the first component in which the positive PC1 scores are associated with the TNB trend, highlighting the mineralization trend is closely associated with the existing Ni-Cu mines.

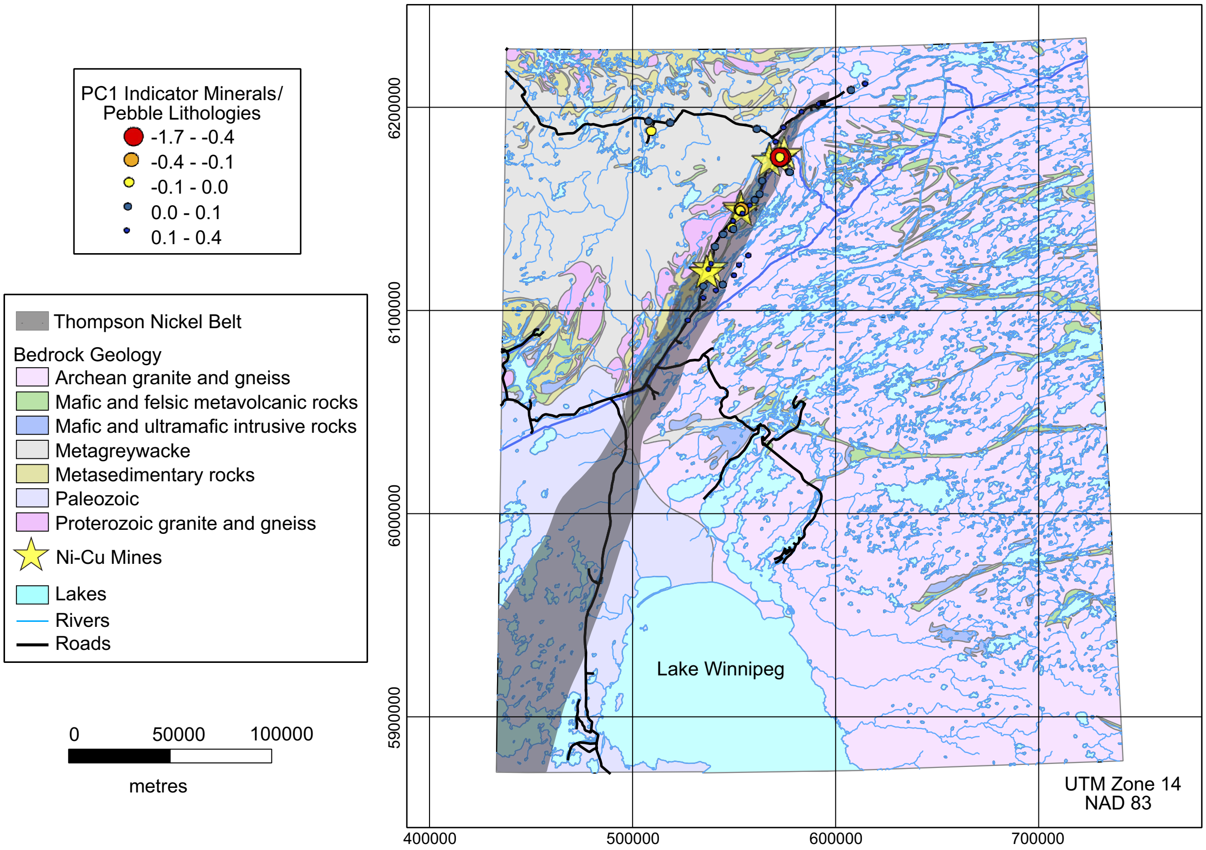

Figure 7. Map showing the distribution of the first principal component scores derived from the combined indicator mineral and pebble-lithology data.

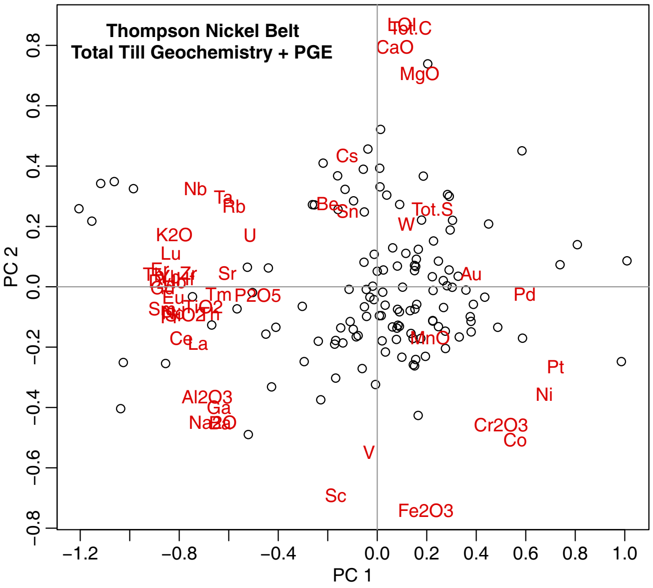

Figure 8. Biplot of the first two principal components (PC1 vs. PC2) of the till geochemical data based on Na-metaborate fusion ICP-ES/MS analyses.

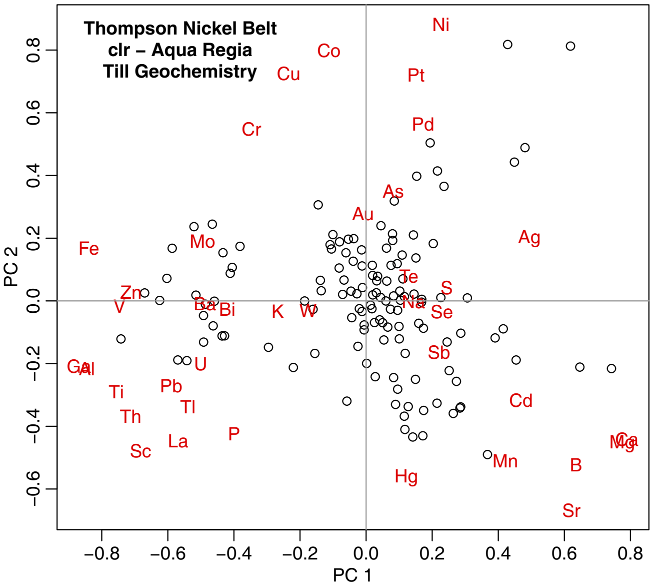

Figure 10. Biplot of the first two principal components (PC1 vs. PC2) of the till geochemistry determined by aqua regia digestion using ICP-ES/MS analyses.

Partial-Digestion Till Geochemical Results

The same till samples (130) were analyzed using aqua regia digestion and ICP-ES/MS instrumentation. Platinum, Pd, and Au (fire assay) data were added to the composition of each sample followed by a log-centred transformation. A principal component analysis was carried out on the 39 elements in which the first three components account for more than 56% of the total variability. Figure 10 shows a biplot of the first two principal components (PC1 vs. PC2) in which the

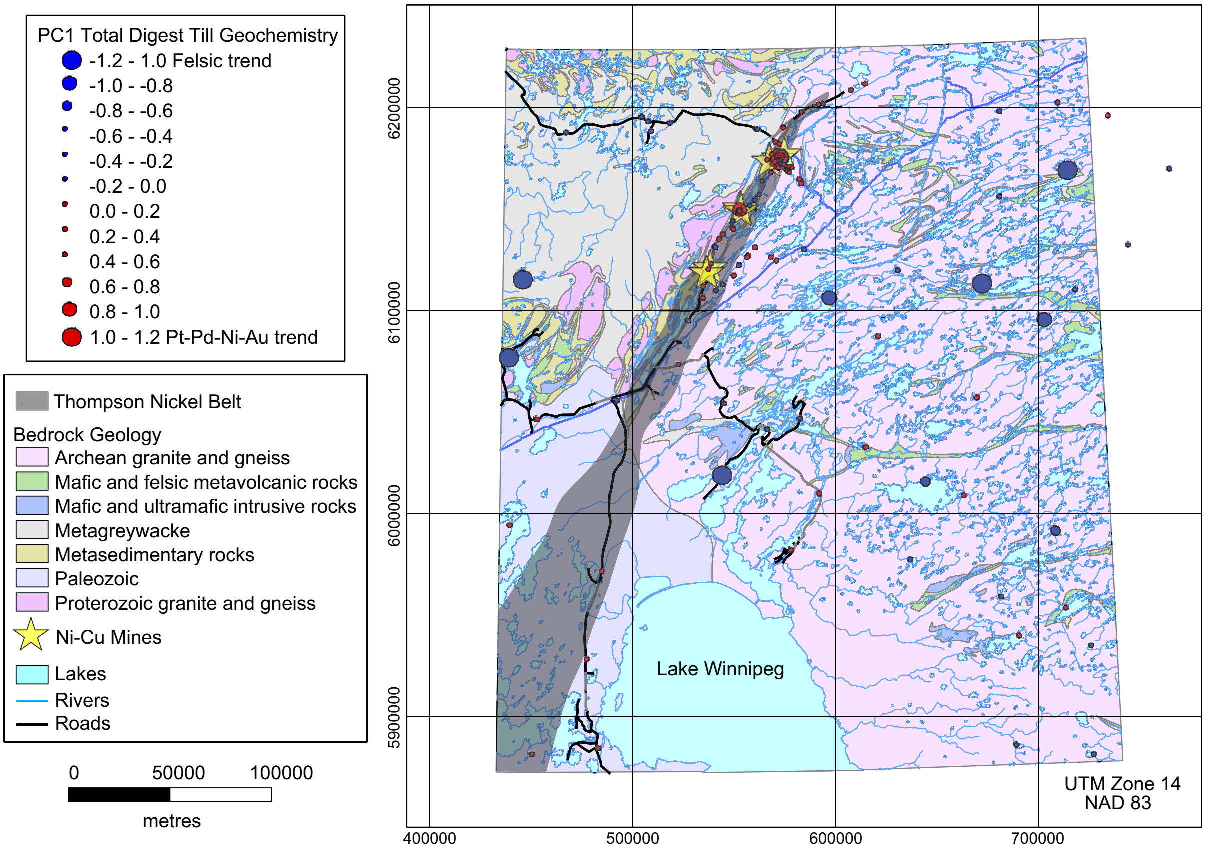

Figure 9. Map showing the distribution of the first principal component scores for the total-digestion till geochemical analyses. The association of the mineral enrichment with the PCA positive scores is highlighted along the TNB trend.

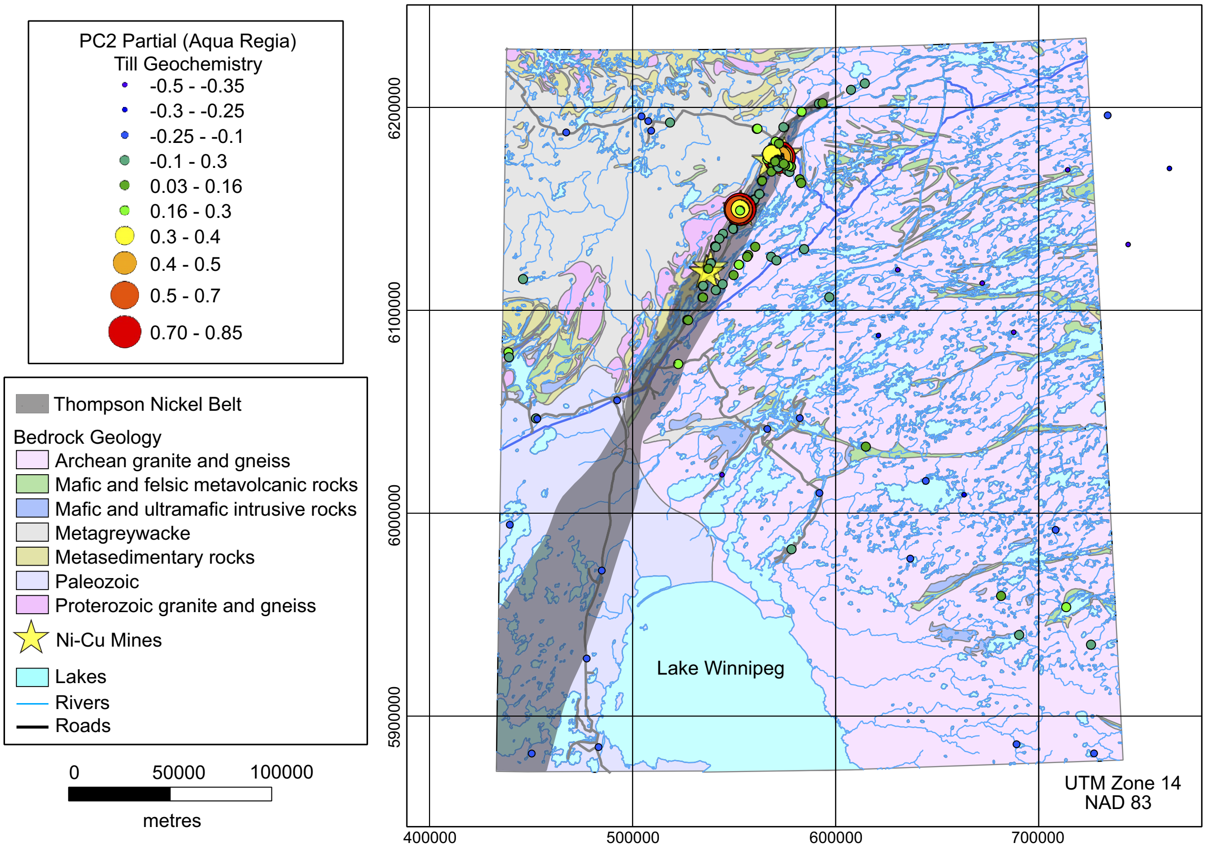

Figure 11. Map of the second principal component scores for till geochemistry determined by partial-digestion analyses.

positive portion of the second principal component shows a relative increase in Ni-Co-Cu-Pt-Pd-Cr-As-Au-Ag, clearly identifying a mineralization trend in the partial digestion analyses. Figure 11 shows the PC2 scores plotted over the regional map. Elevated PC2 scores show a distinctive trend along the Ni-Cu mine trend.

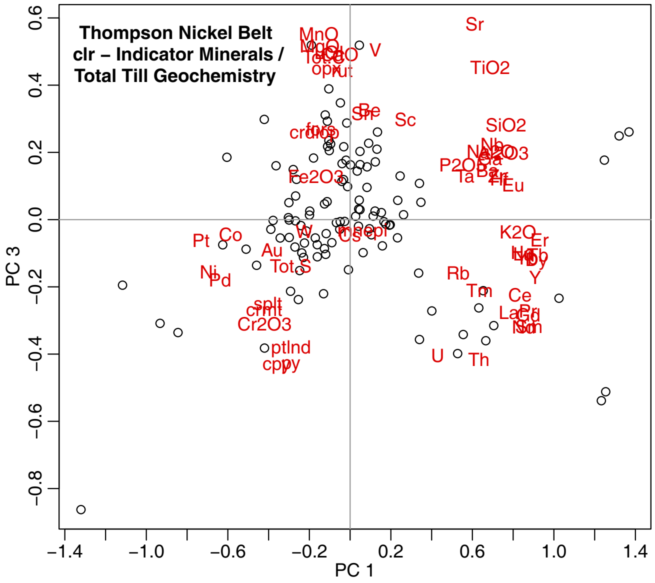

Figure 12. Biplot of the first principal component versus the third principal component (PC1-PC3) for the till geochemistry based on Na-metaborate fusion digestion using ICP-ES/MS analyses. The Ni-PGE-enrichment trend is shown along the negative portions of the PC1 and PC3 axes (see text for a further discussion).

Indicator Mineral and Total-Digestion Geochemical Results

The indicator mineral data set was combined with the total-digestion data set for a total of 80 samples, each with 10 minerals and 50 elements for a total of 60 variables per sample. The ratio of observations (samples) to variables (minerals+elements) is very low (1.3) and the results derived from a principal component analysis of this data set may not be reliable or representative. A ratio of 10 observations to each variable (10:1) is preferable. The results of the PCA reveal that 57% of the overall variability is accounted for by the first three components. A biplot of the first principal component versus the third principal component (PC1 vs. PC3: Fig. 12) shows a cluster of minerals and elements (chalcopyrite, pentlandite, pyrite, sperrylite, chromite, Pt, Ni, Pd, Co, Au, S) associated with the negative PC1 and PC3 components. PC1 and PC3 were rotated clockwise by 10 degrees in order to yield a clearer mineral-

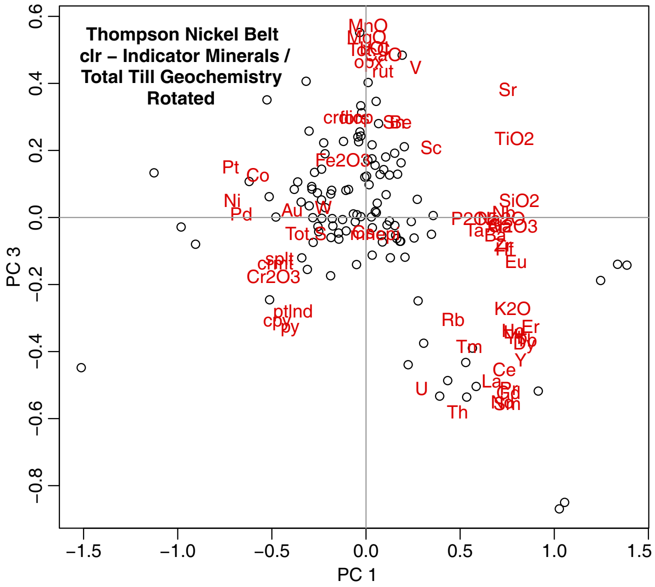

Figure 13. Rotated biplot from Figure 12 of the till geochemistry based on Na-metaborate fusion digestion using ICP-ES/MS analyses. The Ni-Cu-PGE-enrichment trend is now shown along the negative PC3 axis.

ization trend. The rotated biplot is shown in Figure 13 and a map of the rotated PC1 scores is shown in Figure 14; once again, the negative PC1 scores are aligned with the TNB Ni-Cu deposits trend. It is worth noting that there are several large negative PC1 scores in the southern part of the map area that may or may not reflect distal transport of the indicator minerals of more than two hundred kilometres to the south. Elevated PC1 scores to the north of the TNB may be indicative of unrecognized Ni-Cu mineralization.

Indicator Mineral and Partial-Digestion Geochemical Results

The indicator mineral data set was also combined with the partial-digestion data set for a total of 113 samples, each with analyses for 10 indicator minerals and 39 elements. The number of observations compared to the number of variables is also low (2.3) and therefore the results must be interpreted with caution. A principal component analysis of the data shows that the first three components account for 49% of the overall data variation. A biplot of first two principal components (PC1 vs. PC2) shows a trend of Ni-Cr-Co-Cu-Au enrichment between the positive PC2 and negative PC1 axes. These scores were rotated 45 degrees counter-clockwise with the resulting associations shown in Figure 15. A map of the rotated PC1 scores is shown in Figure 16, indicating that samples with high negative PC1 scores occur along the Ni-Cu mine trend in the TNB.

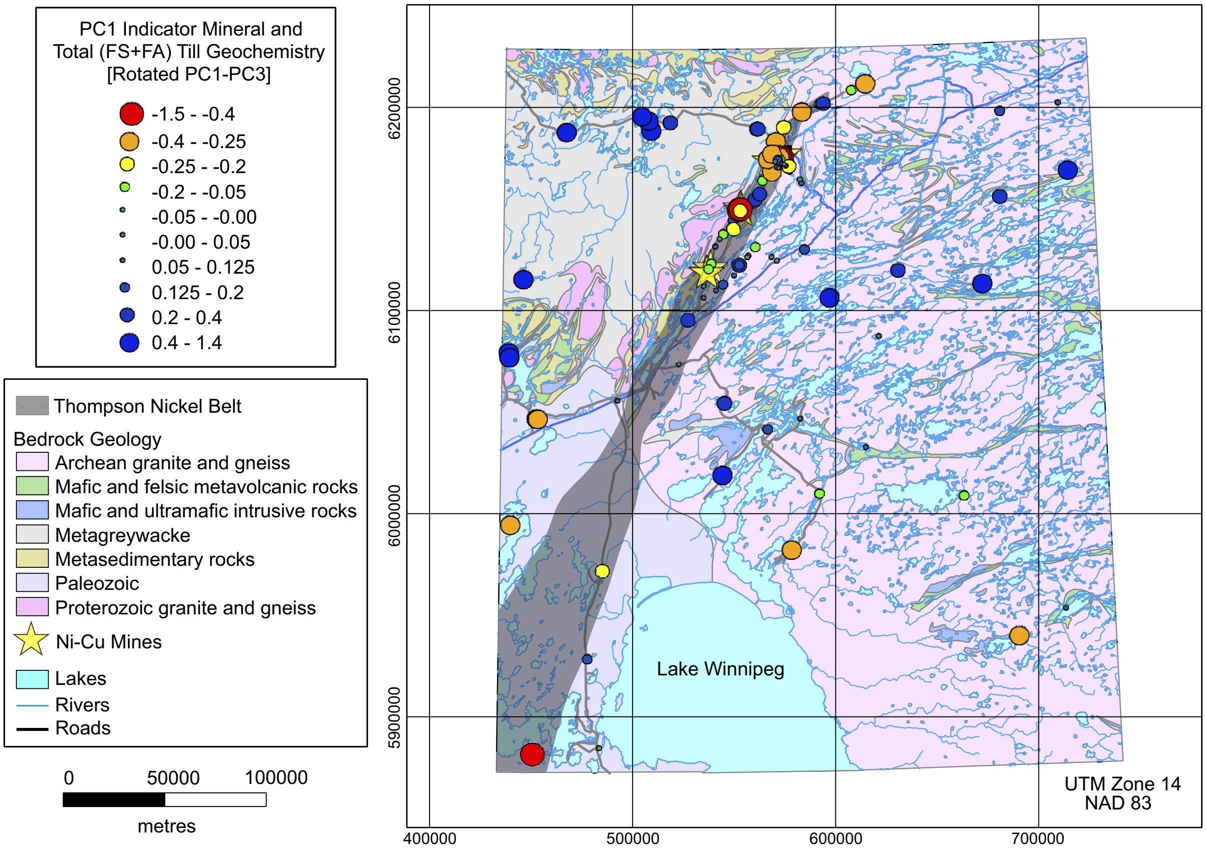

Figure 14. Map showing the distribution of the rotated PC1 scores,note the Ni-PGE-enrichment trend along the TNB zone of Ni-Cu mines.

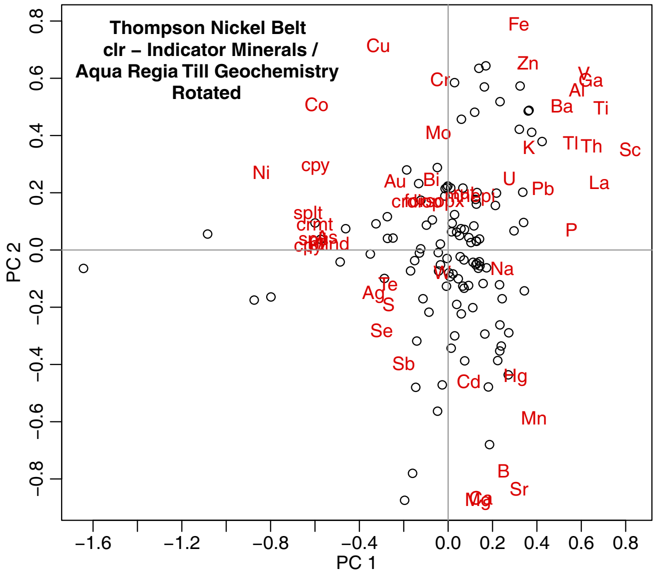

Figure 15. Rotated biplot of the first two principal component (PC1 vs. PC2) scores using till geochemical results determined by aqua regia digestion. The Ni-Cu-PGE mineralization trend is parallel to the negative PC1 axis.

Combined Indicator Minerals – Total- and Partial-Digestion Till Geochemical Results

The three sets of indicator mineral, partial-digestion, and total-digestion till geochemical data were combined to examine if any relationship could be established among the indicator minerals and the multi-element geochemistry determined by total- and partial-digestion methods. A principal component analysis was carried out on 80 samples each with 96 variables (10 indicator minerals, 36 total digestion, 47 partial digestion, and 3 fire assay elements). In this case, the number of variables exceeds the number of observations and the results of any multivariate analysis must be interpreted with caution. A principal component analysis was applied to the combined data. The first two components accounted for nearly 45% of the overall data variability, which indicates that most of the "structure" in the data is accounted for in the first few components. Figure 17 shows the biplot for the first two principal components (PC1 vs. PC2) where the indicator minerals, including sperrylite, pyrite, chalcopyrite, pyrite, chromite, and pentlandite, show an association with elements analyzed by fire assay (Au, Pd, Pt), total digestion (S, Ni, Cr, Co), and partial digestion (Ni, Co, As, Ag, S). The interpretation of these associations is equivocal between partial and total digestions for identifying mineralized environments as both digestions appear to highlight the same associations.

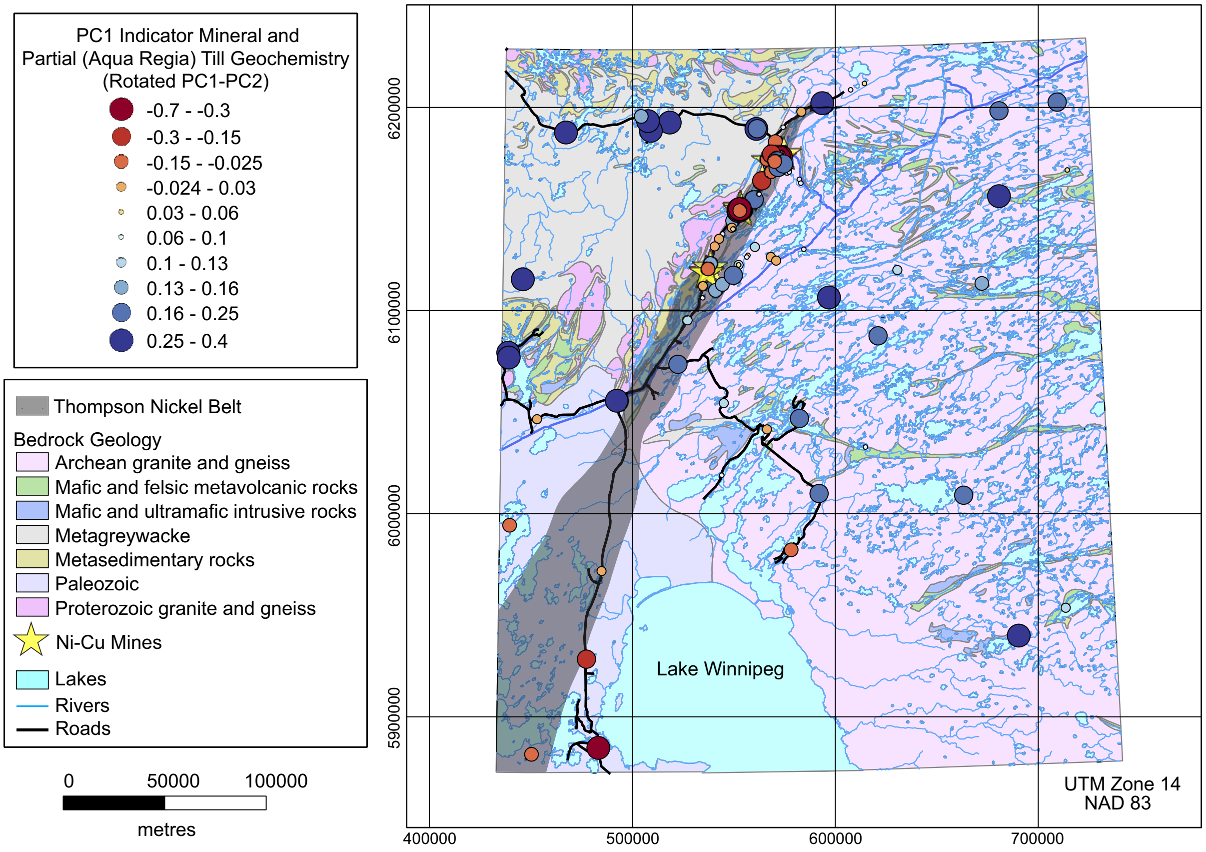

Figure 16. Map showing the distribution of the rotated PC1 scores. Note that several of the samples with large negative PCA scores are associated with the Ni-Cu mine trend.

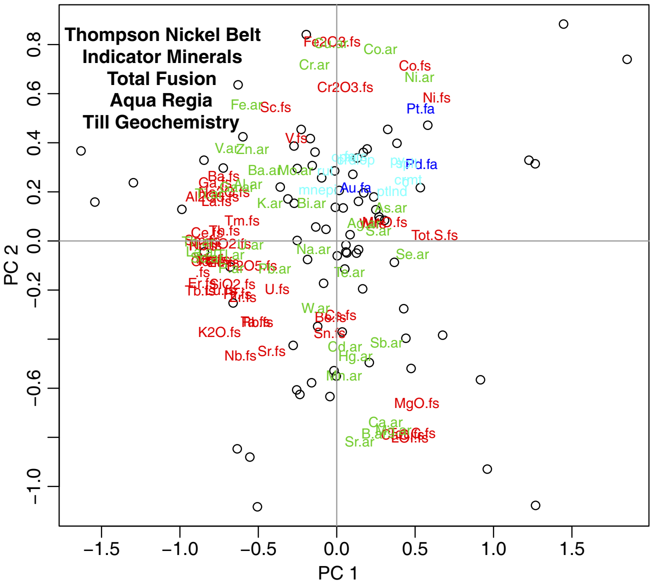

Figure 17. Biplot of the first two principal component scores (PC1 vs. PC2) using the indicator mineral data combined with the fire assay, aqua regia digestion, and total Na-metaborate fusion till geochemistry. The association of the elements with Ni-Cu-PGE and sulphide minerals show and association with some of the total-digestion and partial-digestion geochemical analyses. See text for details.

CONCLUDING REMARKS AND IMPLICATIONS FOR EXPLORATION

Till mineralogy and geochemistry are useful Ni-Cu exploration tools in the TNB. The application of multivariate methods applied to multi-element data using different digestions and indicator mineral counts shows that there is a close correspondence of ore elements (Cu-Ni-PGE) with the indicator minerals associated with Cu-Ni mineralization (chalcopyrite, pentlandite, sperrylite) in the till samples collected over the TNB.

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DISCOVERY AND DELINEATION OF THE RAINY RIVER GOLD DEPOSIT USING GLACIALLY DISPERSED GOLD GRAINS SAMPLED BY DEEP OVERBURDEN DRILLING: A 20 YEAR ODYSSEY

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INTRODUCTION

The Rainy River gold deposit, in the southwest corner of northern Ontario, Canada, near the border with Minnesota, U.S.A. (Fig. 1), consists of a cluster of six gold zones within a deformed Archean caldera in the Rainy River Greenstone Belt. The deposit is covered by unconsolidated glacial deposits ~30 m thick. Each of the gold zones was discovered by tracing glacially dispersed gold grains to their bedrock sources using till samples obtained by deep overburden drilling.

When the first gold-grain anomalies were identified, the Rainy River district was truly a “New Frontier” as

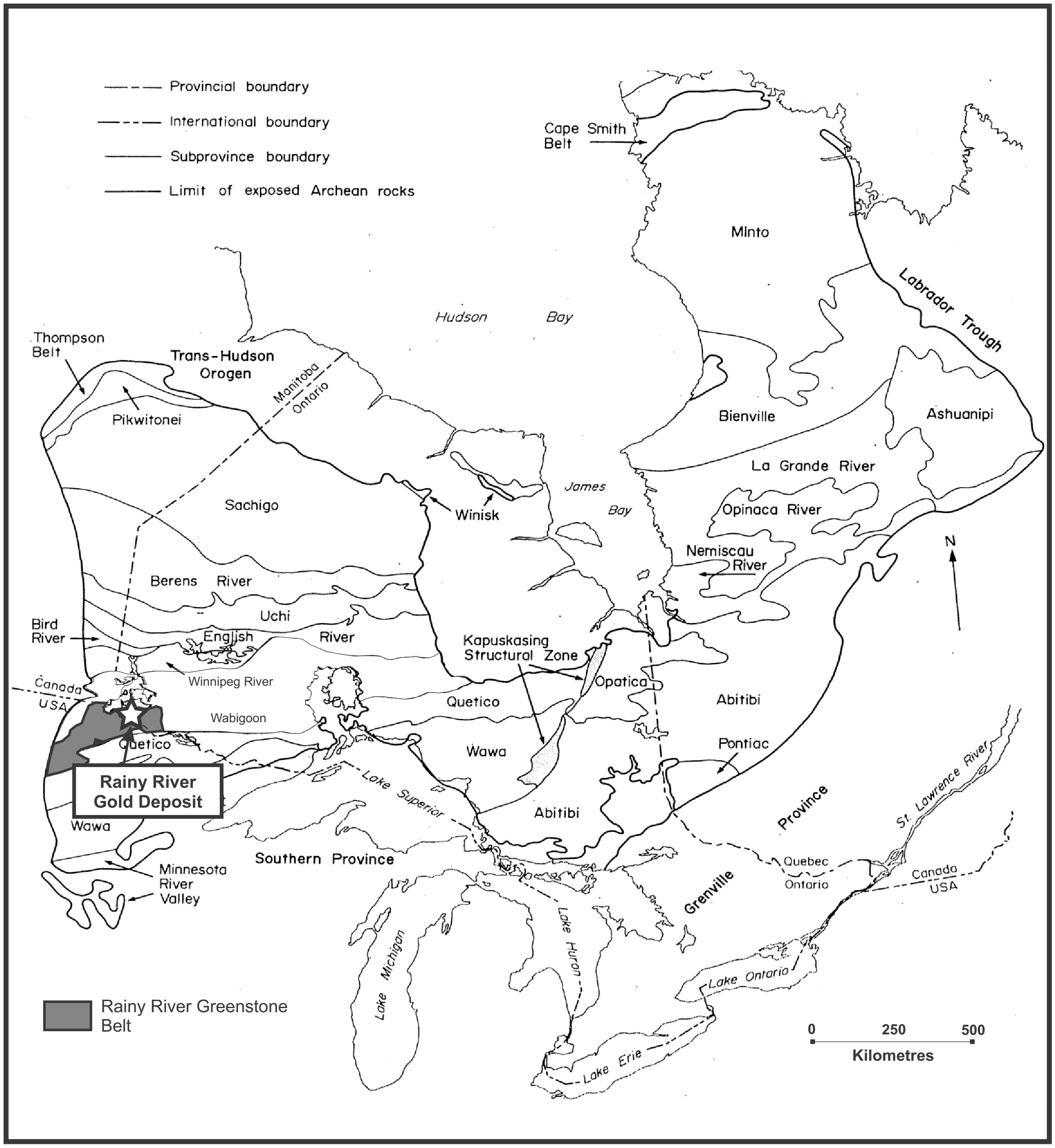

Figure 1. Location and geological setting of the Rainy River gold deposit (Thurston, 1991).

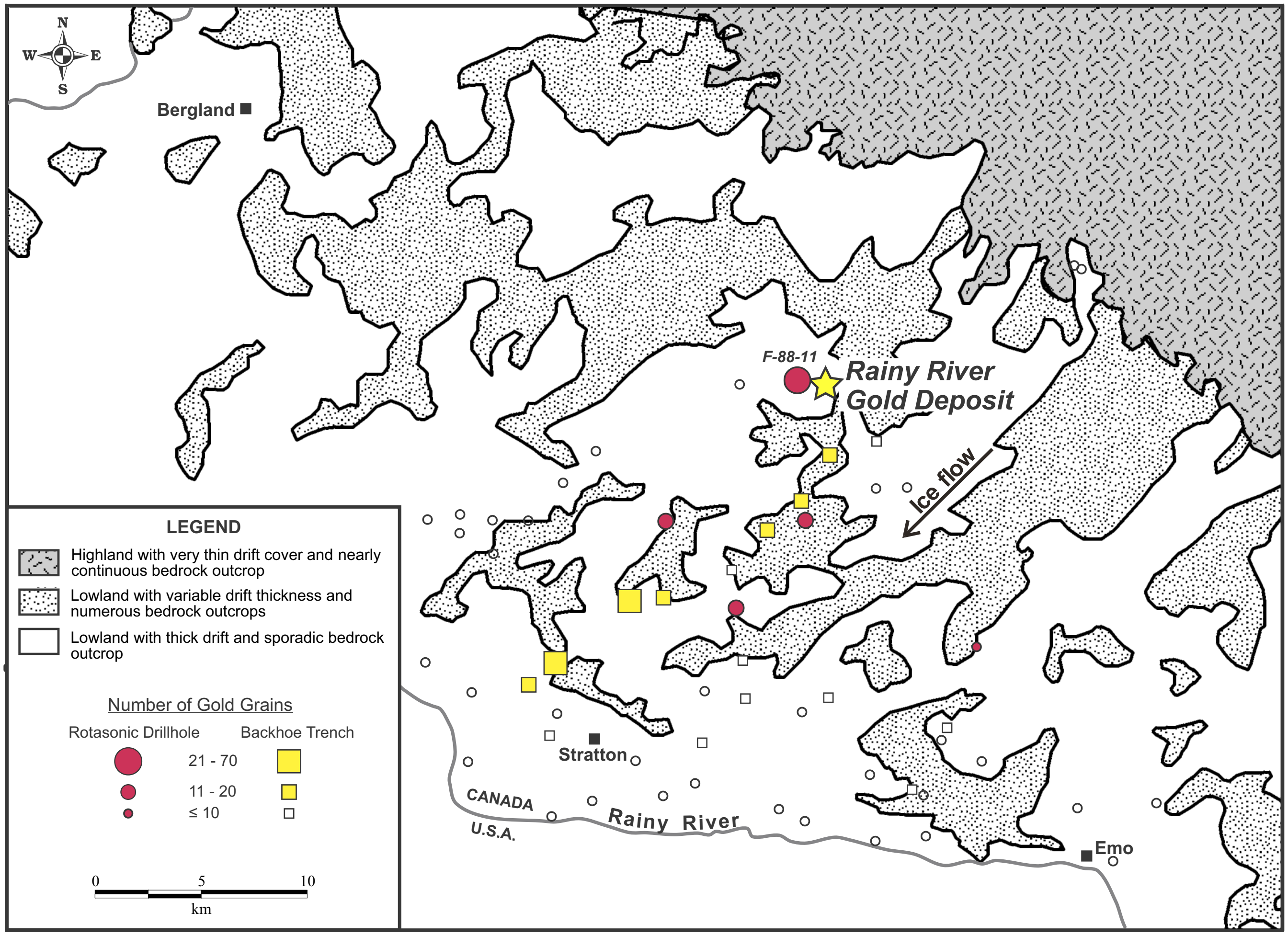

Figure 2. Maximum gold-grain abundance in samples of Labradorean till collected from rotasonic drillholes and backhoe trenches in 1987-88. Modified from Bajc (1991). Gold-grain counts have been normalized to a constant 7.5 kg of processed -2 mm till matrix.

the bedrock geology and mineral potential were essentially unknown. The initial gold grain anomalies were identified by Andy Bajc of the Ontario Geological Survey (OGS) in 1987-88 (Bajc, 1991) in till samples obtained mainly by rotasonic core drilling. Two major mining companies immediately followed up these anomalies with till sampling by reverse circulation (RC) rotary tricone drilling. However, a junior company, Nuinsco Resources Limited, painstakingly acquired a better land position near the strongest anomaly and, using RC drilling, located the first gold deposit — the 17 Zone — in 1994, followed by the 433 Zone in 1998. Despite these successes, Nuinsco defined only a small, ~0.5 million ounce (Moz) gold resource and, following a long period of depressed gold prices triggered by the Bre-X scandal, sold the project to a newly incorporated junior company, Rainy River Resources Ltd. (RRR) in 2005. With continued till sampling by RC drilling, RRR discovered the large ODM Zone at the west end of the 17 Zone along with the smaller Beaver Pond, Cap, and South zones. These deposits are now at the pre-development stage with a combined NI 43-101 compliant measured + indicated gold resource of 6.2 Moz and an inferred resource of 2.3 Moz.

The discovery and delineation of the Rainy River gold deposit illustrates (a) the important role played by regional government surveys in driving mineral exploration in frontier areas of Canada; (b) the effective use of gold grains to detect, from afar, lode gold deposits hidden beneath thick glacial sediments; and (c) the importance of the entrepreneurial spirit and agility of junior exploration companies in the discovery process. Another key factor at Rainy River was the use of the same, highly experienced laboratory, owned and operated by Overburden Drilling Management Limited (ODM, for whom the largest gold zone is named) to extract and classify the gold grains from the till samples collected in each drilling campaign. As shown in the following sections, which summarize the successive OGS, major company, Nuinsco, and RRR overburden drilling campaigns, this constant permitted integration of the gold-grain data between surveys over the long, 20 year discovery odyssey.

ONTARIO GEOLOGICAL SURVEY, 1987-88

The OGS survey covered a 30 km wide x 120 km long lowland, partly shown in Figure 2, between the Rainy River waterway, which forms the Canada/USA boundary, and a thinly covered to rocky highland to the northeast (Bajc, 1991). During meltdown of the Laurentide ice sheet, which had advanced from the Labradorean ice centre southwestward (225º) through the Rainy River area (Dyke et al., 1989) and deposited a layer of stony till that directly overlies bedrock and thus is ideal for gold grain sampling, this lowland was flooded by meltwater that spread eastward from glacial Lake Agassiz on the plains to the west (Nielsen et al., 1981). An ice lobe, related to the Keewatin ice centre west of Hudson Bay, then advanced eastward through the lake, eroding its fine bottom sediments and depositing a thick, conductive layer of clay-rich, stone-poor Keewatin till upon the Labradorean till. This upper till layer impedes electromagnetic, induced polarization, and geochemical surveys and its presence precludes boulder prospecting. However, it has beneficially prevented any oxidation of dispersed sulphide mineral grains in the Labradorean till and these heavy sulphide grains can be recovered from till samples collected from overburden drillholes and, along with the dispersed gold grains, used as indicator minerals to locate covered mineral deposits.

The OGS drilled and sampled 71 rotasonic holes in the most thickly covered parts of the lowland, typically at 2 to 5 km spacing. Of these, 33 were in the central part of the lowland between the Rainy River gold deposit and the Canada/U.S.A. border (Fig. 2). Some additional samples were collected by backhoe in areas of thin cover around isolated bedrock outcrops within the lowland (Bajc, 1991). Four of the central drillholes yielded one or more till samples that were anomalous in gold grains using a normalized threshold value of 11 grains per 7.5 kg of processed -2 mm matrix (Fig. 2). The most distal anomaly was ~12 km glacially down-ice from the subsequently discovered 17 Zone, and the strongest anomaly, 70 gold grains, was in Hole F-88-11, located 2 km west of this zone. Eight of the samples obtained from backhoe pits between the anomalous drillholes were also anomalous. Being so far apart, the anomalies were assumed not to be directly related but rather to indicate a general, previously unknown gold fertility in the district (Bajc, 1991).

As is normal in till (Averill, 2001), ~90% of the gold grains were silt-sized, i.e., <0.063 mm or 63 microns wide, and the grains were variably of pristine, significantly modified, or fully reshaped morphology, reflecting their variable distance of glacial transport from source (Fig. 3). Many samples from the western part of the survey area also yielded grains of native copper. These grains were much larger than the gold grains, with some reaching 1 to 2 mm (Fig. 4). Their surfaces were bright and fresh, illustrating the completely unoxidized condition of the Labradorean till and underlying bedrock and thus the total immobility of any contained metals and consequent ineffectiveness of surface geochemistry for exploring the district.

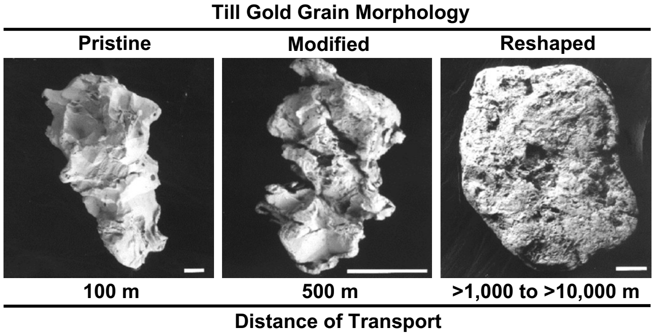

Figure 3. Backscatter electron images of gold grains from till illustrating the relationship between grain wear and distance of transport. The wear processes are compressional (infolding and compaction) and do not reduce the mass of the gold grain. Scale bars = 50 µm. Source: Averill (2001).

MAJOR COMPANIES, 1991-1994

In 1991, following the release of the OGS report (Bajc, 1991), two major mining companies staked all of the available Crown land in the vicinity of the anomalous drillholes and performed follow-up till sampling by RC drilling. One company focused on the central gold-grain anomalies and the other focused on the western native copper anomalies. However, the lowland is surveyed into quarter-section lots measuring 800 x 800 m and only ~10 percent is Crown land — the rest is privately held farmland and bush lots. The two companies tested only the Crown land, which occurs in an irregular patchwork. This piecemeal approach resulted in the identification of a series of seemingly unconnected

Figure 4. Binocular microscope photograph of representative grains of native copper recovered from the till. Note the large size and euhedral form of the grains.

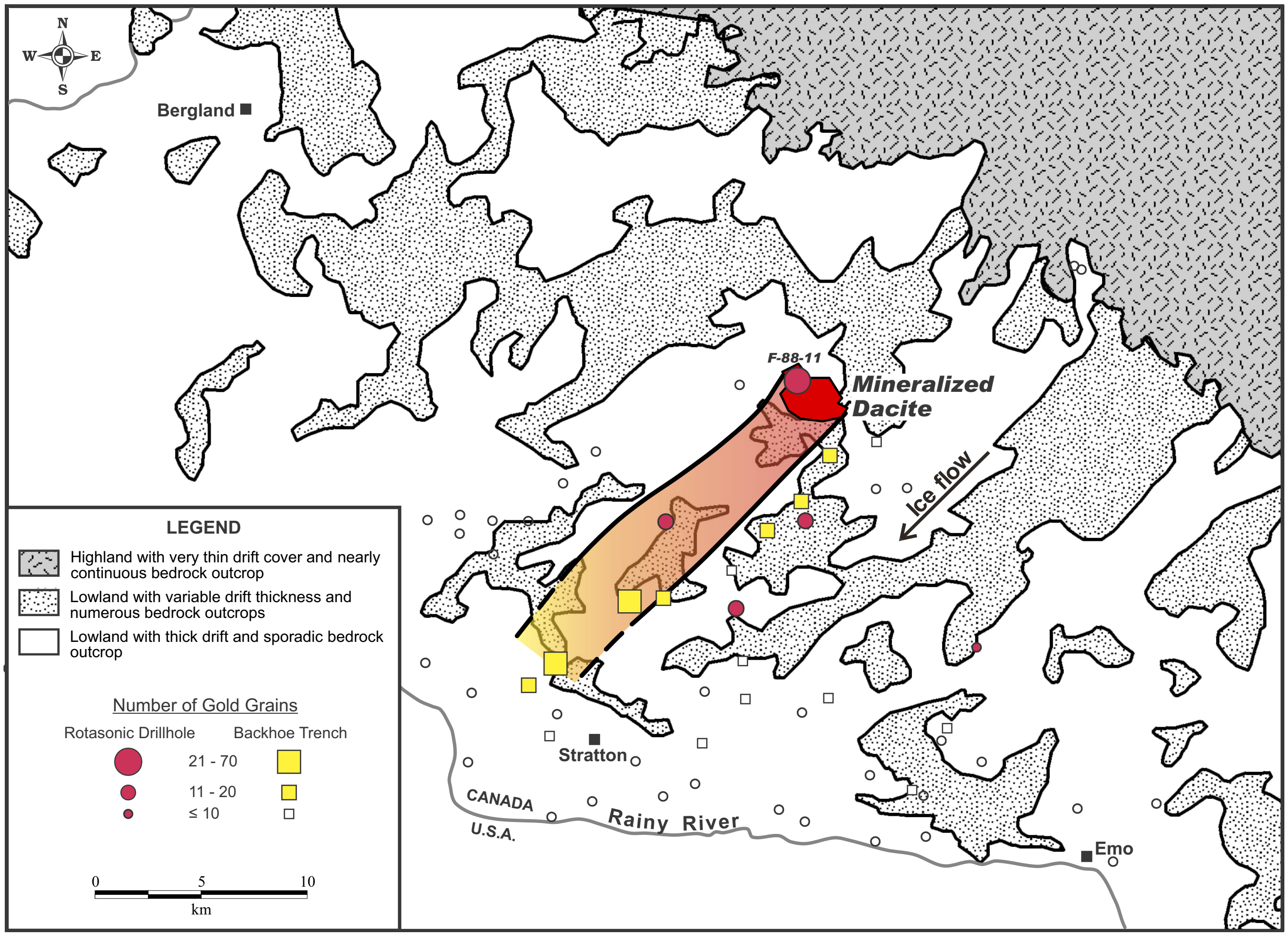

Figure 5. Approximate limits of the gold-grain dispersal train from the broadly mineralized dacite hosting the Rainy River gold deposit. Most till samples collected within the train contained >10 gold grains per 7.5 kg of -2 mm matrix.

anomalies rather than substantive gold-grain or native-copper dispersal trains that could be traced to source. As a result, both major companies abandoned their projects by 1994.

NUINSCO, 1994-1998

While the major companies were testing the deep till in the lowland, Nuinsco was independently employing RC drilling to explore thinly covered gold properties on the highland to the north, thereby gaining experience with gold grains and becoming interested in the activity to the south. Nuinsco's president, Douglas Hume, patiently assembled, lot-by-lot, a large parcel of privately held land east of the strong OGS gold-grain anomaly in Hole F-88-11. This was a critical decision as it allowed systematic anomaly follow-up to be performed for the first time.

Nuinsco's initial exploration in 1993 consisted of diamond drill testing of airborne electromagnetic anomalies on the more thinly covered eastern margin of the property. The targeted anomalies were found to be due to conductive pyrrhotite in thin, cherty sediments between basalt flows. In 1994, Nuinsco contracted ODM to execute a 20-hole RC drilling program, which identified the largest and strongest gold-grain anomaly encountered in till in Canada to that date and led the company to the 17 Zone. As a precaution, Nuinsco immediately staked all of the available Crown land to the southwest in the lowland and, in 1995-96, tested it by RC drilling. Uniformly negative gold results were obtained from both the till and bedrock. However, the source of the native copper grains in the till was resolved; the present bedrock erosional surface is just below a formerly overlying Mesozoic redbed basin, and Cu leached from the permeable basin sediments by acidic reservoir brines was precipitated erratically, along with silica, marcasite, and Mn-rich siderite, in pre-existing fractures in the underlying basement rocks.

Nuinsco returned to the 17 Zone in 1997-98, after establishing the unprospectivity of the rest of the thickly covered lowland, and performed additional, systematic RC drilling in the area surrounding the gold zone, resulting in a final project total of 597 holes. The

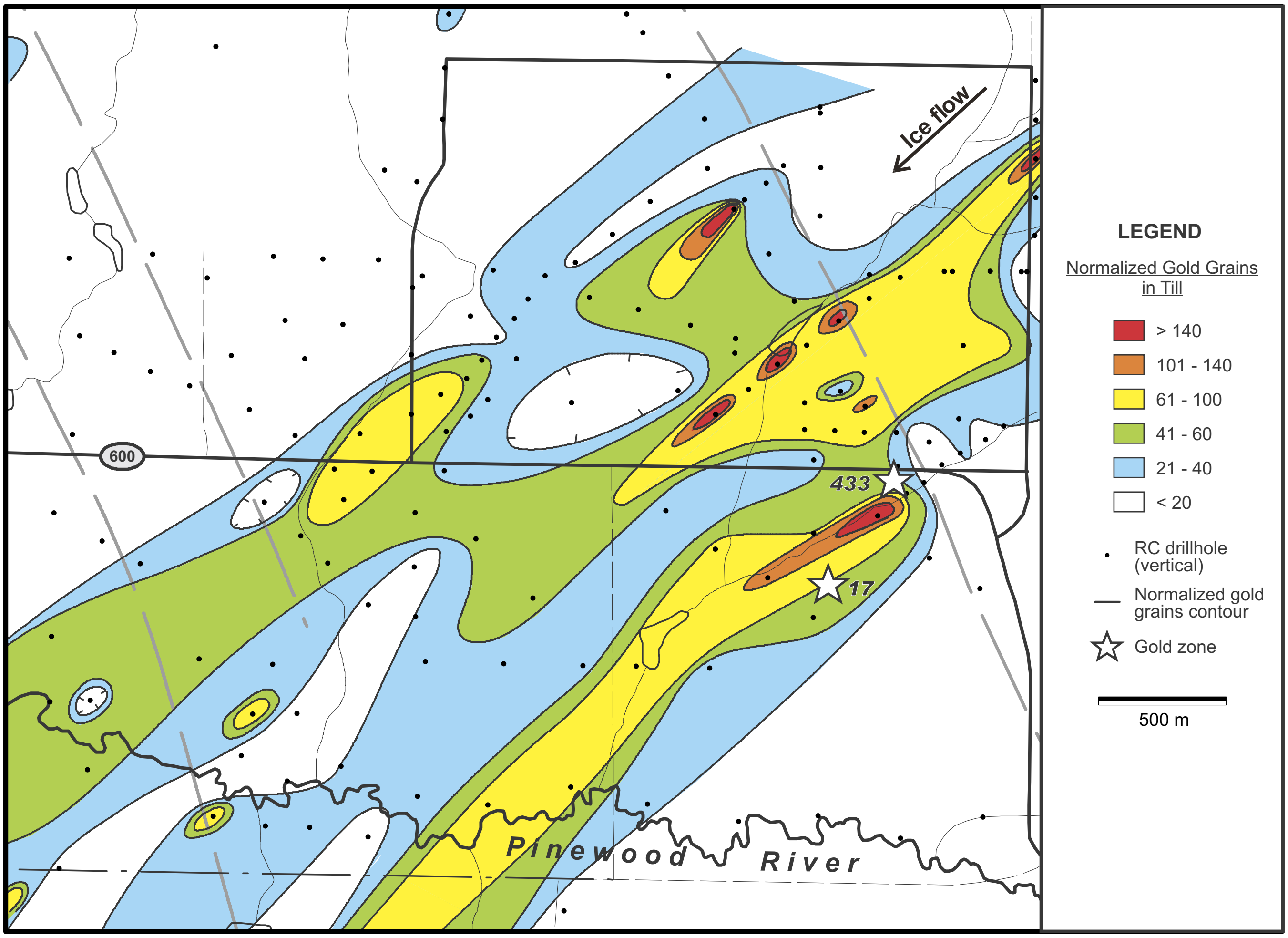

Figure 6. Head of the gold-grain dispersal train as defined by Nuinsco in 1998. The train was established from the average normalized number of gold grains per till sample in the RC drillholes, irrespective of the till thickness and number of samples collected from the hole. The actual gold-grain counts were normalized to a constant 7.5 kg weight of processed -2 mm till matrix.

1997-98 drilling defined the limits of the gold-grain anomaly in the Labradorean till and showed that it represents the head of a 3 km wide x 15 km long dispersal train (Fig. 5) that extends southwestward to include some of the weak gold-grain anomalies identified by the OGS ten years earlier. It also showed that the till within the head of the train was anomalous in gold grains from top to bottom. Therefore the relative strength of the anomaly in any drillhole could be measured very simply by averaging the number of gold grains per sample, normalized to the typical 7.5 kg weight of -2 mm matrix processed from the original, ~10 kg samples.

Within the overall train, several subtrains averaging >100 grains per sample emerged (Fig. 6), indicating that undiscovered gold zones were present in addition to the known 17 Zone (Nuinsco, 1997). One of these subtrains appeared to be superimposed on the train emanating from the 17 Zone but continued northeastward across this zone, suggesting that another gold zone was present further up-ice. A detailed examination of representative gold grains from this train by scanning electron microscope (SEM) revealed that these grains were larger than those in the 17 Zone train, implying a higher grade gold source, and that the main sulphide and silicate minerals intergrown with the gold were chalcopyrite (Fig. 7a) and chlorite (Fig. 7b), rather than pyrite and sericite as in the 17 Zone train. The strongest gold-grain response was in RC Hole 433, ~400 m up-ice from the 17 Zone. Follow-up diamond drilling here intersected significant mineralization, the 433 Zone, but Nuinsco did not perform sufficient drilling to define this zone.

The RC drillholes also sampled 1.5 m of bedrock beneath the till. The bedrock cuttings were logged systematically and analyzed geochemically, resulting in the first meaningful bedrock map of the unexposed portion of the Rainy River Greenstone Belt in the lowland area. The generally unprospective part of the greenstone belt southwest of the gold deposit consists of a monotonous succession of basalt and greywacke. Near the gold deposit, these lithologies yield abruptly along

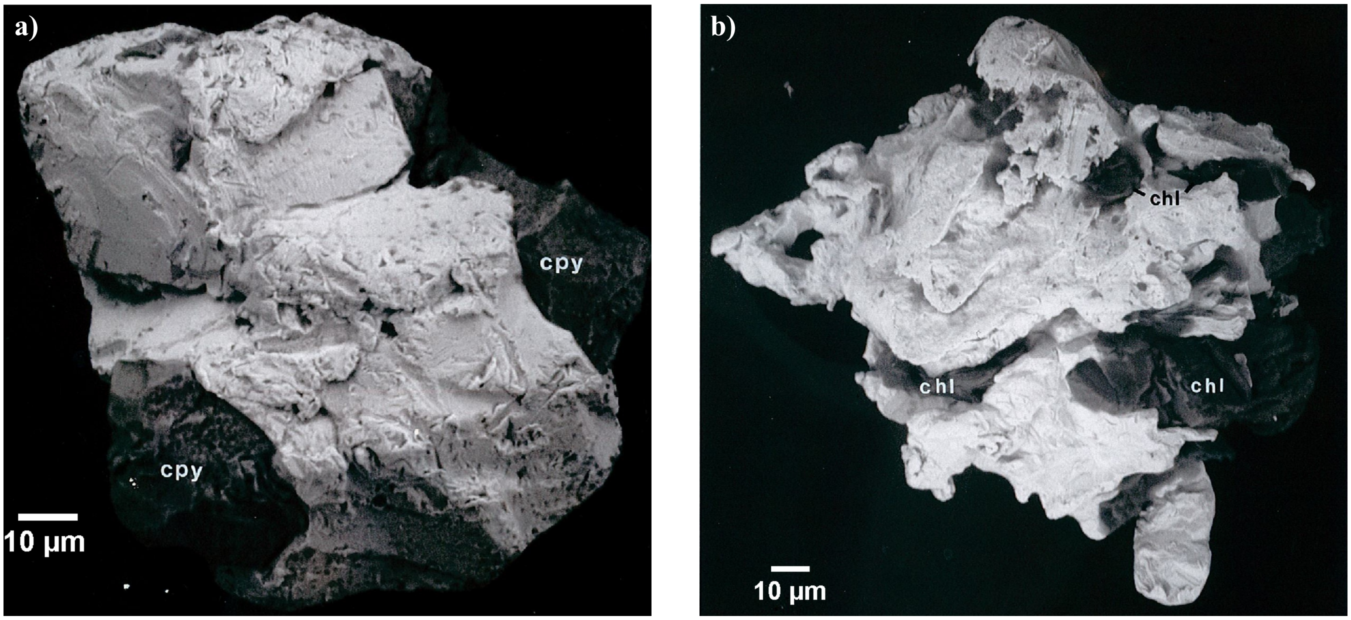

Figure 7. SEM images of representative gold grains from the 433 Zone dispersal train. **a)** Slightly modified grain with intergrown chalcopyrite. **b)** Slightly modified grain with intergrown chlorite.

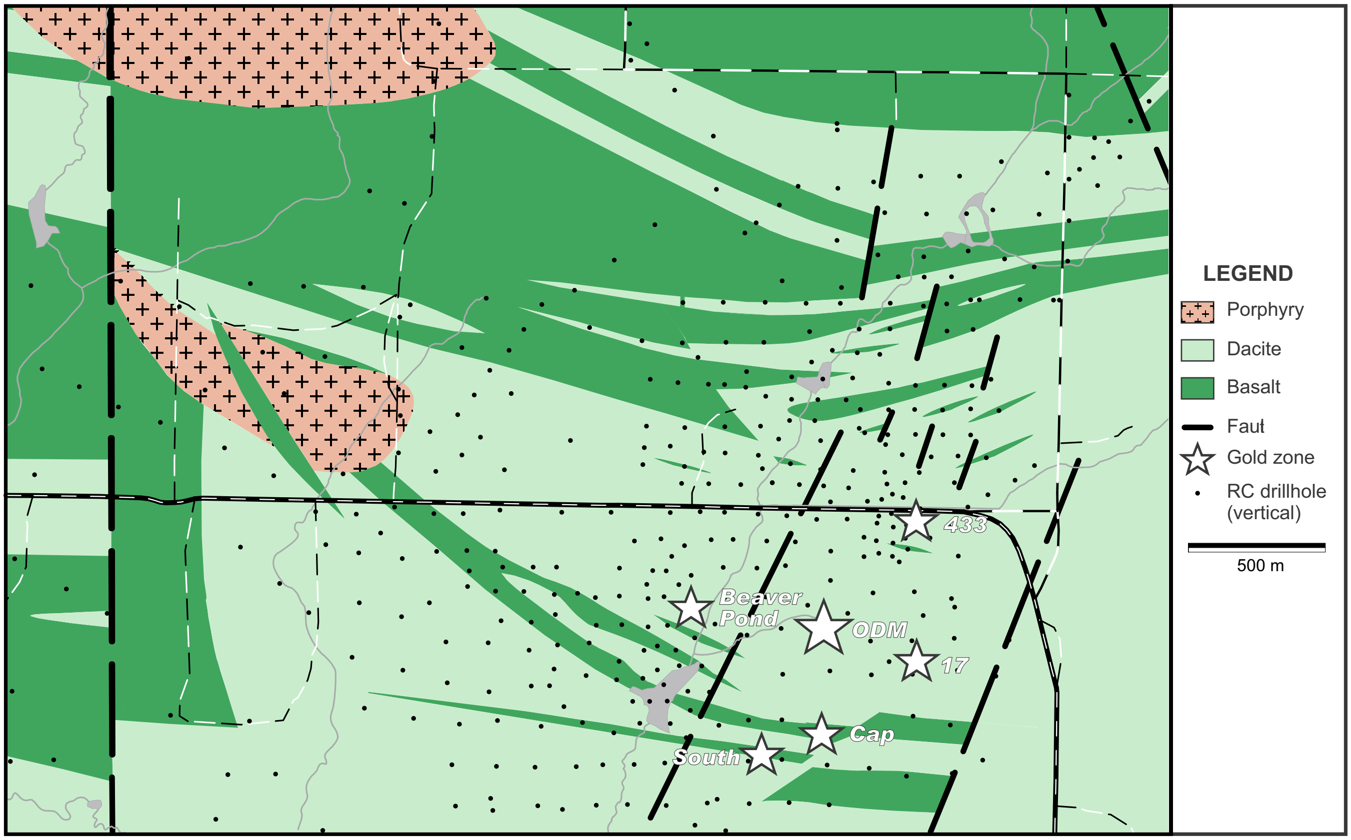

Figure 8. Bedrock geology in the area of the Rainy River gold deposit. The bedrock is covered by ~30 m of glacial deposits and the geology was determined from 1.5 m bedrock intercepts at the bottoms of RC holes drilled by Nuinsco and Rainy River Resources. The thick dacite occurs in a basin structure, probably a caldera, on the western flank of a volcanic edifice and yields abruptly westward along strike to basalt. The volcanic rocks are folded and the dacite dips 50° south.

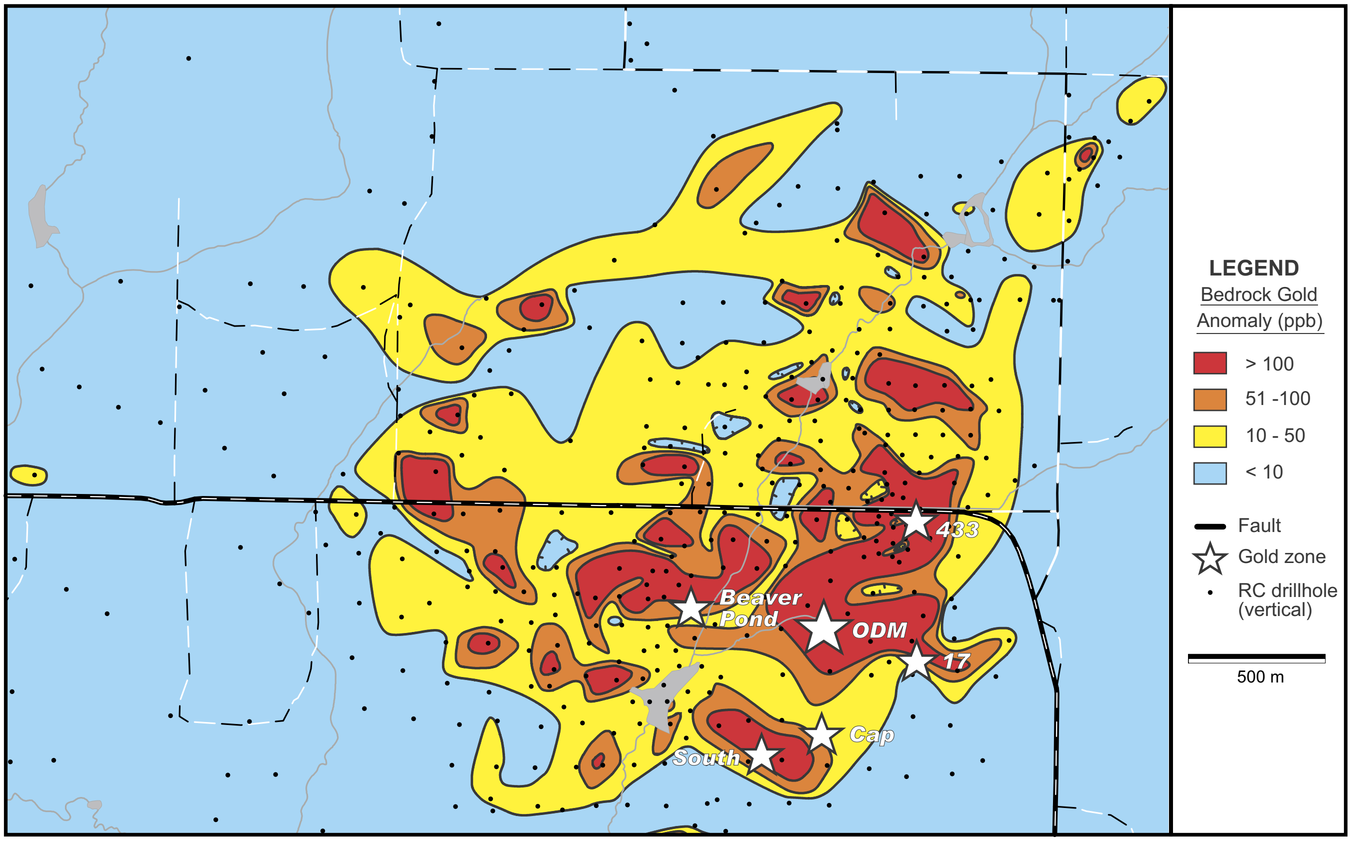

Figure 9. Gold content of the bedrock subcrop beneath the till in the area of the Rainy River gold deposit. The gold assays were obtained from 1.5 m bedrock intercepts at the bottoms of RC holes drilled by Nuinsco and Rainy River Resources.

strike to a bimodal succession of dacite and basalt (Fig. 8). The dacite is mostly fragmental. It includes chaotic lenses of coarse, vent-facies breccia which is thought to have been deposited mostly subaqueously in a caldera basin on the western flank of a large volcanic edifice (SRK Consulting, 2009; RRR, 2010). A 2 km thickness of the permeable dacite within the caldera sequence was pervasively hydrothermally altered and is continuously mineralized with 2 to 5% pyrite and is anomalous in gold at the ~50 ppb level (Fig. 9). The higher grade mineralization found in the gold zones of economic interest appears to have been concentrated by fluid pooling at aquitards in the reservoir; consequently these gold zones are roughly stratiform.

The Rainy River Greenstone Belt area has been affected by regional folding and the caldera sequence is now tilted ~50° southward and metamorphosed to lower greenschist facies. The total area of pervasively altered and gold-anomalous dacite that was exposed to glaciation and now underlies the till was a remarkable 600 hectares or 6 km^2 (Fig. 9), accounting for the great, 3 km width and 15 km length of the gold-grain dispersal train in the till (Fig. 5). Shear deformation associated with the regional folding was concentrated in the most altered and best mineralized dacite units. Therefore, as at similar volcanogenic gold deposits, such as LaRonde in the Bousquet district of Quebec (Dubé et. al., 2007), the Rainy River deposit superficially resembles a shear-controlled deposit. As at LaRonde, the introduced Mn alteration occurs as spessartine garnet ($Mn_3Al_2(SiO_4)_3$) and the excess alumina resulting from feldspar destruction occurs partly in kyanite (Al_2SiO_5) despite the lower greenschist grade of metamorphism.

RAINY RIVER RESOURCES, 2005-2013

The acquisition of the Rainy River gold project by RRR in 2005 was spearheaded by the company's president, Nelson Baker, who recognized the great potential of such a large, gold-rich, volcanogenic, hydrothermal alteration system. From 2005 to 2010, RRR drilled another 278 RC holes to further define the gold-grain subtrains in the till and locate their bedrock sources. These subtrains were defined both by the normalized average number of gold grains per sample in the till section (Fig. 10) and the average analyzed Au content of the heavy mineral fraction of the samples (Fig. 11). The Au analyses were normalized to a constant 250:1 laboratory heavy mineral concentration factor because the weights of the concentrates varied greatly with pyrite abundance. Approximately 90% of the gold in the concentrates was found to be still encased in pyrite grains rather than occurring as liberated grains (RRR, 2010). The 433 Zone was found, as foretold by the size

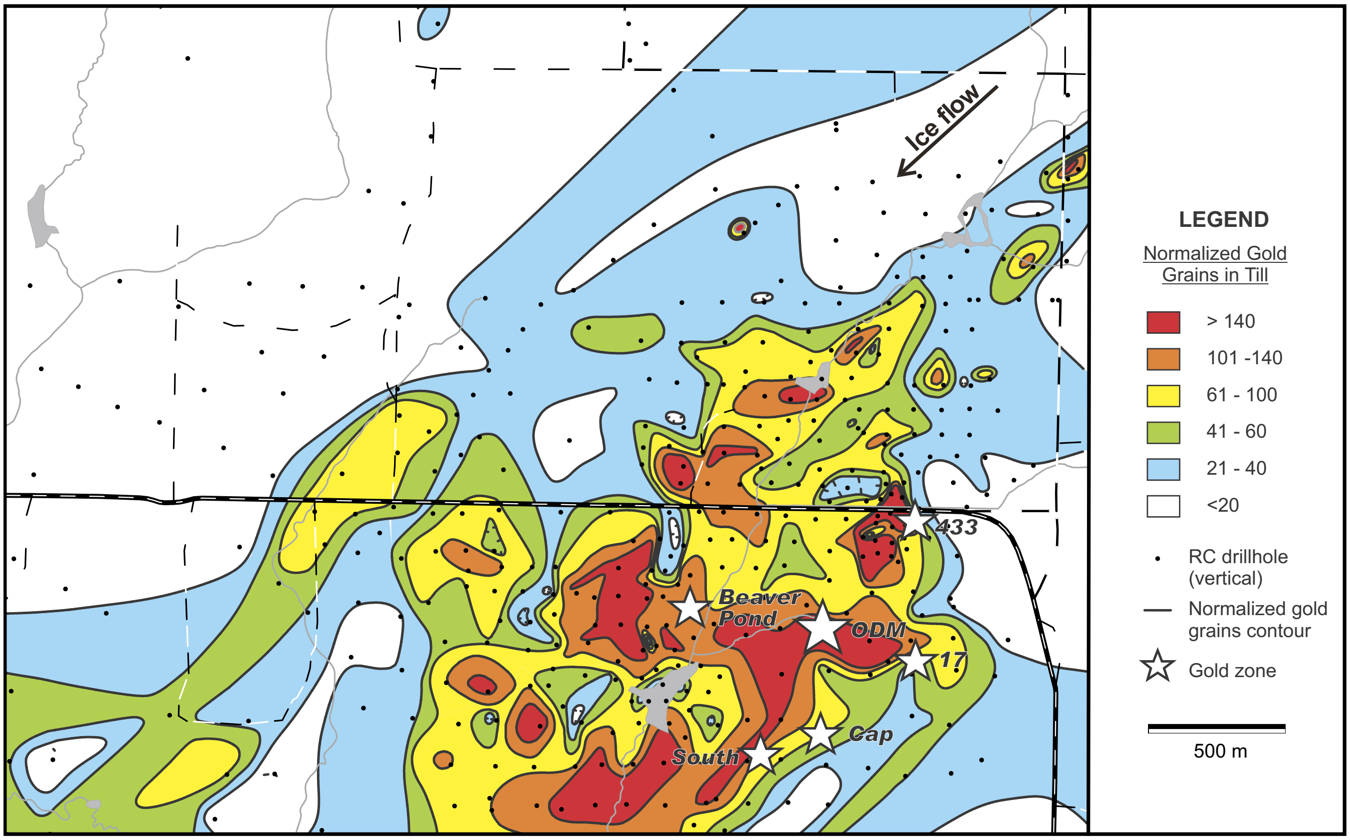

Figure 10. Head of the gold-grain dispersal train as defined in 2010 by Rainy River Resources. The train was established from the average normalized number of gold grains per till sample in the RC drillholes irrespective of the till thickness and number of samples collected from the hole. The actual gold-grain counts were normalized to a constant 7.5 kg weight of processed -2 mm till matrix.

and inclusion mineralogy (Fig. 7) of the gold grains in the till, to be of a significantly higher grade than the 17 Zone and to be characterized by chloritic alteration with significant chalcopyrite. The 17 Zone blossomed westward along strike into the large ODM Zone. A new gold zone, Beaver Pond, was found further west at the same stratigraphic level and two others, the Cap and South zones, were found to the south at a higher stratigraphic level.

Diamond drilling conducted in concert with the RC drilling has established significant gold resources in all six gold zones. Recently RRR's early confidence in the project was again rewarded with the discovery further to the east of the new Intrepid Zone. This gold zone is in virgin ground east of the area shown in Figures 8 to 11. It is glacially across-ice from the area tested by RC drilling and is the first significant discovery made on the property without the aid of gold grains. It is expected that deep gold zones, which were not exposed to glaciation and thus are not reflected in the till, will also be discovered as the property is developed.

DISCUSSION AND CONCLUSIONS

The six gold zones currently comprising the Rainy River gold deposit were all discovered by tracing glacially dispersed, till-hosted gold grains to their bedrock sources. These gold deposits are of volcanogenic origin. They are stratiform and occur within a 6 km^2 area of hydrothermally altered and pervasively gold-anomalous fragmental dacite deposited within a probable caldera basin, resulting in an exceptionally large, 3 km wide x 15 km long gold-grain dispersal train in the till. Near the head of this train, the till section is anomalous in gold grains from top to bottom, regardless of its thickness, reflecting the great breadth of the gold-bearing source rocks. However, subtrains related to economically significant gold zones are readily recognizable from both the average number of gold grains per sample in the till section and the average analyzed Au grade of the heavy mineral fraction of the till.

The observed, glacially liberated gold grains represent only ~10% of the total gold present in the till because the grains are silt-sized and 90% are still encapsulated within pyrite grains. These pyrite grains have remained fresh since glaciation because the auriferous till is covered by a thick layer of younger, clay-rich impervious till. During glaciation, new gold grains were continually liberated from the pyrite along the length of the dispersal train such that even its distal part

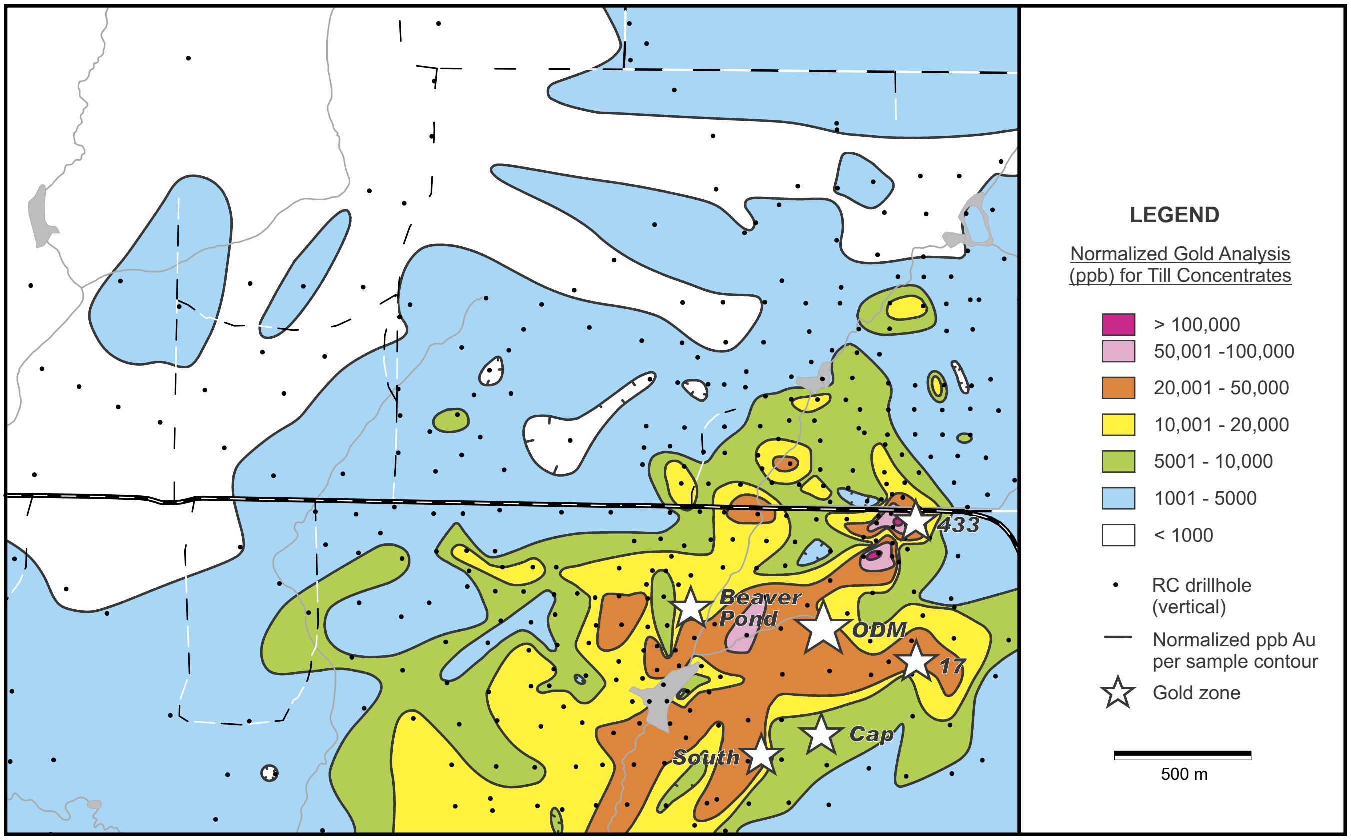

Figure 11. Head of the gold dispersal train as defined in 2010 by the gold assays for the heavy mineral fraction of the till samples. The train was established from the average normalized heavy mineral concentrate gold assay per till sample in the RC drillholes, irrespective of the till thickness and the number of samples collected from the hole. The concentrate weights were normalized to both a constant 7.5 kg weight of processed -2 mm till matrix and a constant 250:1 laboratory heavy mineral concentration factor.

contains some pristine grains that may appear proximal. This, along with the patchwork land ownership in the area, may have contributed to the long odyssey from train discovery to deposit discovery.

The discovery of the Rainy River gold deposit and resolution of the six gold zones comprising the deposit is an excellent example of the effective use of gold grains in an area of thick cover that impedes most other exploration methods. The fact that the initial impetus was provided by a regional government survey illustrates the importance of such surveys, especially in a "New Frontier" such as the Rainy River district. However, the ~20-year period and long succession of companies required to complete the discovery is a reminder of the stamina, perseverance, and imagination needed to be successful in mineral exploration. The entrepreneurial spirit and agility of the two junior exploration companies, Nuinsco and RRR, were particularly important to the discovery process.

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FOLLOWING KIMBERLITE INDICATOR MINERALS TO SOURCE IN THE CHIDLIAK KIMBERLITE PROVINCE, NUNAVUT

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ABSTRACT

The discovery of diamond-bearing kimberlite within the Chidliak kimberlite province on Hall Peninsula, southern Baffin Island, Nunavut, is a classic example of the application of traditional diamond-exploration techniques in a glaciated terrain. To date, 64 kimberlite pipes have been discovered: 61 on the Chidliak project and three on the adjacent Qilaq project. The first discovery was made in 2008, making Chidliak the most recent kimberlite province discovered in Canada. Comprehensive kimberlite indicator mineral (KIM) classification and interpretation techniques, including abrasion and geochemical analyses have played a significant role in these discoveries and have evolved over the course of the project.

INTRODUCTION

The southern half of Baffin Island, in the Canadian Arctic, was targeted for greenfields diamond exploration by BHP Billiton and Peregrine Diamonds Ltd. (Peregrine) in 2005. The area was selected for exploration because it was thought to be relatively underexplored. In addition, the presence of 1.85 Ga to 2.92 Ga aged zircons in basement ortho- and paragneiss in the region (Scott 1999), suggested that at least a portion of the area might be underlain by Archaean cratonic basement. As a result of the reconnaissance-scale 2005 sampling campaign, KIMs were recovered from glacial till samples collected on the Hall Peninsula (Fig. 1). Follow-up KIM sampling in 2006 better defined the anomalous KIM distributions. Additional sampling in 2007 was designed to increase sample density. Preliminary studies of the glacial history and indicator dispersion trains allowed for the design of focused air-

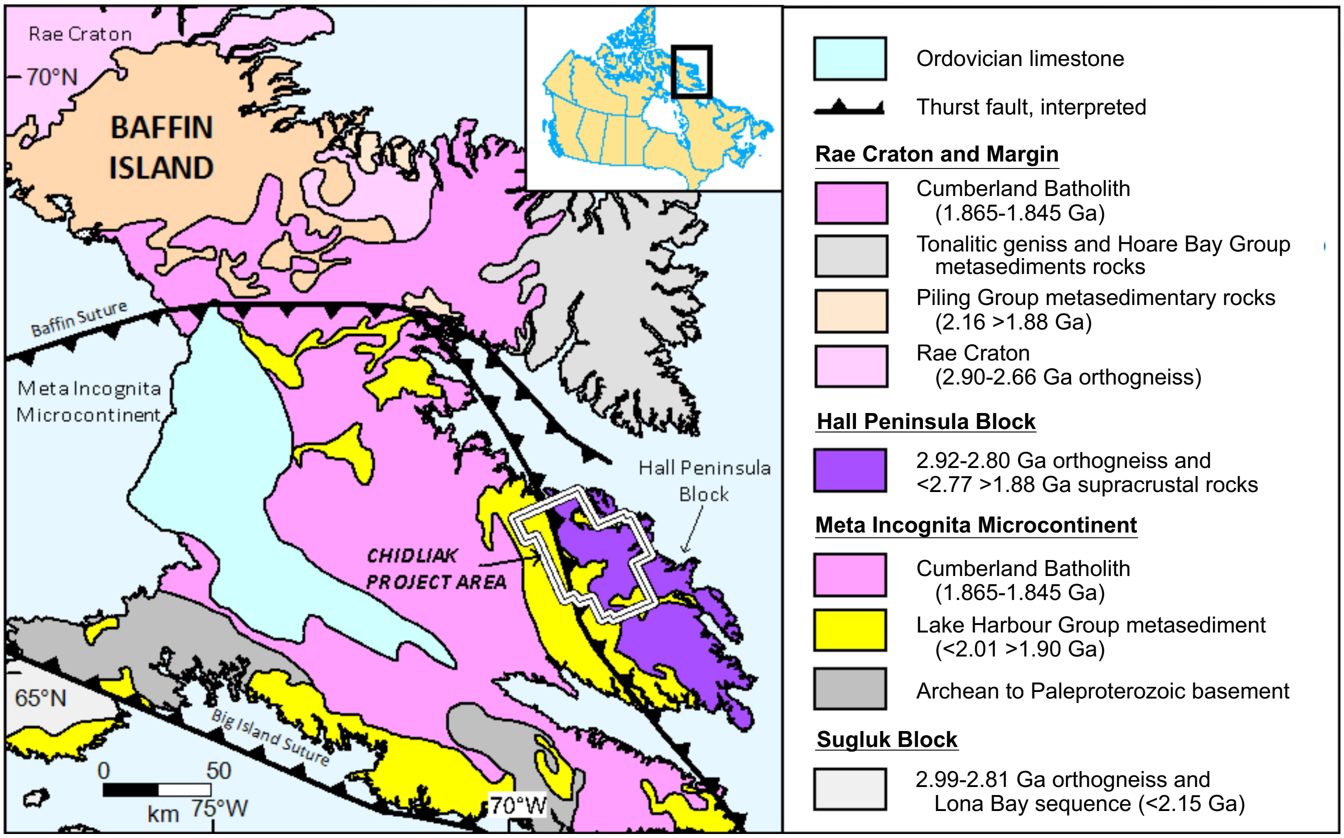

Figure 1. Simplified geological map of southern Baffin Island showing the major tectonostratigraphic assemblages and bounding crustal structures (after St-Onge et al., 2006 and Whalen et al., 2010; modified from Pell et al., in press).

Table 1. Exploration statistics for the Chidliak project, 2005 to 2012.

Activity Year	2005	2006	2007	2008	2009	2010	2011	2012*	Total
Till samples collected (#)	166	232	872	221	1861	1402	1039	412	6,205
Probe confirmed KIM-positive till samples (#)	5	31	275	102	126	172	400		1,111
Analysed KIMs from till (#)	44	460	3,811	1,798	2,679	3,593	9,587		21,972
Airborne geophysics (line-km)				11,700	-	20,442	15,178		47,320
Ground geophysics (line-km)				157	1,096	1,884	2,113	6,353	11,603
Anomalies ground-checked (#)				12	63	113	99	40	327
Kimberlite discoveries (#)				3	13	36	10	2	64
Core drilling (m)					3,952	7,672	8,865		20,489
RC drilling (3.625-inch, m)						1,445	1,713		3,158
Analysed KIMs from kimberlite (#)				1,635	5,451	8,487	17,447		33,020
Microdiamond sample processed (kg)				899	3,404	7,470	9826	251	21,849
Mini-bulk sample processed (t)					49.7	61.3	32.5		143.5

2012* - Sample processing ongoing, final results not yet received

borne geophysical surveys that were flown in 2008. Kimberlite-type anomalies, typically discrete, isolated magnetic high, magnetic high dipole, or magnetic low anomalies were identified from these surveys and ground prospecting resulted in the discovery of the first three kimberlite pipes, CH-1, CH-2, and CH-3, in the summer of 2008. Microdiamond analyses of these three kimberlite samples, using caustic fusion methods, proved they were diamondiferous (Pell et al., 2012 in press). These results set the stage for the next phase of work, the evaluation of the economic potential of this new diamond district, which involved additional till sampling, ground and airborne geophysics, core and reverse-circulation (RC) drilling, and sampling of kimberlite to recover KIMs and micro- and macrodiamonds. Chidliak now hosts 64 kimberlites over an area that is approximately 70 km in a north-south direction and 40 km east-west.

QUATERNARY GEOLOGY OF THE CHIDLIAK AREA

The Quaternary geology of the Hall Peninsula is complex. The area was inundated by the Laurentide Ice Sheet during the last glacial maximum (LGM) at approximately 18,000 to 9,000 years B.P (Dyke et al. 2003; Dyke 2004), and remnants of ice are still present at Chidliak at approximately 700 m above sea level. Initially, regional ice-flow directions were believed to be dominated by the Hall Ice Divide, with the primary ice-flow direction interpreted to be from northwest to southeast, parallel to the ice divide, and then emanating to the north and south away from it (Dyke and Prest 1987). Fieldwork and KIM distributions at Chidliak bear evidence for at least three main ice-flow regimes (Johnson et al., in press). There is evidence of ice flow related to the Hall Ice Divide; however, glacial dispersion is dominated by a later north and northeastward ice flow into prominent fjords, which is particularly evident in the northern half of the project area. Southeasterly ice flow associated with deglaciation postdated the north and northeastward ice flow but, importantly, had only minor effects on KIM dispersion.

KIMBERLITE INDICATOR MINERAL SAMPLING, ANALYSIS, AND INTERPRETATION

KIMs were recovered from five of the original 166 reconnaissance glacial till samples collected on the Hall Peninsula in 2005. Follow-up KIM sampling in 2006 better defined the anomalous KIM distributions. Additional sampling in 2007 and 2008 was designed to increase sample density and develop a geochemical signature. A total of 1491 samples were collected through 2008, 413 of which contained KIMs (Table 1). The compositions, as determined by electron microprobe analysis, of 6,113 of the recovered KIMs, showed evidence that the kimberlite pipes had sampled mantle peridotite from within the diamond stability field. Data for over 2,000 peridotitic pyrope garnets showed that approximately 10% of the grains had a high Cr_2O_3/low CaO harzburgitic (G10) geochemical signature (Dawson and Stephens 1975; Gurney 1984), indicating good diamond potential for the source kimberlite (Fig. 2a). Diamond inclusion-type chromite and eclogitic garnet were also recovered (Fig. 2b). Single-grain clinopyroxene thermobarometry (after Nimis and Taylor 2000) constrained a model-conductive geotherm colder than obtained for the diamondiferous kimberlite of the central Slave Craton, with entry into the diamond stability field at approximately a temperature of more than 850°C (Fig. 2c). The pressure-temperature data suggested a thermal disturbance over the approximate pressure range of 62 to 68 kbar, at the base of the lithosphere. Many of the KIM grains had preserved delicate surface textures, such as kelyphite rims on garnet and alteration rinds on picroilmenite. Most KIM grains showed no evidence of rounding in the surface environment. These abrasion characteristics suggested minimal glacial transport and proximal kimberlite sources. Initial studies of the picroilmenite mineral

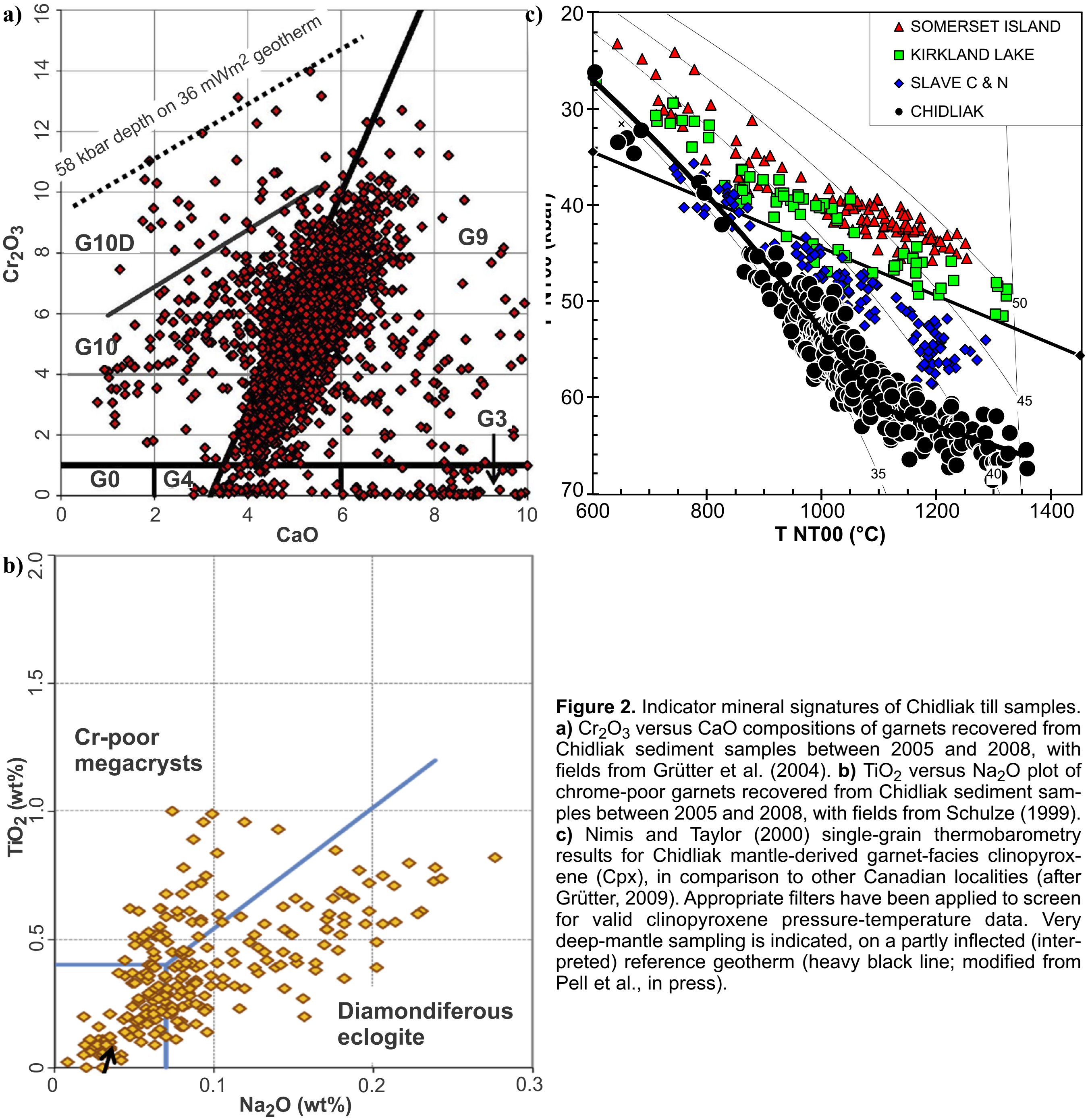

Figure 2. Indicator mineral signatures of Chidliak till samples. **a)** Cr_2O_3 versus CaO compositions of garnets recovered from Chidliak sediment samples between 2005 and 2008, with fields from Grütter et al. (2004). **b)** TiO_2 versus Na_2O plot of chrome-poor garnets recovered from Chidliak sediment samples between 2005 and 2008, with fields from Schulze (1999). **c)** Nimis and Taylor (2000) single-grain thermobarometry results for Chidliak mantle-derived garnet-facies clinopyroxene (Cpx), in comparison to other Canadian localities (after Grütter, 2009). Appropriate filters have been applied to screen for valid clinopyroxene pressure-temperature data. Very deep-mantle sampling is indicated, on a partly inflected (interpreted) reference geotherm (heavy black line; modified from Pell et al., in press).

compositions revealed broadly variable signatures on the project scale, suggesting that multiple kimberlite sources were present at Chidliak.

As sample density within the project area increased (Table 1), it became evident that in order to resolve individual mineral-dispersion trains, rate their prospectivity, and link them to potentially unique kimberlite sources, simply looking at probe-confirmed KIM counts was not sufficient and it was necessary to evaluate the data more thoroughly. During the 2009 exploration program, it was recognized that picroilmenite chemical fingerprinting techniques (e.g. Lee 1993) were only of limited help in resolving the relationships between grains derived from known kimberlite and those found in till (Neilson et al. 2012), as many of the kimberlite pipes at Chidliak, including some of the significantly diamondiferous bodies, were found to be picroilmenite-free. Where present, however, ilmenite did prove to be a useful tool in resolving individual mineral trains. Kimberlitic picroilmenite was identified using the criteria of Wyatt et al. (2004). Four distinct ilmenite populations were recognized based on their Cr_2O_3 and MgO contents. Ratios of the four ilmenite populations vary between kimberlite sources. Within

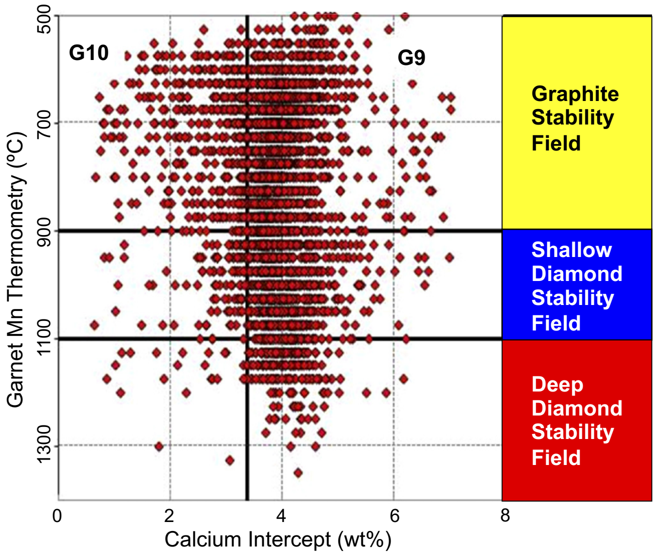

Figure 3. Mn temperature versus Ca intercept of Cr-pyropes in Chidliak sediment samples. T-Mn <900ºC = graphite-facies, T-Mn 900 to 1100ºC = shallow diamond-facies, T-Mn >1100ºC = deep diamond-facies (from Neilson et al., 2012).

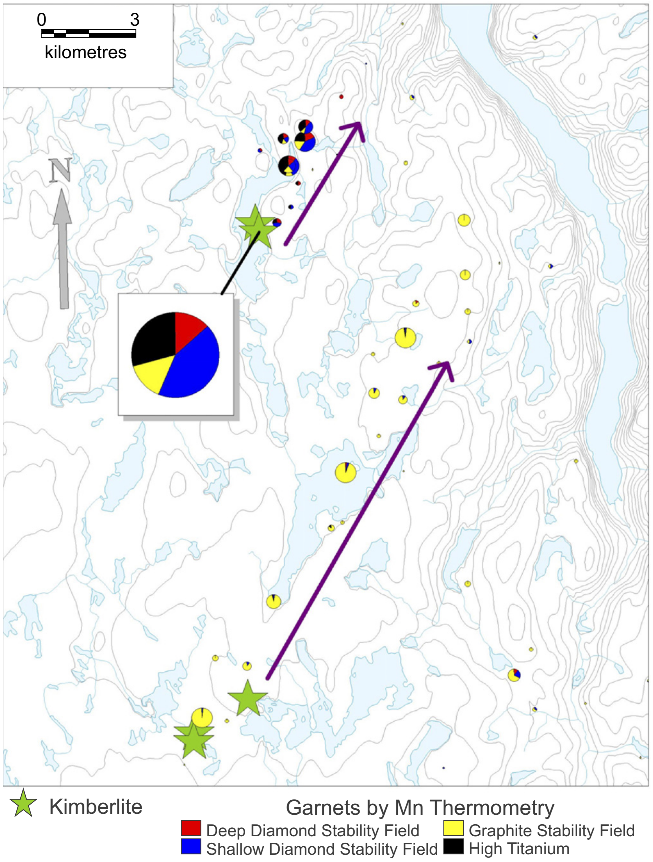

Figure 4. Map of mantle tenor as determined by garnet T-Mn and garnet abundances (size of circles) in Chidliak sediment samples. Inset shows garnets from the kimberlite sources of the two trains (pies not to scale). The different kimberlite sources have distinctly different mantle signatures and this is clearly reflected in the trains derived from them. Arrows indicate interpreted ice-flow direction (modified from Neilson et al., 2012).

zones of abundant indicator minerals, the variation of the ilmenite population ratios in sediment samples enables the resolution of individual trains (Neilson et al. 2012).

Garnet, however, is a ubiquitous mineral in Chidliak KIM samples. Starting in 2009, in order to leverage the information available from G9 (lherzolitic) and other garnet types, new KIM classification and interpretation techniques, similar to those described in Grütter et al. (2004) and Grütter and Tuer (2009), were implemented, placing substantial emphasis on Mn-thermometry (T-Mn) of pyrope garnets. A project-specific T-Mn calibration (modified after Grütter et al. 1999) was tailored to reflect the specific analytical protocol and Mn-standardization of the single commercial microprobe service provider used since the first KIM recoveries at the Chidliak project. Chrome-pyrope grains were categorized as graphite-facies (T-Mn <900ºC), shallow diamond-facies (900ºC< T-Mn <1100ºC), or deep diamond-facies (T-Mn >1100ºC) (Fig. 3), or as high titanium (G1 or G11 garnet with TiO_2 >0.6 wt%). The categorization provided a simple, four-fold representation of peridotite-affinity garnet abundance relative to graphite-diamond in any given sample (i.e. the mantle tenor of Grütter and Tuer 2009).

At this time, it was also recognized that the integration of the garnet Mn-thermometry results had served to highlight distinct mineral trains (Fig. 4) and to fingerprint specific kimberlite sources and their associated glacial dispersion trains, which often occurred at high angles to originally interpreted regional ice-flow direction. The mantle tenor fingerprints observed in Chidliak sediment samples were used to discriminate individual, source-specific KIM trains in somewhat-confusing areas that were characterized by high KIM garnet recovery. This information helped to constrain ice-flow models and to resolve mineral trains derived from known kimberlite sources and those from discrete sources that remain to be discovered (Neilson et al. 2012). The mantle tenor signature of individual trains, together with the distribution and relative abundance of diamond-facies peridotitic (G10D), eclogitic (G3D), and websteritic-eclogitic (G4D) garnets, as defined by Grütter et al. (2004), was used to prioritize high-potential prospecting areas and geophysical targets.

The discovery of thirteen new kimberlites during the 2009 field season, and the assessment of their KIMs and diamond content, through heavy mineral abundance and composition studies and caustic fusion analyses, respectively, stimulated further evolution of the interpreted relationships between KIM garnet compositions and the diamond content of the kimberlite sources at Chidliak. It was recognized that the absolute abundance per unit weight of kimberlite of diamond-facies eclogitic-websteritic garnets constitutes an

Table 2. Mantle tenor of garnets (in %) and diamond content of selected kimberlite samples.

Kimberlite Name	Deep Diamond Facies Pgar %*	Shallow Diamond Facies Pgar %*	Graphite Facies Pgar %*	High TiO_2 Pgar %*	Diamond Facies Egar %**	Diamond Content (ct/t)
CH-6	2	12.9	82.4	2.7	69.9	2.8^{dms}
CH-7 N	30.2	23.5	42.7	3.6	90.1	1.04^{dms}
CH-3	3.6	15.3	74.5	6.6	none	Low^{x}

Pgar = peridotitic garnet; Egar = eclogitic and websteritic garnet

*100 x Pgar Type/Total Pgar; Pgar Type as a per cent of Total Pgar

**100 x (G3D+G4D)/(G3+G4+G3D+G4D); Diamond Facies Egar as a per cent of Total Egar

2.8^{dms} – diamond content determined by mini-bulk sample processed by dense media separation

Low^{x} – A 254 kg surface exploration sample of boulders processed by caustic fusion yielded 110 stones larger than the 0.106 mm sieve size with the largest diamond being from the +0.425 mm sieve size.

Modified from Neilson et al. (2012) and Pell et al. (in press).

important gauge of diamond mineralization (Table 2). The garnet classification scheme that was implemented readily separated the important G3D (diamond-facies eclogite) and G4D (diamond-facies websterite-eclogite) garnets from compositionally similar G1 (megacryst) garnet, unlike the Angolan case discussed in Rogers and Grütter (2009). It was also recognized that a low tenor of diamond-facies Cr-pyrope garnets and a correspondingly high tenor of graphite-facies Cr-pyrope garnets should not be interpreted as indicating poor diamond potential at Chidliak (Table 2, Fig. 5). This outcome strongly contrasts with examples from the Daldyn-Alakit, Archangelsk (e.g. Malkovets et al. 2007) and Sarfartoq (Grütter and Tuer 2009) kimberlite provinces, in which kimberlite-hosted diamond content has been correlated with the tenor of diamond-facies Cr-pyrope garnets. At Chidliak, any kimberlite with significant total garnet content per unit weight is assessed as potentially having significant diamond content, especially if eclogitic or websteritic garnets are present (Table 2). The corollary for exploration at Chidliak is that any source of high garnet counts in sediment samples is considered worthy of pursuit, regardless of garnet compositions (Neilson et al. 2012).

Understanding the relationships between grains derived from samples of the known kimberlite pipes and those found in glacial tills has been of paramount importance in determining the local ice-flow regime, which includes a surprising array of flow directions. Travel distances for KIMs across the property vary. Distinct source signatures can be recognized over distances of approximately 3 km to over 20 km in one instance; however, in areas of interpreted stagnant or oscillating ice movement, transport distances can be as short as one kilometre or less. At Chidliak, KIM transport is often more affected by topography than by larger scale interpreted glacial flow, implying that later localized Alpine-type glaciations had a greater effect on KIM dispersion than earlier, regional ice flow (Neilson et al. 2012).

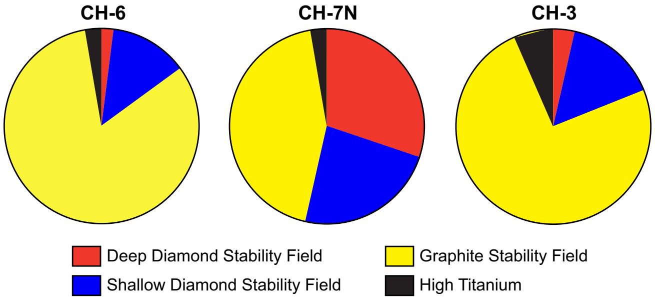

Figure 5. Graphical representation of the mantle tenor of garnets from the kimberlite pipes listed in Table 2 (modified from Neilson et al., 2012).

SUMMARY AND CONCLUSIONS

The Chidliak kimberlite pipes were discovered using a traditional exploration model focused on constraining the location of primary sources for KIMs recovered from surficial glacial sediments. KIM compositions highlighted the prospect of locating diamondiferous sources in an Archaean cratonic setting prior to discovery of the first kimberlite in July 2008. Subsequent interpretation of KIM data has permitted surficial indicator mineral populations to be matched with their primary sources. Mineral trains determined to have sourced from known kimberlites are being used to refine the understanding of the ice-flow directions on Hall Peninsula. In some areas, local ice-flow directions appear to have had more local influence on kimberlite indicator mineral dispersion than regional ice flow.

Exploration will continue to establish the potential of Chidliak, Canada's newest diamond district. Concurrent with the evaluation of the known kimberlite pipes with economic potential, exploration for new kimberlites will continue. The presence of unexplained high-interest indicator mineral trains within glacial sediments suggests more kimberlite will be discovered.

ACKNOWLEDGEMENTS

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VOLCANOGENIC MASSIVE SULPHIDE EXPLORATION IN GLACIATED TERRAIN USING TILL GEOCHEMISTRY AND INDICATOR MINERALS

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INTRODUCTION

Volcanogenic massive sulphide (VMS) deposits are a significant exploration target because they account for 27% of Cu, 49% of Zn, 20% of Pb, 40% of Ag, and 3% of Au production in Canada (Drake, 2011). The majority of Canada's land mass was covered by glaciers and continental ice sheets during the Quaternary, eroding and dispersing metal-rich debris and depositing a blanket of unconsolidated sediments, masking mineral deposits. Thus, drift prospecting using till geochemistry and indicator minerals is an important exploration method for VMS deposits. The application of till geochemical methods to VMS exploration in Canada has a long history, exceeding 5 decades (e.g. Dreimanis, 1958, 1960; Fortescue and Hornbrook, 1969; Shilts, 1975; Hoffman and Woods, 1991; Kaszycki et al., 1996; Parkhill and Doiron, 2003). In the past 10 years, indicator minerals recovered from glacial sediments have complemented traditional VMS exploration methods in the glaciated terrain of Canada. This presentation provides a practical overview of till geochemical and indicator mineral methods that can be used for VMS exploration. Topics addressed will include appropriate size fractions of till for analyses, processing and analytical techniques, and VMS pathfinder elements and indicator minerals. In addition, till sampling case histories around VMS deposits in different regions across Canada will be presented.

SAMPLE MEDIA: TILL VERSUS SOIL

The earliest (1950s-1960s) surficial geochemical investigations around VMS deposits in Canada were made using soil rather than till samples. In the Canadian Cordillera, soil sampling is still used by some exploration companies instead of till sampling (e.g. Kerr and Levson, 1995; Levson and Giles, 1995). The formation of soil through weathering processes destroys labile minerals such as sulphides, and, therefore, the geochemical signatures in soils formed on till are the result of a combination of clastic glacial dispersal and dispersal by aqueous and gaseous processes. As a result, base metal contents and indicator mineral abundances may be lower in soil (i.e. weathered till) versus C-horizon till, and dispersal train geometry may be more difficult to interpret and follow-up (e.g. Hoffman and Woods, 1991; Kaszycki et al., 1996; Lett and Jackaman, 2002; Hall et al., 2003). To obtain an unimpeded signal of clastic glacial dispersal, unoxidized till is the target media. A more in-depth discussion of till sampling strategies to obtain this optimal till are summarized by Levson (2001a, b); McMartin and McClenaghan (2001), McMartin and Campbell (2009), Paulen (2009), Spirito et al. (2011), Plouffe et al. (in press), and McClenaghan et al. (in press).

GEOCHEMICAL ANALYSIS

Till and soil geochemical studies between the 1950s and 1980s typically only determined the main economic metals in VMS deposits, Cu, Pb, and Zn, as analyses for these elements was readily available and cost effective. The earliest determinations of the base metal content of till relied on "cold extraction" techniques (abbreviated as cx, cx-THM, CxCu) that determined the content of readily soluble metal, and metals present as free ions or loosely bound ions on the surface of grains (Rose et al., 1979; Levinson, 1980). Since the 1980s, "hot extraction" techniques, have been more commonly used for till geochemical analysis because hot acids can extract more metal from the dried and sieved material than cold extraction techniques. A major advance in VMS exploration came in the 1980s and 1990s with the development of inductively coupled plasma-mass spectrometry (ICP-MS), which made it possible to determine a broad suite of trace elements (Piercey, 2010) to identify VMS deposits' multi-element signatures in till down-ice. An extensive suite of VMS pathfinder elements can now be determined in till (Cu, Pb, Zn, Ag, Au, Se, Sb, Bi, As, Cd, Hg, Sn, Ga, In, Tl, V) and can be used to indicate if the eroded VMS mineralization is Ag-rich or Au-rich, and if a deposit is enriched in deleterious trace elements such as Se.

Most current exploration programs that utilize till geochemistry employ a strong partial digestion, such as aqua regia, to determine the contents of the major ore elements Cu, Pb, and Zn, as well as pathfinder elements Hg, Ag, V, Sb, As, Bi, Cd, and Tl. Total digestions techniques, such as borate fusion or 4-acid digestion followed by ICP-MS measurement or instrumental neutron activation analysis (INAA), are used to determine the contents of other pathfinder elements such as In, Sn, Se, and Au. Use of both partial and total digestion analyses allows for exploration for VMS as well as a broad range of deposit types, such as magmatic Ni-Cu-PGE, orogenic Au, porphyry Cu, IOCG, kimberlite) (e.g. McClenaghan et al., 2011; McMartin et al., 2011).

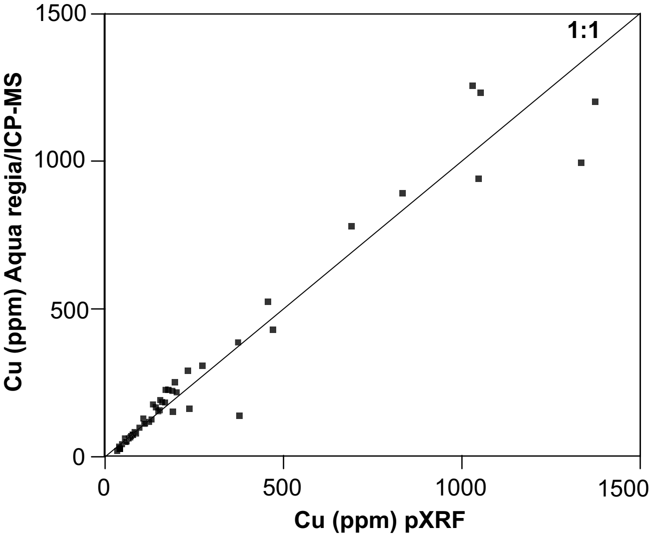

Figure 1. Comparison of Cu (ppm) content in till as determined by portable XRF (InnovX Delta with Ta tube) on dry, unsieved till versus dry, sieved (<0.063 mm) till analyzed using aqua regia/ICP-MS from the Halfmile Lake VMS deposit, New Brunswick, Canada.

PORTABLE XRF

Portable x-ray fluorescence spectrometry (pXRF) is another method for geochemically analyzing till. It is increasingly being used in the field to actively guide till sampling and to follow-up anomalies in the same field season. Metal contents determined by pXRF can also be used after the samples have been collected to prioritize till samples for lab-based geochemical analyses (e.g. Peter et al., 2010; Hall and McClenaghan, 2013; Sarala, in press). Comparisons of pXRF analyses of total till to aqua regia analyses of the <0.063 mm fraction of base metal-rich till from the Halfmile Lake deposit (Fig. 1) illustrate the ability of pXRF to determine metal contents of till.

SIZE FRACTIONS FOR GEOCHEMICAL ANALYSIS

The main VMS ore minerals, chalcopyrite, galena, and sphalerite, are relatively soft (hardness <4) and therefore are readily comminuted during glacial transport to the finest fraction of till (silt+clay) over short distances (Kauranne, 1959; Salminen, 1980; Nevalainen, 1989). Thus, the geochemical compositions of the silt + clay (<0.063 mm) or the clay (<0.002 mm) fraction of till are ideal for geochemically detecting glacial dispersal from VMS deposits. The advantage of geochemically analyzing the <0.002 mm fraction of till is the high contrast between background and anomalously high metal contents (e.g. Shilts, 1975, 1996). The disadvantages of using the <0.002 mm fraction include 1) the costly and time-consuming clay separation process required to isolate the <0.002 mm fraction and the large volume of material (~1 kg) needed to recover sufficient clay-sized material for analysis (Lindsay and Shilts, 1995; Klassen, 2003); 2) the low (<2%) clay content of typical Canadian tills; and 3) the clay-size fraction's susceptibility to false anomalies produced by hydromorphic dispersion of metals not necessarily related to base metal mineralization in bedrock (Pronk, 1987).

The <0.063 mm fraction of till is the most commonly analyzed size fraction for regional geochemical surveys and base metal exploration because 1) it is readily and quickly recovered by sieving, especially in till samples with only minor (<2%) clay; 2) it provides reasonable contrast between background and anomalous metal contents; and 3) it is less susceptible to hydromorphic dispersion effects (Pronk, 1987).

Geochemical analyses of a coarser size fraction of till, such as the -80 mesh fraction (<0.177 mm), is not recommended because this fraction consists mainly of fine sand. The fine-sand component contains abundant quartz and feldspar (Dreimanis and Vagners, 1972; Klassen, 2003) that will dilute metal contents and thus decrease the geochemical indications of a nearby VMS deposit.

Less commonly, a split of the heavy mineral fraction (HMC) (SG >2.9 or >3.3) of till has been geochemically analyzed for base metals (e.g. Garrett, 1971; Gleeson and Cormier, 1971; Smith, 1992) as this has been shown to enhance the contrast between background and anomalous values. Initially, till HMC were pulverized and geochemically analyzed because the commercial ability did not exist to systematically visually examine and identify indicator minerals for VMS and other base metal deposits. Today, if geochemical analysis of the HMC is warranted, it is carried out on a split of the <0.25 mm HMC in order to preserve the coarser fraction (0.25-2.0 mm) for visual examination and identification of VMS indicator minerals.

INDICATOR MINERAL METHODS

Volcanogenic massive sulphide indicator minerals can be visually identified and counted in the sand-sized (0.25-2.0 mm) heavy mineral fraction of till (e.g. Averill, 2001; Budulan et al., 2012; Hicken et al., in press). The main advantage of using indicator minerals in till to explore for VMS deposits is that the indicator mineral grains are visible and can be examined, thus providing 1) physical evidence of the presence of mineralization or alteration; 2) information about the source that traditional geochemical methods cannot, including the nature of the ore, alteration, and proximity to source; 3) sensitivity to detect only a few grains, which is the equivalent of ppb-level indicator mineral abundances, even in regions where regional rocks dilute concentrates with non-indicator heavy minerals; and 4) the ability to visually identify and remove

Table 1. Common indicator minerals of hydrothermal alteration zones associated with metamorphosed VMS deposits in glaciated terrain (modified from Averill, 2001).

Indicator Mineral	Chemical Composition	Specific Gravity	Hardness (Mohs)
Sillimanite	Al_2SiO_5	3.23	6.5-7.5
Kyanite	Al_2SiO_5	3.61	4.0-7.0
Corundum	Al_2O_3	4.05	9
Anthophyllite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$	3.5	5.0-6.0
Orthopyroxene	$(Mg,Fe)_2Si2O_6$	3.4	5.0-6.0
Mg-Spinel	$MgAl_2O_4$	3.64	8
Sapphirine	$(Mg, Al)_8(Al, Si)_6O_{20}$	3.45	7.5
Staurolite	$(Fe,Mg,Zn)_2Al_9(Si,Al)4O_{22}(OH)_2$	3.65-3.77	7.0-7.5
Tourmaline	$(Na,Ca)(Mg,Fe)_3Al_6(BO_3)_3(Si_6O_{18})(OH)_4$	3.06	7.0-7.5
Dumortierite	$Al_7(BO_3)(SiO_4)_3O_3$	3.3-3.4	7.0-8.5
Mn-Epidote	$Ca_2(Al,Fe,Mn)_3Si_3O_{12}(OH)$	3.3-3.6	6.0-7.0
Spessartine	$Mn_3Al_2Si_3O_{12}$	4.15	6.5-7.5
Gahnite	$ZnAl_2O_4$	4.38-4.60	7.5-8.0
Franklinite	$(Zn, Mn,Fe)(Fe,Mn)_2O_4$	5.07-5.22	5.5-6.0
Willemite	Zn_2SiO_4	3.9-4.2	5.5
Cr-Rutile	$(Ti,Cr)O_2$	4.23	6.0-6.5
Barite	$BaSO_4$	3.0-3.5	4.48
Chalcopyrite	$CuFeS_2$	4.1-4.3	3.5
Cinnabar	HgS	8.18	2.0-2.5
Loellingite	$FeAs_2$	7.1-7.5	5.0-5.5
Native Gold	Au	16.0-19.3	2.5-3.0

Figure 2. Photographs of selected VMS indicator minerals as they appear in till heavy mineral concentrates around VMS deposits.

anthropogenic contamination (i.e. material from previous exploration or mining activity).

Indicator minerals characteristic of VMS deposits include sulphide ore minerals (sphalerite, galena, chalcopyrite, pyrite, pyrrhotite) and native gold, as well as more physically robust oxide and silicate minerals indicative of metamorphosed VMS deposits, such as gahnite (Spry and Scott, 1986; Heimann et al., 2005), staurolite, and spessartine (Table 1). Photos of some of these minerals as they appear in a HMC are shown in Figure 2. VMS indicator minerals are recovered from a till sample after processing to concentrate the heavy mineral (SG >3.2) fraction. Some of the common processing methods used to concentrate heavy minerals and recover indicator minerals from till are described and illustrated in McClenaghan (2011). In Canada, the most widely used method to recover VMS indicator minerals from till is a combination of tabling and heavy liquid separation (e.g. McClenaghan, 2011; McClenaghan et al., 2012a,b,c; Plouffe et al., 2013). Methods for collecting large till samples suitable for indicator mineral recovery are summarized in Plouffe et al. (in press), which includes a discussion of suitable sample size for clay-rich or sand-rich tills.

LEAD ISOTOPE ANALYTICAL METHODS

In addition to routine geochemical analysis of till, Pb isotopic analysis of till may also be used to aid in the exploration for VMS deposits. Certain VMS deposits contain Pb (as galena) with an isotopic composition that is distinctly different from that of the surrounding country rocks (Sangster et al., 2000). This difference in compositions allows for isotopic fingerprinting of Pb in the deposits as well as its determination in glacial sediments to identify signatures that may be indicative of VMS mineralization up-ice. Examples of the application of this technique to till samples are reported by Bell and Franklin (1993), Bell and Murton (1995), Simonetti et al. (1996), and Hussein et al. (2003). At the time these results were published, Pb isotopic analyses of the till fine fraction were conducted by thermal ionization mass spectrometry; the application was predicted to be a 'new' approach to mineral exploration for massive sulphide deposits (VMS) in glaciated terrain. Since then, there has been much progress in the application of ICP-MS for Pb isotopic analysis (e.g. Meffre et al., 2008), including the ability to analyze single galena grains from till. The technique is best applied to Pb-rich till samples that display a

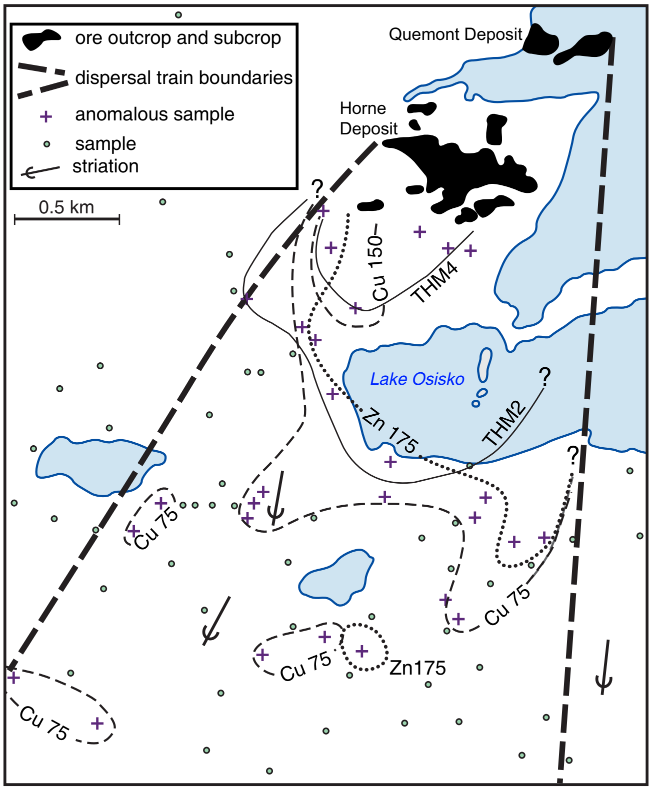

Figure 3. Glacial dispersal train of mineralized clasts and metal-rich till down-ice (south to southwest) of the Horne and Quémont Cu-Zn-Au VMS deposits in Noranda, Quebec in central Abitibi Greenstone Belt (modified from Dreimanis, 1958). THM = total heavy metals.

VMS signature (Cu-Pb-Zn) in areas prospective for VMS mineralization.

EXAMPLES

Noranda Camp, Abitibi Greenstone Belt

The Horne Cu-Au VMS deposit, discovered in 1923 in the central Abitibi Greenstone Belt (AGB), is the namesake for the (former) mining and exploration company. It is the second largest VMS deposit (after Kidd Creek) and one of the largest Au deposits in the AGB. Using extensive surface till sampling and mapping of the locations of mineralized pebbles and cobbles down-ice (south to southwest) of the Horne deposit (Fig. 3), Dreimanis (1958, 1960) demonstrated that the deposit has a well defined glacial dispersal train that extends at least 2400 m down-ice and that till geochemical sampling and analysis (Cu and Zn) is an effective exploration tool. In a second case study carried out at the MacDonald (Gallen) Cu-Zn-Au VMS deposit located 6 km to the northeast of the Horne deposit, Dreimanis (1958, 1960) documented the presence of Cu- and Zn-rich till and clasts up to 900 m down-ice (Fig. 4). In these early studies more than 50 years ago, Dreimanis (1958, 1960) concluded that since Canada is a glaciated landscape, the application of till geochemical and boulder tracing methods, in combination with geophysical and other prospecting methods, would lead to new discoveries of ore deposits.

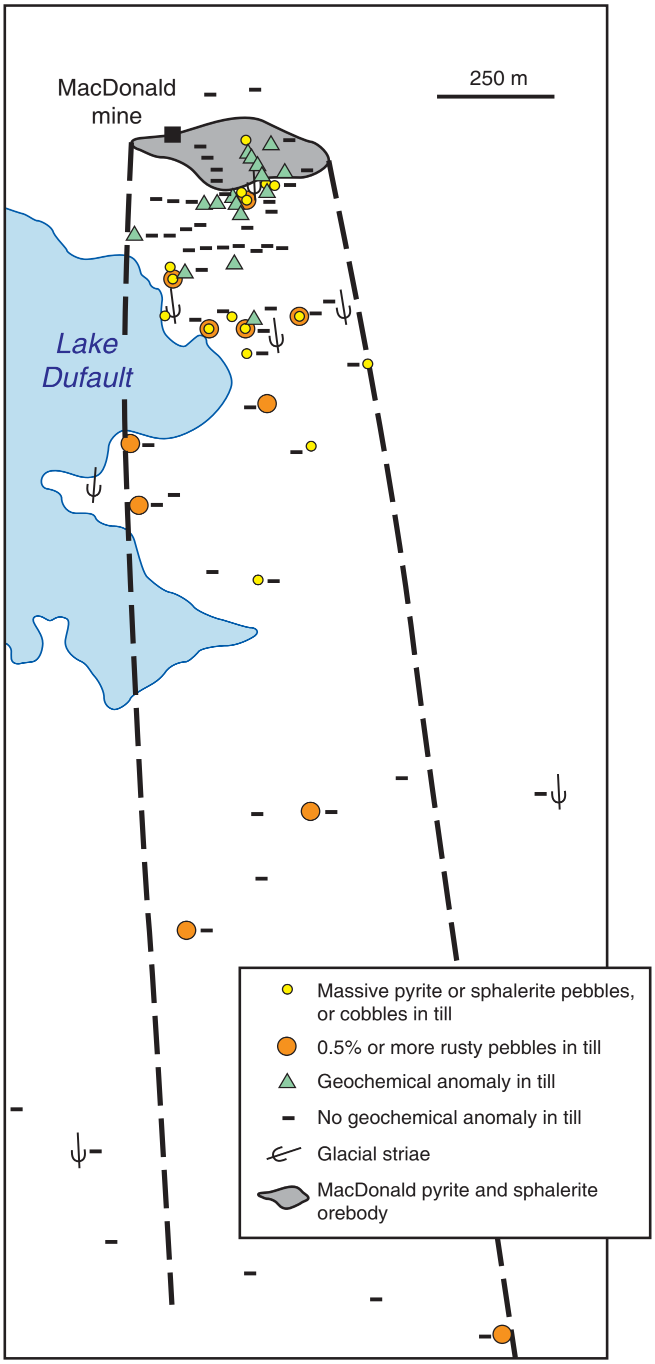

Figure 4. Glacial dispersal train of mineralized clasts and metal-rich till down-ice (south) of the MacDonald Zn-Cu-Ag-Au VMS deposit in the Abitibi Greenstone Belt, Quebec, Canada (modified from Dreimanis, 1958).

Snow Lake Camp, Central Canadian Shield

In the Snow Lake belt 70 km east of Flin Flon, detailed till sampling was used to outline south-southwest-trending glacial dispersal fans defined by Cu and Zn (Fig. 5) in two fractions of C-horizon soil developed on

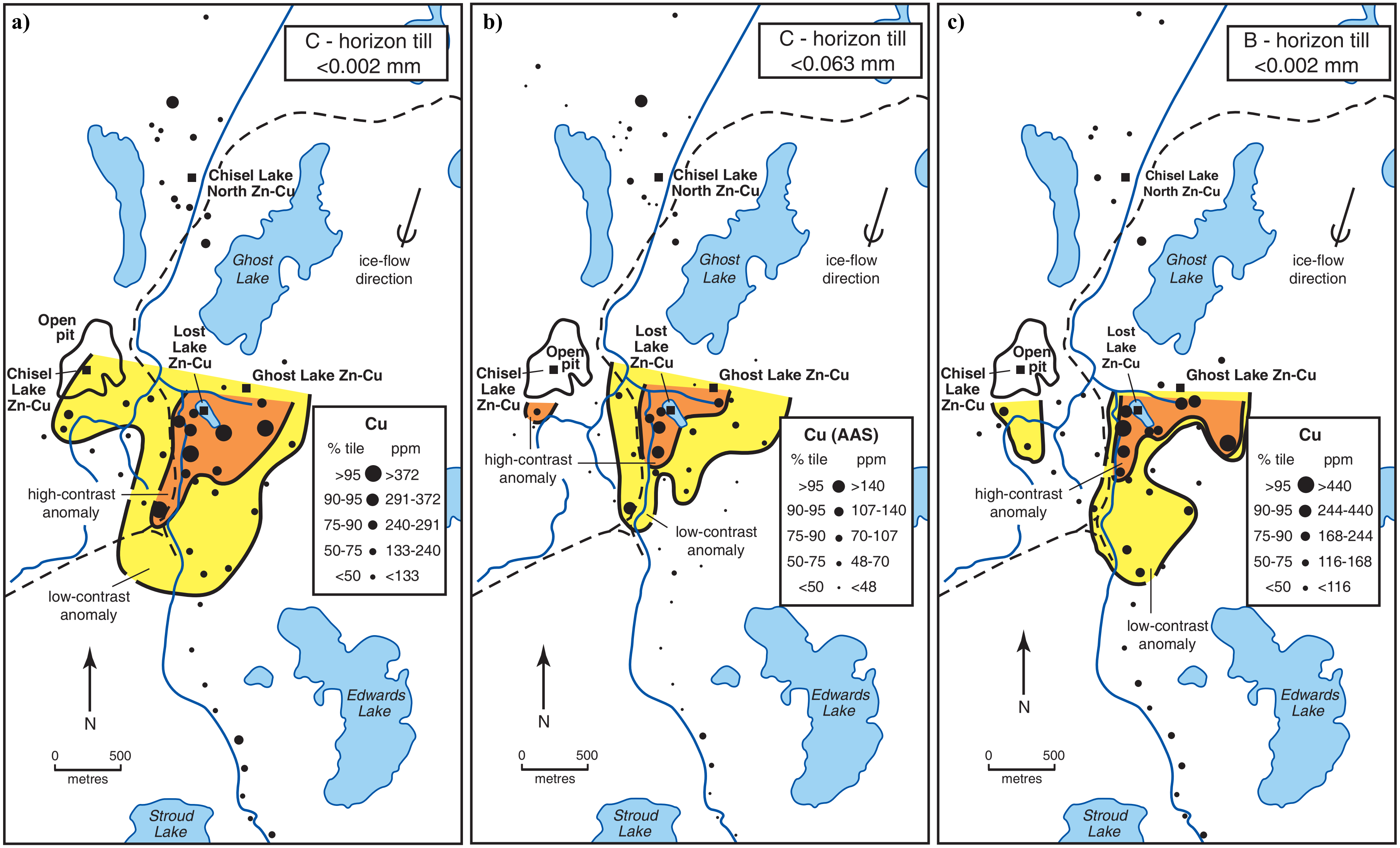

Figure 5. Distribution of Cu (ppm) in surface till around the Chisel Lake, Lost Lake, and Ghost Lake Zn-Cu VMS deposits in the Snow Lake Camp, Manitoba, Canada: **a)** <0.002 mm fraction of C-horizon developed on till; **b)** <0.063 mm fraction of C-horizon developed on till; and **c)** <0.002 mm fraction of B-horizon developed on till (modified from Kaszycki et al., 1996).

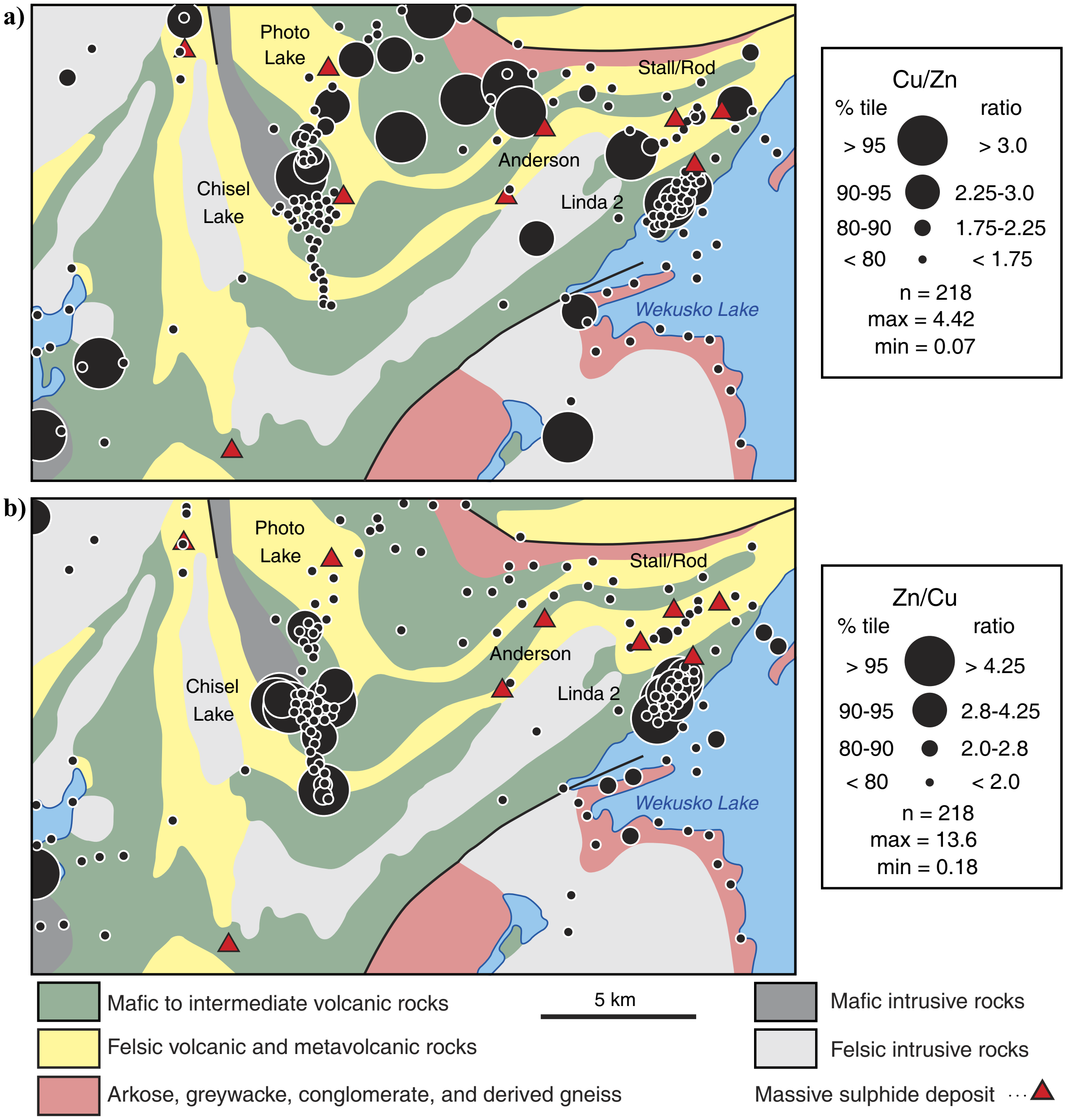

Figure 6. Regional variations in the relative proportions of Cu and Zn in the <0.063 mm fraction of till in the vicinity of past producing deposit in the Chisel Lake area of the Snow Lake greenstone Belt, Manitoba, Canada: **a)** Cu-Zn ratios; and **b)** Zn/Cu ratios (modified from Kaszycki et al., 1996).

till around the Chisel Lake, Lost, and Ghost VMS deposits (Kaszycki et al., 1996). The contrast between background and anomalous Cu and Zn contents is greater in the <0.002 mm fraction of till compared to the <0.063 mm fraction. Glacial dispersal of these metals is detectable up to 1 km down-ice from the deposit. Areas of anomalous metal contents in the B-horizon developed on till are smaller in areal extent, indicating that the B-horizon contains less metals than the C-horizon in this area. Kaszycki et al. (1996) identified a Cu, Hg, Pb, As, Au, and Sb multi-element anomaly in till north of the Chisel Lake deposit, an area that subsequently became known as the Photo Lake VMS deposit. In addition to documenting the multi-element signatures of till down-ice of the VMS deposits, Kaszycki et al. (1996) compared Cu/Zn ratios in till to that of underlying source rocks. They found that high Cu/Zn ratios in till closely match those in underlying felsic rocks that host Cu-rich VMS deposits and that high Zn/Cu ratios in till closely reflect underlying mafic rocks with Zn-rich deposits (Fig. 6).

Adams Lake Area, Cordillera

Deposit-scale till, soil, and vegetation sampling carried out around the Samatosum and Rea Ag-Pb-Zn-Cu VMS deposits, located 80 km north of Kamloops in the

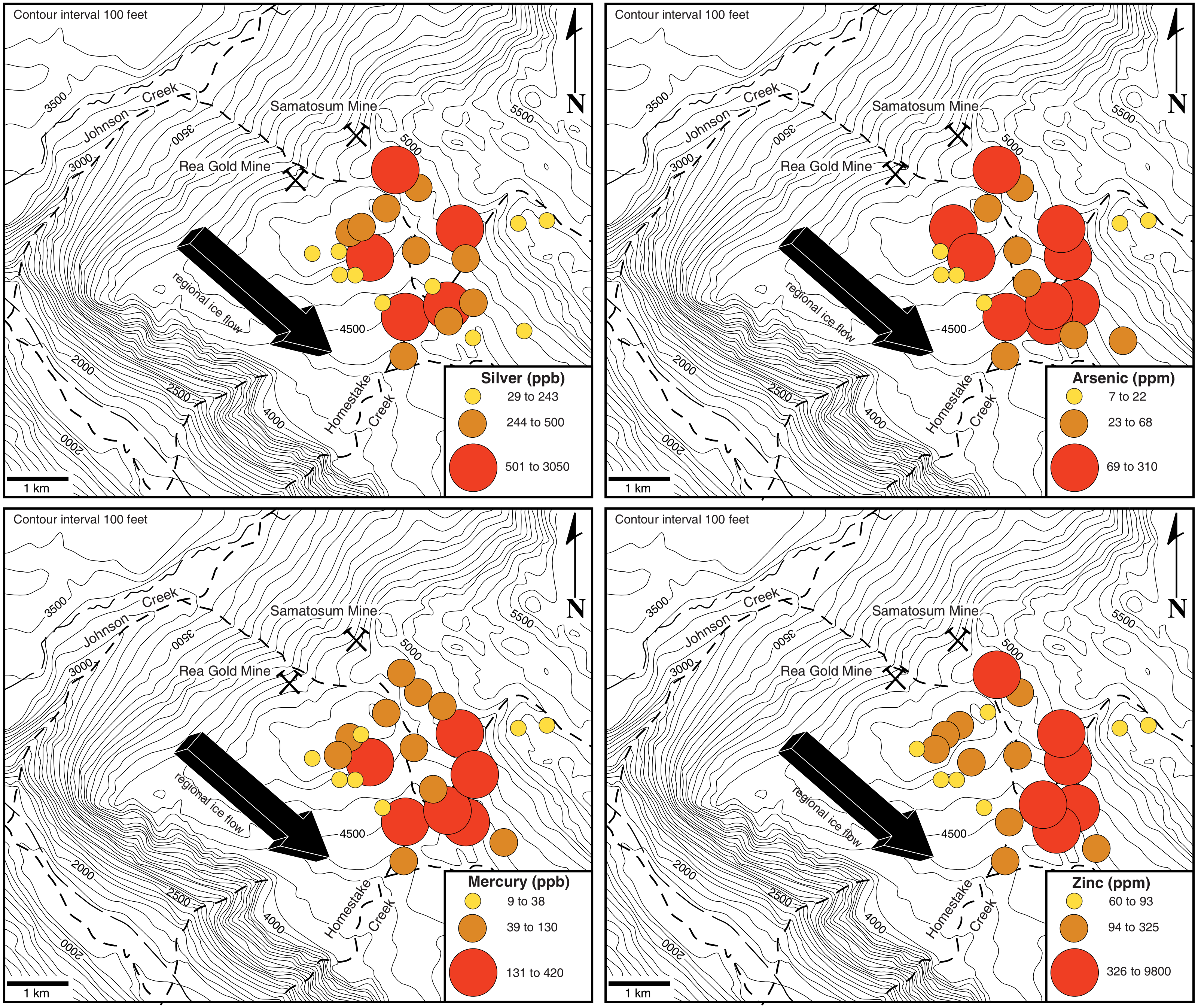

Figure 7. Distribution of Ag, As, Hg, and Zn in the <0.063 mm fraction of till down-ice (southeast) of the Rea Gold and Samatosum VMS deposits, British Columbia, Canada (modified from Paulen, 2001).

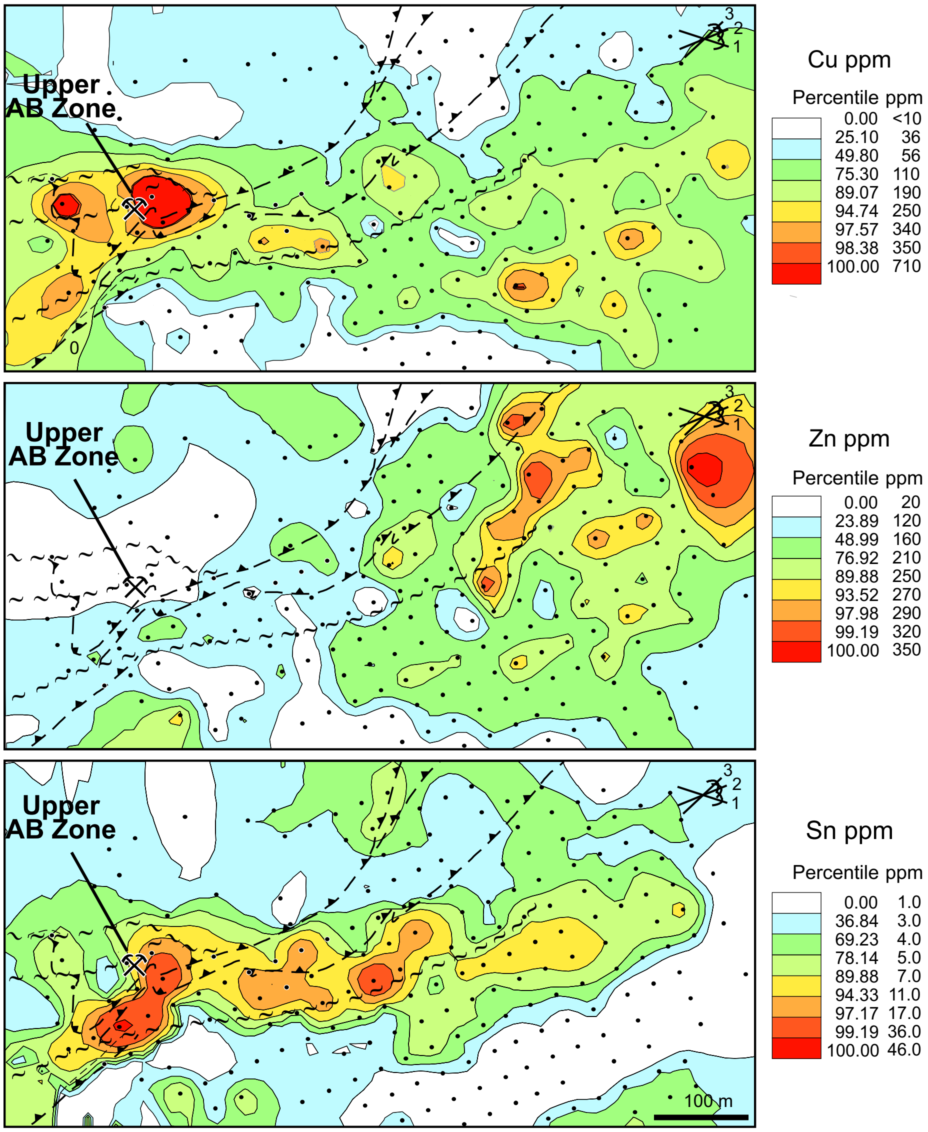

Figure 8. Distribution of Cu, Zn, and Sn in the <0.063 mm fraction of till around the Halfmile Lake VMS deposit, Bathurst Mining Camp, New Brunswick, Canada, showing a well developed west-northwest-trending glacial dispersal train (modified from Parkhill and Doiron, 2003).

Adams Lake area of south-central British Columbia, has been reported by Lett et al. (1998), Paulen (2001), and Lett (2001). These relatively small (each <1 Mt) deposits occur in highly deformed and metamorphosed mafic volcanic and argillaceous sedimentary rocks of the Eagle Bay Assemblage (Bailey et al., 2000). Till and B-horizon soil developed on till around and down-ice of the deposits have elevated Pb, Ag, As, Hg (Fig.7), Sb, Au, and Zn contents in the <0.063 mm fraction of surface till (Lett, 2001; Paulen, 2001). Maximum metal contents of till occur 1.8 km down-ice (southeast); however, the surface till anomalies can be traced up to 10 km down-ice (Bobrowksy et al., 1997).

Halfmile Lake Volcanogenic Massive Sulphide Deposit, Appalachians

The Halfmile Lake Zn-Pb-Cu VMS deposit, in the westernmost part of the Bathurst Mining Camp in northern New Brunswick was discovered in 1952 using soil geochemical and geophysical surveys (Adair, 1992; Parkhill and Doiron, 2003). The deposit is capped by a preglacial massive sulphide gossan that is enriched in Pb, Cu, In, Au, Ag, Sn, As, Sb, Bi, and Se (Boyle, 2003). A well developed ribbon-shaped glacial dispersal train (Fig. 8), extending at least 1 km down-ice (east-northeast to east-southeast), is best defined by Cu, Pb, In, Ag, As, Au, Sb, Bi, Hg, Sb, Se, and Sn in the <0.063 mm till fraction (Parkhill and Doiron, 2003; Budulan et al., 2012). Although Zn is the most abundant base metal in the deposit, it is not a pathfinder element in till immediately down-ice. The low Zn contents in till down-ice are likely due Pb depletion of the gossan cap (Parkhill and Doiron, 2003). Both of these studies of till dispersal around the Halfmile Lake deposit demonstrate the broad multi-element signature of this VMS deposit. Indicator minerals of the VMS sulphide mineralization include chalcopyrite, galena, sphalerite, pyrite, pyrrhotite, and goethite. Indicator minerals of the preglacial gossan cap include gold, beudanite ($PbFe^{3+}3(AsO_4)(SO_4)(OH)$), jarosite ($KFe^{3+}3(SO_4)$

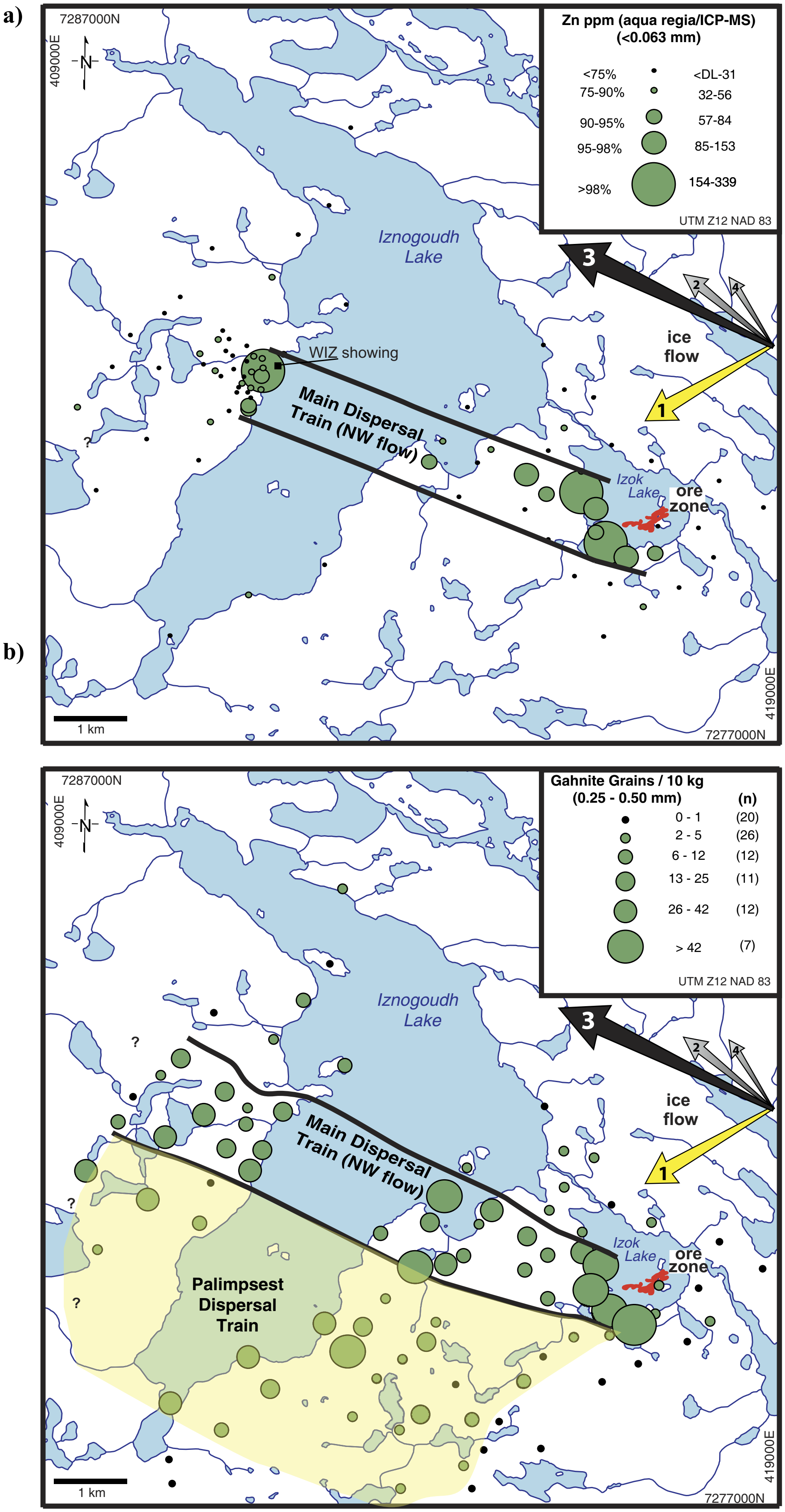

Figure 9. Distribution of **a)** Zn (aqua regia/ICP-MS) in the <0.063 mm fraction of till; and **b)** gahnite in the 0.25-0.5 mm non-ferromagnetic heavy mineral fraction of till around the Izok Lake VMS deposit, Nunavut, Canada, showing a well developed north-west trending glacial dispersal train outlined by thick black lines and older palimpsest dispersal train (shaded yellow) formed by southwest ice flow and subsequent northwest ice flow. Ice flow directions and their relative ages (1= oldest) are shown in bottom right corner. (Modified from Hicken et al. 2012, in press).

$2(OH)_6$), and goethite. Chalcopyrite and gold are the most useful indicator minerals as they survive glacial transport and post-glacial weathering of till. This case study is one of the first reports of recovery of jarosite and beudantite in till.

Izok Lake VMS Deposit (Arctic)

The Izok Lake Zn-Cu-Pb-Ag VMS deposit, 360 km north of Yellowknife, is one of the largest undeveloped Zn-Cu resources in North America (Morrison, 2004). The deposit was discovered by following up mineralized boulders found along the west shore of Izok Lake in the 1970s. Hicken et al. (2012) documented elevated Zn, Cu, Pb, Ag, Cd, and Bi and to a lesser extent Sb, Hg, Se, In, and Tl contents in the <0.063 mm fraction of till overlying the deposit and up to 6 km down-ice (northwest) from the deposit (Fig. 9a). Gahnite is the most useful indicator of glacial dispersal from this deposit (Hicken et al., in press) because it is abundant in the deposit and till down ice, sufficiently dense (SG 4-4.6), and is a physically robust mineral. It is easy to visually identify in heavy mineral concentrates due to its distinct blue-green colour. Till immediately down-ice of the deposit contains 1000s grains/10 kg and gahnite was found at least 40 km down ice (Fig. 9b). Sulphide minerals chalcopyrite, sphalerite, galena, loellingite, and pyrite are also useful indicators of the deposit.

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EXPLORING FOR LEAD AND ZINC USING INDICATOR MINERALS WITH STREAM SILT AND WATER GEOCHEMISTRY IN THE CANADIAN ARCTIC ISLANDS: AN EXAMPLE FROM VICTORIA ISLAND, NORTHWEST TERRITORIES

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INTRODUCTION

Companies and individuals exploring for minerals in the Arctic undertake considerable financial risk. By providing regional bedrock and surficial maps, and geophysical and geochemical data, the federal government lessens the risk. New methods of exploration have been developed, traditional methods have been adapted to take advantage of technological advances such as portable XRF analyzers, and on-site computing power with internet connections have become integral parts of exploration camps. Nevertheless, the remote locations, large areas that need to be covered, weather conditions, and the cost of fixed-wing and helicopter support, as well as ongoing land claim issues, lead to uncertainty and well founded reluctance on the part of smaller companies to take the risk. Given the potential for economic mineralization in the Arctic Islands however, good planning, experienced personnel, and support services, combined with up-to-date regional data, can offset some of the financial risk.

Regional geochemical surveys carried out by the Geological Survey of Canada (GSC), or by provincial/territorial partners following GSC specifications, did not routinely sample in areas underlain by Palaeozoic carbonate rocks, mainly because the Canadian Shield and Canadian Cordillera were seen as areas with both higher overall mineral potential and lower recovery costs but also because the elevated pH values of surface waters reduce the mobility of many metals of economic interest. With the advent of relatively inexpensive multi-element inductively coupled plasma mass spectrometry (ICP-MS), current detection limits for methods of geochemical analyses are up to two orders of magnitude better than were previously available. Along with these improved data and a better understanding of the processes controlling the geochemical distribution of elements, surveys have been extended into areas formerly avoided.

Great Northern Mining and Exploration (GNME) carried out extensive exploration for Cu-Ni-PGE mineralization as well as diamondiferous kimberlite within the Minto Inlier between 2005 and 2008 (Montjoie and Solic, 2008). In addition to a drilling program, several hundred stream sediment samples and several thousand till and soil samples were collected for geochemical analysis and indicator mineral identification. Geophysical surveys, petrographic studies, and detailed surficial and bedrock mapping were also carried out (GNME, 2009). GNME provided the GSC with all of the information and data acquired during their exploration program on Victoria Island. A regional stream sediment and water geochemical survey, of selected areas north and east of the Minto Inlet on northwest Victoria Island (Fig. 1), was completed over two field seasons by the GSC in 2011. This activity was carried out as part of the Victoria Island Project funded under the Geo-Mapping for Energy and Minerals Program.

POTENTIAL FOR Pb-Zn MINERALIZATION

The regional geology of northwestern Victoria Island is favourable for the formation of Pb-Zn mineralization. Potential host rocks include platform carbonate deposits of the early Neoproterozoic Shaler Supergroup (Thorsteinsson and Tozer, 1962) and unconformably overlying lower Paleozoic rocks, including a thick succession of Ordovician carbonate rocks (Rainbird et al., 1996). Regional mapping and an airborne EM survey by the GSC identified an extensive network of east-northeast-striking faults that cut these rocks and appear to have been reactivated (Kiss and Oneschuk, 2010). Dolomitization adjacent to some of these faults indicates focussed hydrothermal activity. Fluid inclusion studies currently underway will assess the nature and composition of these fluids (E. Turner, pers. comm., 2012). Host rocks also include organic-rich strata (potential reductants for metal-rich fluids) and sulphates, which could be reduced to generate sulphide (Leach et al., 2010). Additional support for potential Pb-Zn mineralization on Victoria Island is based on comparisons with established former mining camps, including Polaris, Pine Point, and Nanisivik, as well more recent Pb and S isotope data from Bathurst Island and Pine Point.

SURVEY DESIGN

The goal of the 2010-2011 geochemical survey was to obtain a surficial geochemical profile covering the maximum area possible for resource assessment of a previously unexplored region. Strict limits were

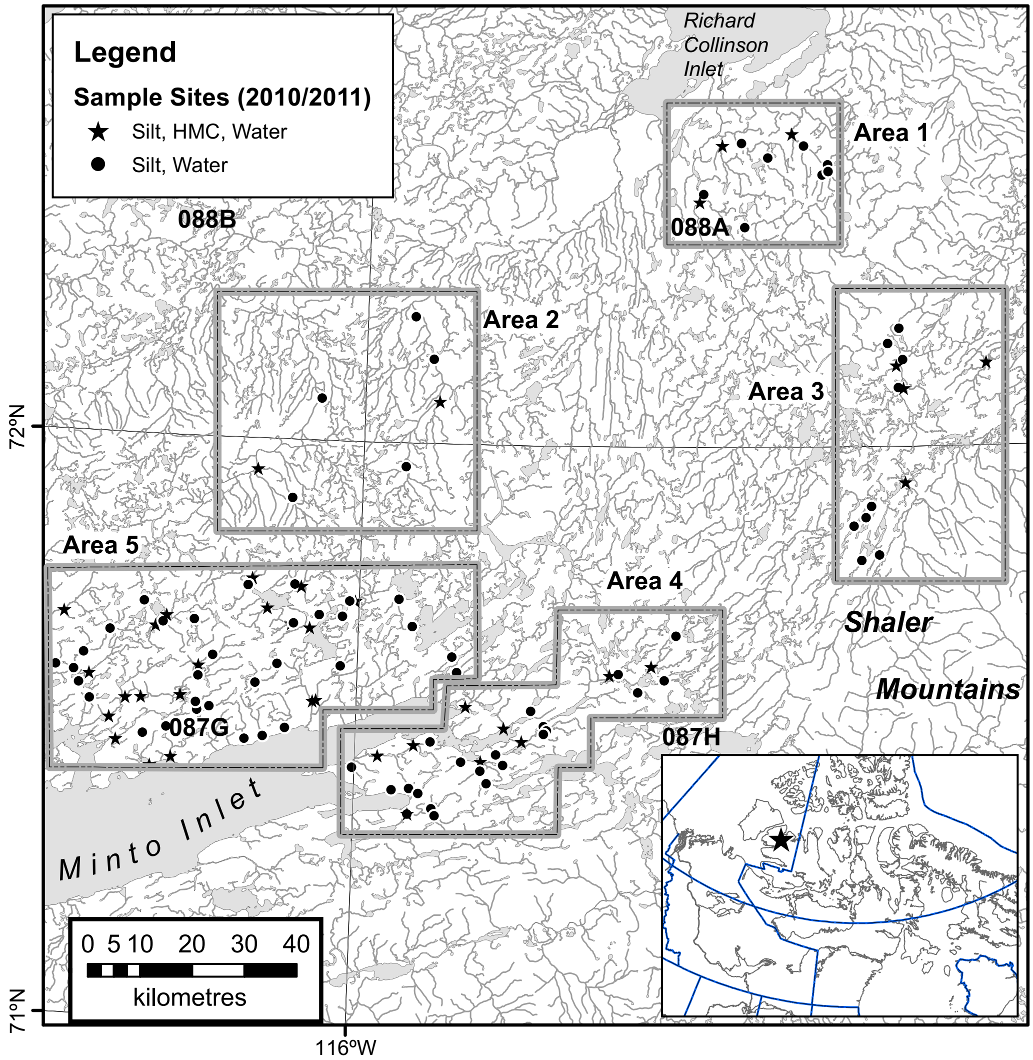

Figure 1. Location of sample sites on Victoria Island, NT: sample sites are grouped based on relationships to underlying and adjacent geology.

imposed by time, human resources, helicopter access, and money. A lake sediment and water survey was proposed, however the difficulty of obtaining a helicopter on floats led to the decision to carry out a stream sediment and water survey with heavy mineral collection. This turned out to be a fortunate choice, as most of the lakes had retained ice cover at the beginning of July 2010, when the geochemical survey began.

Survey costs were based on the time required to collect samples, the distance between sites, and the hourly rate for helicopters. The cost of shipping, sample preparation, and analysis are known. High priority areas were selected based on GNME soil, till, and stream geochemistry, geophysical data, including aeromagnetic data, and previous GSC maps and reports for Victoria Island. Drainage basins in these areas were defined by hand. Sites were selected in advance, although the actual location depended on local conditions, such as site access, availability of sampling material, and proximity to wildlife.

METHODS

Stream silts and waters were collected at 121 sites. Bulk sediment samples (10 to 12 kg screened; <2 mm) for mineralogical analysis were also collected at 37 of these sites. Mineralogical data, field observations, and concentrations of 53 elements in stream silts by a partial method of analysis (aqua regia digestion), 35 elements in stream silts by a total method (Instrumental Neutron Activation), and 62 elements in waters were released in GSC Open File 7198 (McCurdy et al., 2012).

RESULTS

Sampling was concentrated in two areas draining Shaler Supergroup sedimentary rocks into Minto Inlet, but samples were collected from three other areas representing different geological settings (Fig. 1).

1. Area 1, south of the Richard Collinson Inlet, is underlain by undifferentiated Cambrian and Ordovician sedimentary rocks. Evidence of a

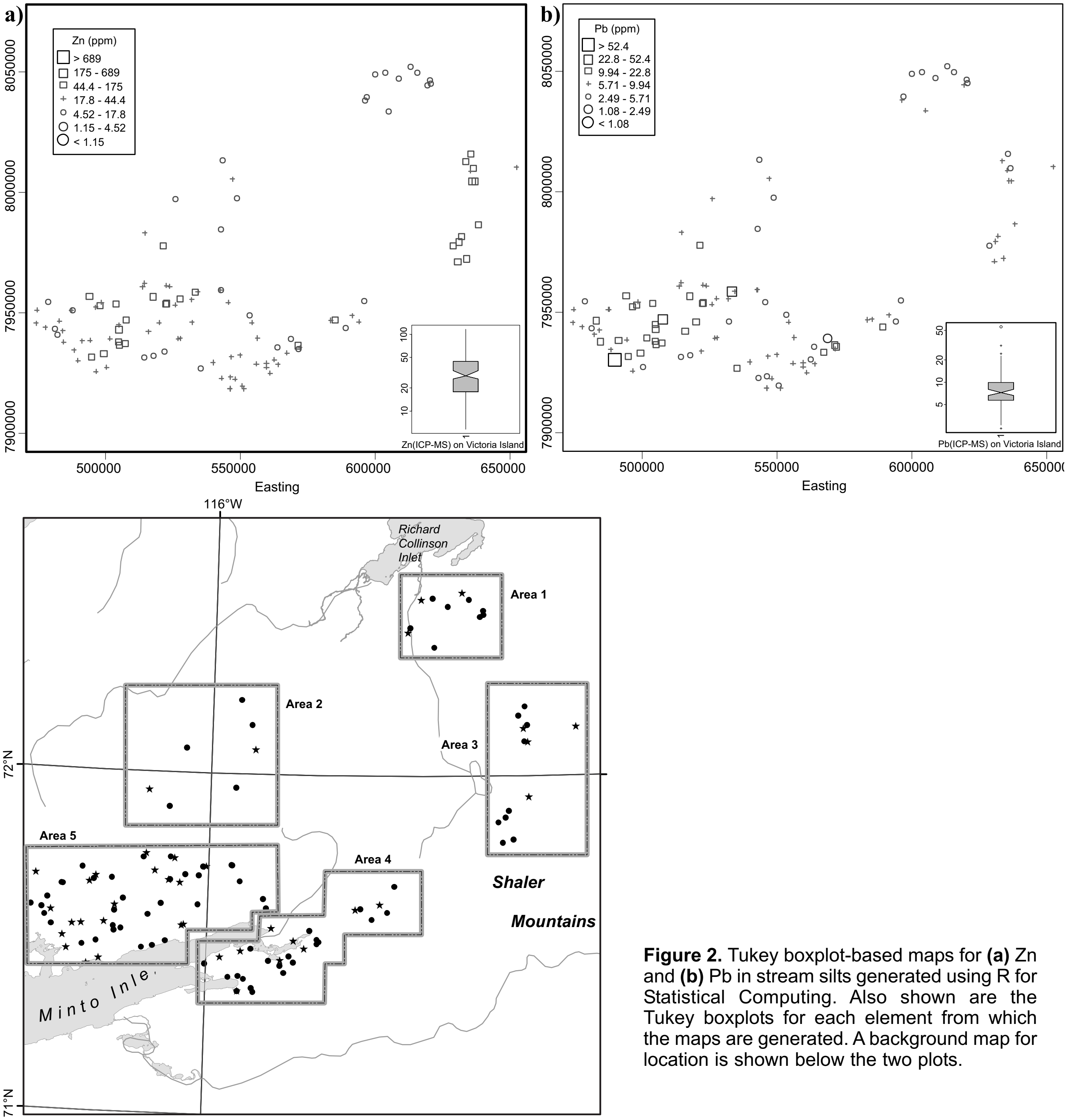

Figure 2. Tukey boxplot-based maps for **(a)** Zn and **(b)** Pb in stream silts generated using R for Statistical Computing. Also shown are the Tukey boxplots for each element from which the maps are generated. A background map for location is shown below the two plots.

meteor impact was recovered by geologists doing field working in the area.

2. A number of samples were collected in Area 2 north of the Minto Inlet, over undifferentiated Cambrian and Ordovician sedimentary rocks (limestone, dolostone, sandstone).
3. Area 3 covers NTS map sheets 87H and 88A northwest of the Shaler Mountains. Streams drain Natkusiak Formation basalt and gabbro and Shaler Supergroup sedimentary rocks, and incorporate material from tills derived from these sources.
4. Area 4 samples were collected over Wynniatt Formation dolostone of the Shaler Supergroup, east and south of Minto Inlet.
5. Sampling was concentrated in Area 5, over Reynolds Point Group dolomitized clastic rocks of Shaler Supergroup, north of Minto Inlet.

Stream Silt Geochemistry

Simple maps where the data are represented at their spatial locations by symbols using Tukey boxplot-based symbology were used to evaluate Pb (Fig. 2a)

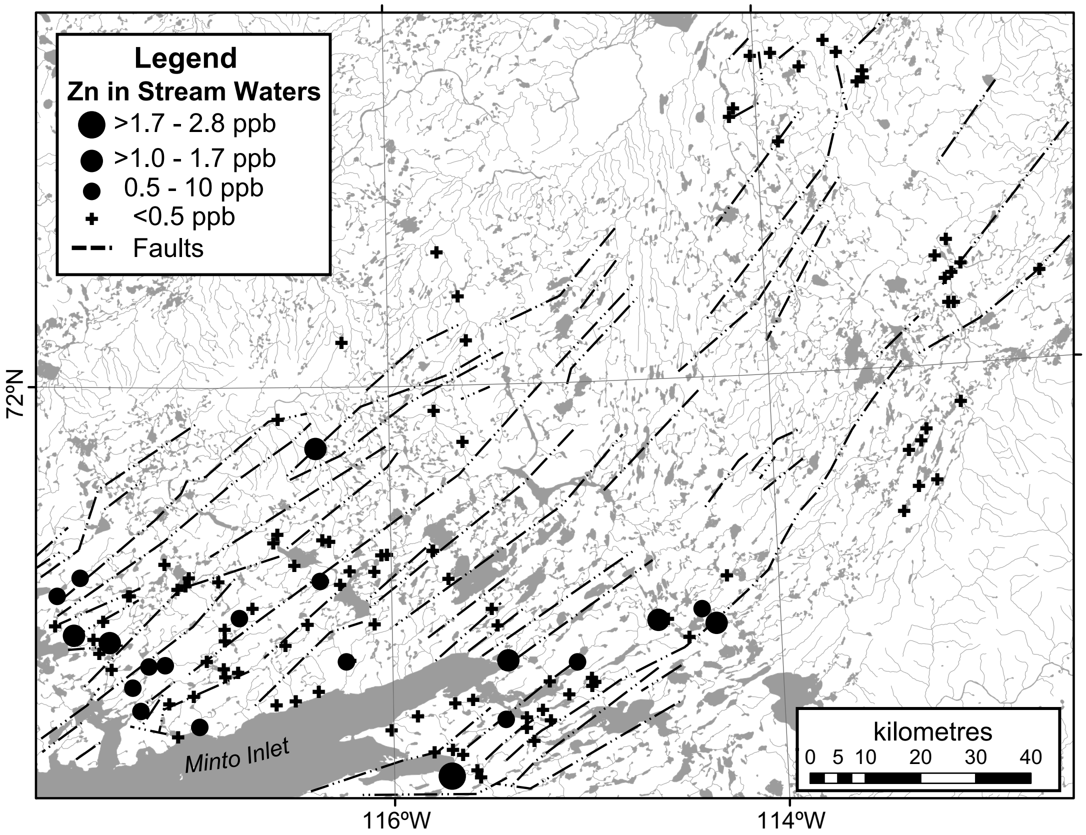

Figure 3. Graduated symbol plot for Zn concentrations in stream waters.

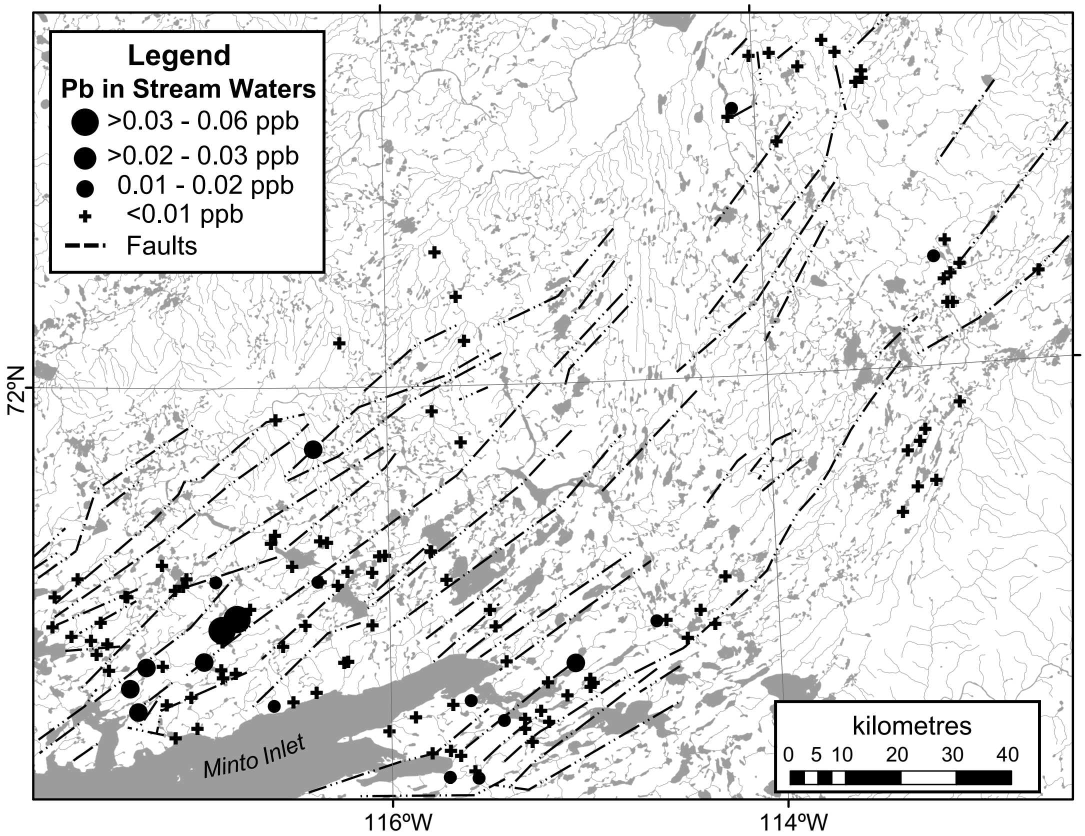

Figure 4. Graduated symbol plot for Pb concentrations in stream waters.

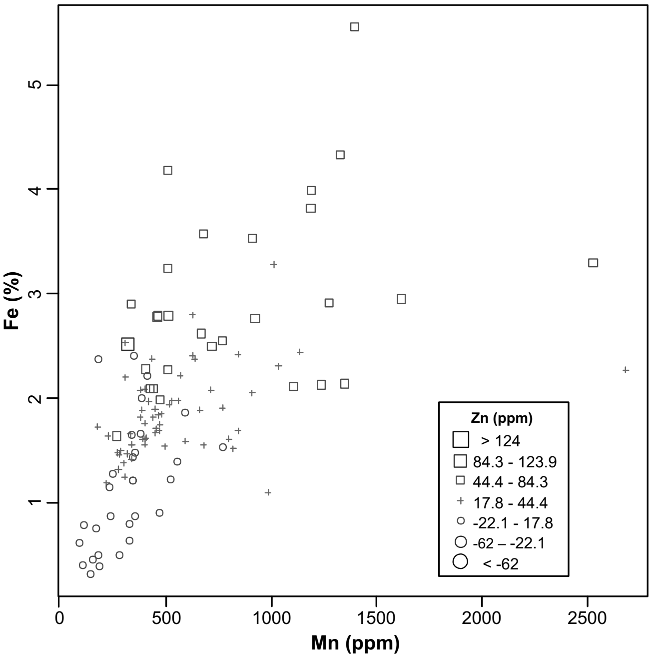

Figure 5. Exploratory Data Analysis (EDA) plot of Mn (ppm) versus Fe (%) with Tukey boxplot-based symbols for Zn (ppm) in stream silts.

and Zn (Fig. 2b) concentrations in silt (Garrett, 2013). Because geochemical data typically have a right-skewed distribution (Reimann et al., 2008), data were log-transformed. Zn values in the upper range of the distribution are evident in Areas 3 and 5 (Fig. 2a). Pb values above the middle 50% of the data distribution are concentrated in Area 5, and to a lesser extent, in Area 4 (Fig. 2b).

Stream Water Geochemistry

Most (83%) Zn values returned for water samples were below the detection limit of 0.5 ppb and were thus not suitable for advanced statistical analysis. However, a simple plot of graduated symbols was sufficient to illustrate that elevated concentrations are present in stream waters north of Minto Inlet (Area 5), with a few values above detection limit appearing in Area 4, east of Minto Inlet (Fig. 3).

A majority of the values (85%) returned for concentrations of Pb in stream waters were below the detection limit of 0.01 ppb, and were thus not suited for advanced statistical analysis. A plot of values using graduated symbols indicates that Pb values above detection are confined to two adjacent drainage basins north of the Minto Inlet (Fig. 4).

Indicator Minerals

Sphalerite and galena were identified in stream sediments in Areas 4 and 5 (Fig. 5). Although 29 grains of sphalerite were identified in one sample, in most cases only 1 or 2 grains were recovered from 8 of 37 samples of bulk sediment. Galena was identified in 6 samples, from which one, located at the far northwest corner of Area 5, yielded 7 grains. No galena was noted in samples from Area 4.

Discussion

Concentrations of Pb and Zn in the silts <177 µm (-80 mesh) fraction of stream sediment digested in aqua regia and analyzed by ICP-ES/MS techniques were represented at their spatial locations using symbols to represent ranges of data divided by Tukey boxplot-based computation following a logarithmic transformation of the data. The seven groups outline areas of relatively high concentrations, median, and low concentrations of the two elements in stream sediment. These simple plots, however, do not provide any obvious clues to the transport mechanisms or chemical processes affecting the patterns of distribution.

Both Zn and Pb are relatively soluble in surface waters in acid environments, with solubility decreasing with increasing pH (Drever, 1997). The mean pH value of Victoria Island stream waters sampled for this study is 8.14, and thus an overall reduction in the mobility of Zn and Pb in this environment could reasonably be expected. Adsorption by Fe-Mn hydroxides is another factor controlling the distribution of many metals, including Zn and Pb, in the surface environment. This can be demonstrated to be a controlling factor on Victoria Island by plotting Zn as a third variable using Tukey boxplot-based symbology against Fe and Mn (Fig. 5). Elevated values of Zn are clearly related to increasing Fe and Mn in this plot. Most of the elevated Fe+Mn points on the plot are derived from Area 3 (Fig. 1), from sediments in streams draining from Natkusiak Formation volcanic rocks. Field observations from these sites record black staining on rocks in the streams, usually associated with Mn-Fe precipitation.

Patterns of distribution of Zn and Pb in stream waters are relatively restricted compared with the distribution in stream sediments, suggesting that these elements are precipitating rapidly as carbonate, oxide, and hydroxide minerals from surface waters with pH values >8. Zn is more widely distributed than Pb, reflecting the mobility of Zn in the surficial environment (Drever, 1997).

In contrast with the geochemical distribution of Pb and Zn described above, controlled mainly by chemical processes, indicator minerals are dispersed by mechanical processes of erosion and transport by ice and water. Multiple cycles of reworking and mixing can follow the initial winnowing from source (Thorleifson, 2009). Sphalerite and galena, characteristic of MVT-style deposits (Paradis et al., 2007), were recovered from stream sediments draining Areas 4 and 5 (Fig. 1).

Direction of ice flow in this part of Victoria Island was to the northwest (Prest et al., 1968; Dyke et al., 2003). Despite the possibility of transport across considerable distances, the recovery of sphalerite and galena grains was restricted to Areas 4 and 5 (Fig. 1). Given the fragile nature of sphalerite (Plouffe et al., 2007) and especially galena (hardness 2.5-2.75), transport distance was likely relatively short. The coincidence of elevated Zn and Pb values in stream sediments and waters, with sphalerite and galena identified in the same drainage basins, points to a yet unidentified source of Pb-Zn mineralization.

CONCLUSIONS

The geochemistry of stream silts and waters is consistent with a local source of Pb and Zn in dolomitized Shaler Supergroup rocks on Victoria Island north of Minto Inlet. Sphalerite and galena identified in stream sediments proximal to elevated Pb and Zn concentrations in both stream sediments and waters support the presence of Pb-Zn mineralization. Regional geology and the identification of a series of east-northeast-striking faults in the areas where Pb and Zn are elevated suggest good potential for MVT-style mineralization in Shaler Supergroup rocks north of Minto Inlet.

ACKNOWLEDGEMENTS

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IRON OXIDES: INDICATOR MINERALS FOR EXPLORATION

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INTRODUCTION

The iron oxides (magnetite and hematite) form major to accessory minerals in a range of mineral deposits and rocks. Iron oxides incorporate a large suite of minor and trace elements in their crystalline structure as a function of the conditions during crystallization. This variation in mineral composition is used to fingerprint a range of magmatic, hydrothermal, and sedimentary mineral deposit types. Because iron oxides are resistant to mechanical abrasion and chemical alteration during transport and burial in sediments, and because they can be easily separated in ferro/paramagnetic fractions of heavy mineral concentrate, they constitute a useful indicator mineral for exploration.

ANALYTICAL METHODS AND SAMPLE PREPARATION

The database of magnetite and hematite mineral chemistry is based on study of more than 120 mineral deposits ascribed to 13 magmatic, hydrothermal, and sedimentary mineral deposit types. The deposits selected for the database offer a cross section of the range of deposits through geological history, including a significant number of large and well characterized deposits. For each deposit, one to more than 10 polished sections were studied from which at least 3 to 4 grains were analyzed using Electron Probe Micro-Analyzer (EPMA; Dupuis and Beaudoin, 2011) and Laser Ablation Inductively Coupled Plasma Mass Spectrometry (LA-ICP-MS; Dare et al., 2012). EPMA analyses have detection limits to 10s of ppm for small areas (beam diameter of 10 µm), which make it possible to avoid small inclusions in the target mineral. LA-ICP-MS analyses have detection limits to ppb levels, but the investigated volume is larger; typically a linear trench is ablated with an 20-80 µm-diameter laser beam. The larger area required for LA-ICP-MS limits analyses to larger grains that are devoid of abundant inclusions. However, an advantage of larger beam size of LA-ICP-MS is that small exsolutions formed by sub-solidus processes are incorporated in the mineral analyses, which facilitates measuring the original composition of the grain before sub-solidus exsolution. Dare et al. (2012) showed that both methods produce highly correlated analytical results down to the detection limit of the EPMA method.

CHEMISTRY OF IRON OXIDES IN MINERAL DEPOSITS

Dupuis and Beaudoin (2011) constructed a series of discriminant diagrams to distinguish several types of mineral deposits. The diagrams use the average composition of a deposit in order to define the characteristic composition of iron oxides in a deposit type using a step-wise analysis of the data. Dupuis and Beaudoin (2011) demonstrated that Ni-Cu-PGE deposits can be separated from all other deposit types using the Ni+Cr versus Si+Mg diagram (Fig. 1). Additional work using Ni-Cu deposits with a large range of ages, magma types, and geological environments, including most major Ni-Cu deposits worldwide, has confirmed the efficiency of the Ni+Cr versus Si+Mg discriminant diagram (Boutroy et al., 2012).

A study of Ni-Cu deposits from the Sudbury district showed that the composition of magnetite evolved during the fractional crystallization of the sulphide liquid into the early Fe-rich monosulphide solid solution (MSS) cumulate and the residual Cu-rich intermediate solid solution (ISS; Dare et al., 2012). Lithophile elements were found to be compatible and enriched in the MSS magnetite, such that the magnetite became depleted in lithophile elements in the later-forming ISS (Fig. 2). This pattern is found in Ni-Cu deposits worldwide (Boutroy et al., 2012). The efficiency of the Ni+Cr versus Si+Mg diagram is in part a consequence of the contrasting behaviour of lithophile Cr and chal-

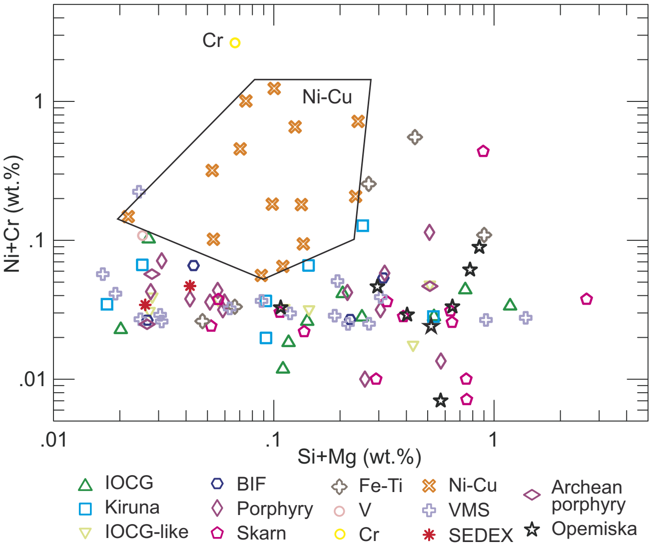

Figure 1. Ni+Cr versus Si+Mg discriminant diagram for Ni-Cu-PGE deposits (modified from Dupuis and Beaudoin, 2011).

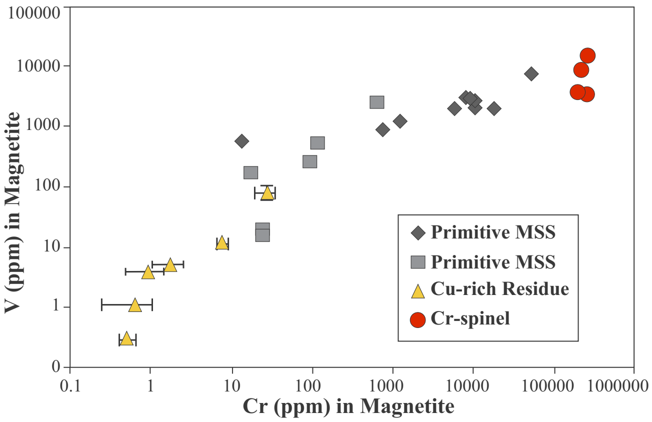

Figure 2. Covariation of lithophile elements in magnetite in the sulphide liquid during fractional crystallization from monosulphide solid solution to intermediate solid solution and chrome spinel (Cr-spinel) crystallized from the mafic magma in Sudbury (modified from Dare et al., 2012).

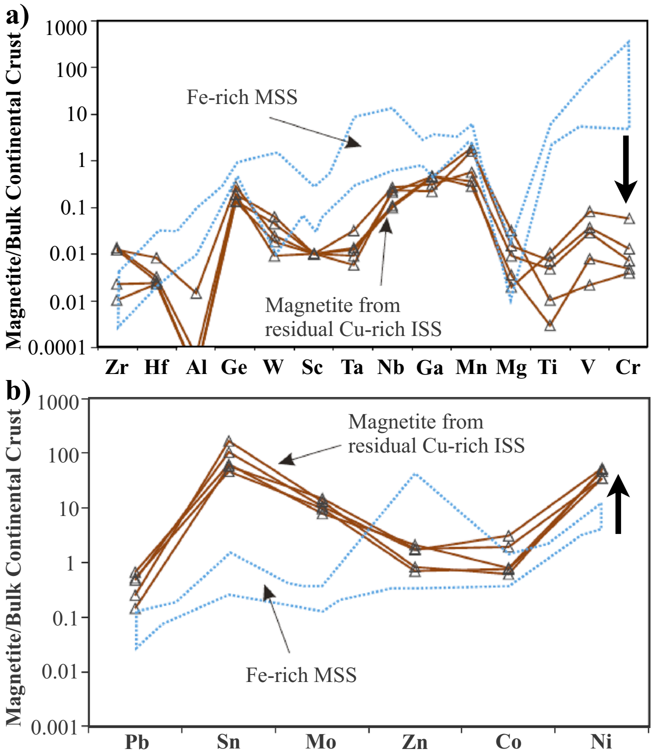

Figure 3. Spider diagrams of **(a)** lithophile and **(b)** chalcophile elements in monosulphide solid solutions (MSS) and intermediate solid solutions (ISS), normalized to bulk continental crust (Rudnick and Gao, 2003). Arrows shows depletion of lithophile Cr (a), and enrichment of Ni (b) during fractional crystallization of the sulphide liquid from MSS to ISS (modified from Dare et al., 2012).

cophile Ni. Spider diagrams of lithophile elements (Fig. 3a) and chalcophile elements (Fig. 3b) show that most lithophile elements, such as Cr, that are enriched in the MSS magnetite become depleted in the residual sulphide melt forming ISS magnetite (Fig. 3a; Dare et al., 2012). In contrast, chalcophile elements, such as Ni, partition preferentially in the MSS depleting the coeval magnetite, whereas the late-forming magnetite in the ISS preferentially incorporates Ni in absence of abundant Fe-sulphides (Fig. 3b; Dare et al., 2012). Boutroy et al. (2012) also showed that secondary magnetite in veins in massive sulphide bodies and disseminated in host rocks has a composition that is different from that of primary magmatic magnetite, and plot outside the field typical for Ni-Cu-PGE deposits (Fig. 1).

The second step of data analysis is to test for iron oxides typical of Cu-Zn volcanogenic massive sulphide (VMS) and Zn-Pb sedimentary exhalative (SEDEX) deposits using the Cu/(Si+Ca) versus Al/(Zn+Ca) diagram (Fig. 4; Dupuis and Beaudoin, 2011). Magnetite in VMS and SEDEX deposits is typically a product of hydrothermal or metamorphic oxidation and replacement of the massive sulphides lens (Galley et al., 2000). In VMS deposits, magnetite is enriched in Si, Zn, and Ca, and depleted in Al, compared to other deposit types.

The last step of data analyses is to plot iron oxide compositions in a Ti+V versus Ni/(Cr+Mn) diagram (Fig. 5) in order to classify whether the compositions are typical of Fe-Ti-V, Kiruna Fe-P, Cu-Mo-Au porphyry, iron oxide-copper-gold (IOCG), Superior-type banded iron formation (BIF), and skarn deposit types (Dupuis and Beaudoin, 2011). In this diagram, magmatic Fe-Ti-V deposits plot at high Ti+V values, whereas magmatic-hydrothermal and sedimentary deposits are characterized by lower Ti+V values (Fig.

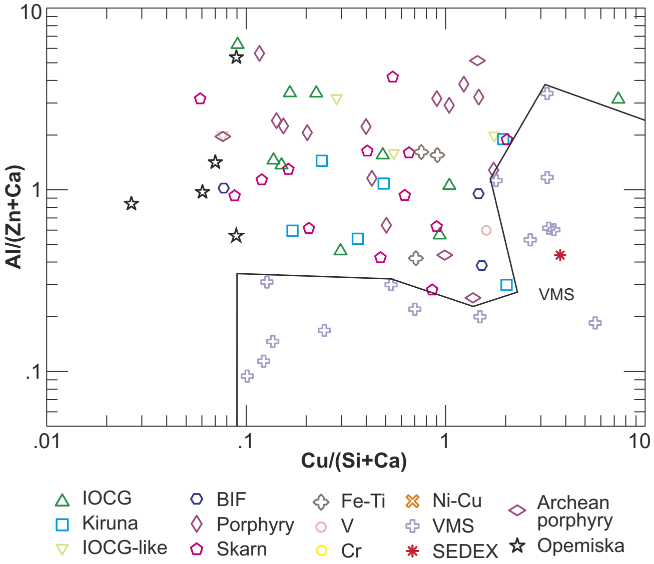

Figure 4. The Cu/(Si+Ca) versus Al/(Zn+Ca) discriminant diagram for Cu-Zn volcanogenic massive sulphide and Zn-Pb sedimentary exhalative deposits (modified from Dupuis and Beaudoin, 2011). Note that deposits whose average compositions plot in the field for Ni-Cu deposits (Fig. 1) are not shown on this diagram.

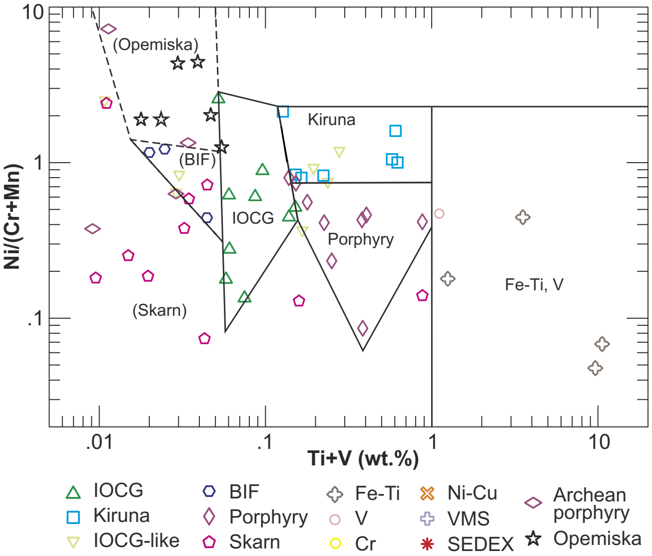

Figure 5. The Ti+V versus Ni/(Cr+Mn) discriminant diagram for Fe-Ti-V, Kiruna Fe-P, Cu-Mo-Au porphyry, iron oxide-copper-gold (IOCG), Superior-type banded iron formation, and skarn deposit types (modified from Dupuis and Beaudoin, 2011). Note that deposits whose average compositions plot in the field for Ni-Cu deposits (Fig. 1) and in the field for volcanogenic and sedimentary exhalative deposits (Fig. 4) are not shown on this diagram.

5). Another diagram using Ti+V versus Ca+Al+Mn yields similar results (Dupuis and Beaudoin, 2011).

Comparison to Other Studies

Nadoll et al. (2012) showed that Ag-Pb-Zn veins hosted by the Belt Supergroup rocks contain magnetite with a chemical signature that is depleted in Mn, Co, Ni, and Zn and can be distinguished from magnetite from metasedimentary host rocks and post-metamorphic intrusions. In contrast, magnetite from sediment-hosted stratiform Cu-Ag deposits has a composition similar to that of its host rocks, thus suggesting that it formed during Belt Supergroup burial metamorphism. Carew (2004) illustrated that the trace element signature of Kiruna-type deposits from Sweden and Chile is different from that of IOCG mineralization of the Cloncurry district (Australia). Rusk et al. (2009) similarly demonstrated that the Ernest Henry IOCG deposit (Cloncurry, Australia) has magnetite characterized by high Mn and low V concentrations compared to Cu-Au-barren magnetite breccia. Singoyi et al. (2006) showed that the Sn/Ga versus Al/Co diagram was useful to distinguish VMS deposits from skarn and IOCG deposits.

APPLICATION TO EXPLORATION

In order to detect the erosion of a mineral deposit containing primary or secondary iron oxides, the ferro/paramagnetic fractions need to be separated from the 0.25-1.0 mm grain-size heavy mineral concentrate of a sediment (fluvial, glacial, eolian). Because the ferro/paramagnetic fractions of samples can contain 10s of grams (1000s grains) per kilogram of sediment, it is necessary to split a representative sample into smaller portions that statistically capture the overall chemical signature of the iron oxides in the sample. This careful separation of the sample is not required when analyzing from some of the other indicator minerals that are found in very limited numbers, such as pyrope garnet; for these indicators minerals, all the grains in the sample would be analyzed for their chemical composition.

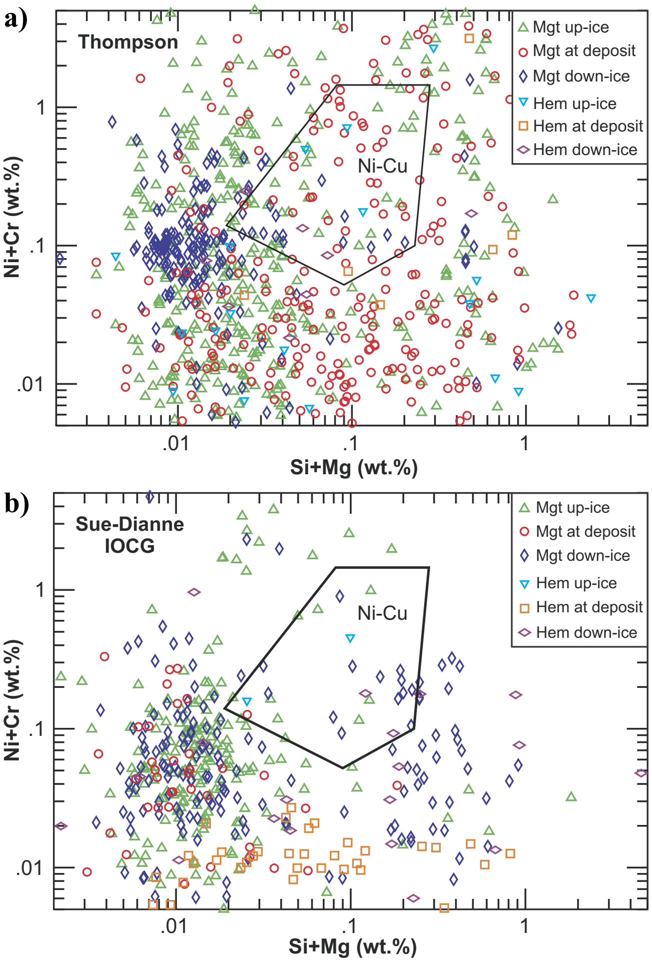

Figure 6. The composition of iron oxides from till samples plotted on a Ni+Cr versus Si+Mg discriminant diagram for Ni-Cu-PGE deposits (modified from Dupuis and Beaudoin, 2011). The samples are from **(a)** Thompson Nickel Belt (Manitoba) and **(b)** Sue-Dianne deposit (Northwest Territories).

Several case studies have now been completed on Ni-Cu, IOCG (Dupuis et al., 2012; Sappin et al., 2012), and VMS (Makvandi et al., 2012) deposits. In these case studies, the chemical composition of iron oxides from the ferromagnetic fraction from a set of till samples collected along the principal ice movement direction, up- and down-ice from the deposits, was analyzed and compared to the composition of iron oxides in the nearby deposits. Figure 6 illustrates the compositional variation of iron oxides from till collected near the Thompson Nickel Belt Ni-Cu deposits (Manitoba) to that from till collected near the Sue-Dianne IOCG deposit (Northwest Territories). In the Thompson Nickel Belt, the glaciers eroded several outcropping Ni-Cu deposits, as is shown by the high number of iron oxides grains that have a composition that plots in the field for Ni-Cu deposits (Fig. 6a). In contrast, the Great Bear magmatic zone, which hosts the Sue-Dianne IOCG deposit, is not known for its Ni-Cu occurrences, and this is reflected in few of the iron oxide grains from the nearby tills having a composition that plots within the field for Ni-Cu deposits (Fig. 6b).

CONCLUSIONS

Iron oxides have chemical compositions that reflect the environment of their formation. Thus, the fractional crystallization of magma and sulphide liquid can be tracked by the change in composition of the iron oxides, which affords new tools to asses the fertility of an intrusion for Ni-Cu deposits. Different deposit types have distinct iron oxide chemical signatures that allow them to be distinguished, identified and traced to an eroded deposit in the surficial sedimentary environment (fluvial, eolian, or glacial).

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FIELD PORTABLE XRF IN EXPLORATION AND MINING

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INTRODUCTION

This presentation is divided into two main areas: firstly, an overview of the results of Phase 1 of a CAMIRO (Canadian Mining Industry Research Organization) project to evaluate portable XRF (pXRF) for the mining industry; and secondly, a comparison of results on ~88 till samples from the environs of the Pine Point Pb-Zn MVT Mining District, NWT collected as part of a Geological Survey of Canada study of the geochemical and mineralogical signatures of these deposits (McClenaghan et al., 2012). Portable XRF analyses were carried out on the unsieved 'as is' till and compared to data for conventional analytical methods of ICP-ES and ICP-MS following fusion or aqua regia digestion of the < 63 µm till fraction.

The CAMIRO project involves the study of the performance of five pXRF instruments (handheld and portable benchtop) from three manufacturers in the analysis of 41 powdered highly varied control reference materials (CRM) — rocks, ores, soils, and sediments — in terms of accuracy and precision using the factory calibrations. In addition to accuracy and precision, optimum beam time, drift, and different films as sample covers were studied. The CRMs were placed in pXRF cups for analysis and measured 10 times each, moving the cup slightly between measurements. Some elements, such as Fe (Fig. 1a) and K (Fig. 1b), show good fit (i.e. good value of r^2) in an x-y plot of pXRF versus referee value across all five instruments, although the slope (i.e. factory calibration) may differ substantially from 1 as is shown for K (slope of 3.6!). The plots in Figure 1c and 1d illustrate the marked differences in performance encountered across instruments for some elements: Barium is well determined by the Benchtop model A (Fig. 1c) but results by Handheld B are so noisy that they are essentially unusable (Fig. 1d). Rubidium is generally well determined by pXRF but several 'fliers' are evident in the results by Handheld B (Fig. 1e). Such outliers do not occur with other instruments, a reflection of the rather surprising difference amongst manufacturers in correcting for interferences. Figure 1f depicts the different responses in the lake sediment CRM, LKSD-4, with beam time for As, Ca, and Cr across the five instruments; note the significant differences in precision from one instrument to another and the drift encountered.

Key conclusions of the Phase 1 CAMIRO project comprise

- Inconsistent performance, particularly accuracy, was observed across the instruments, even within one manufacturer.
- The user must undertake their own calibrations that reflect the sample matrix under study.
- A beam time of 60 s is generally a good compromise between efficiency and precision.
- The 4-µm Prolene® thin-film for use with cups provides a good compromise between strength and absorption of low-energy photons from light elements.
- Portable bench-top units were not superior to their handheld counterparts.
- Guided by the goodness of fit (r^2) for plots of pXRF value against certified concentration, the overall sequence (across all instruments) of elements in the mining mode, from 'good' to 'poor', is Ca, Zn, K, Rb, Sr, Fe, Mn, Cu, S, Ni, Pb, P, Ti, Cr, Al, Si, and Mg. In the soil mode, the sequence is Sr, Rb, Cu, Ca, K, Zn, Fe, Ti, Zr, As, Mn, Th, Pb, Nb, Ba, Cd, Cr, U, and Sb; elements where ratings were less satisfactory include Mo, V, Ni, Co, S, and Sn. Elements where highly erroneous results were obtained include Au, Bi, Cs, Hf, Hg, Sc, Pd, Pt, Se, Ta, Te, and W.
- Repeatability of measurement by pXRF is usually excellent for powders, often better than ±10%. From this work, *typical* RSDs for the CRMs fall into the following groups: <2.5% for Fe, Ca, K, Si; 2.5-4.9 % for Mn, Rb, Sr, Ti, Y, Zn, and Zr; 5-10% for Ag, Cr, Cu, Pb, V, Al, and S; 11-20% for As, Ba, Cd, Co, Ni, S, Th, U, and Mg; and >20% for Sb, Se, Sn, and P.
- 'Real' detection limits in geological materials, particularly for ores or samples enriched in rare earth elements, can be significantly higher than the ~5-50 ppm commonly quoted. There is a high degree of variability in the manufacturers' software in handling interferences such that (a) some correct adequately for the interference, (b) some report erroneous results, and (c) others alert the user to the problem by reporting "0", "VALUE!" or "<LOD".

In the till project, each sample was cupped and three measurements were made by pXRF, moving the cup position between analyses. When comparing the results by pXRF and the referee method, it must be kept in mind that the former technique has been applied to the 'as is' unsieved but dry sample, whereas the latter is

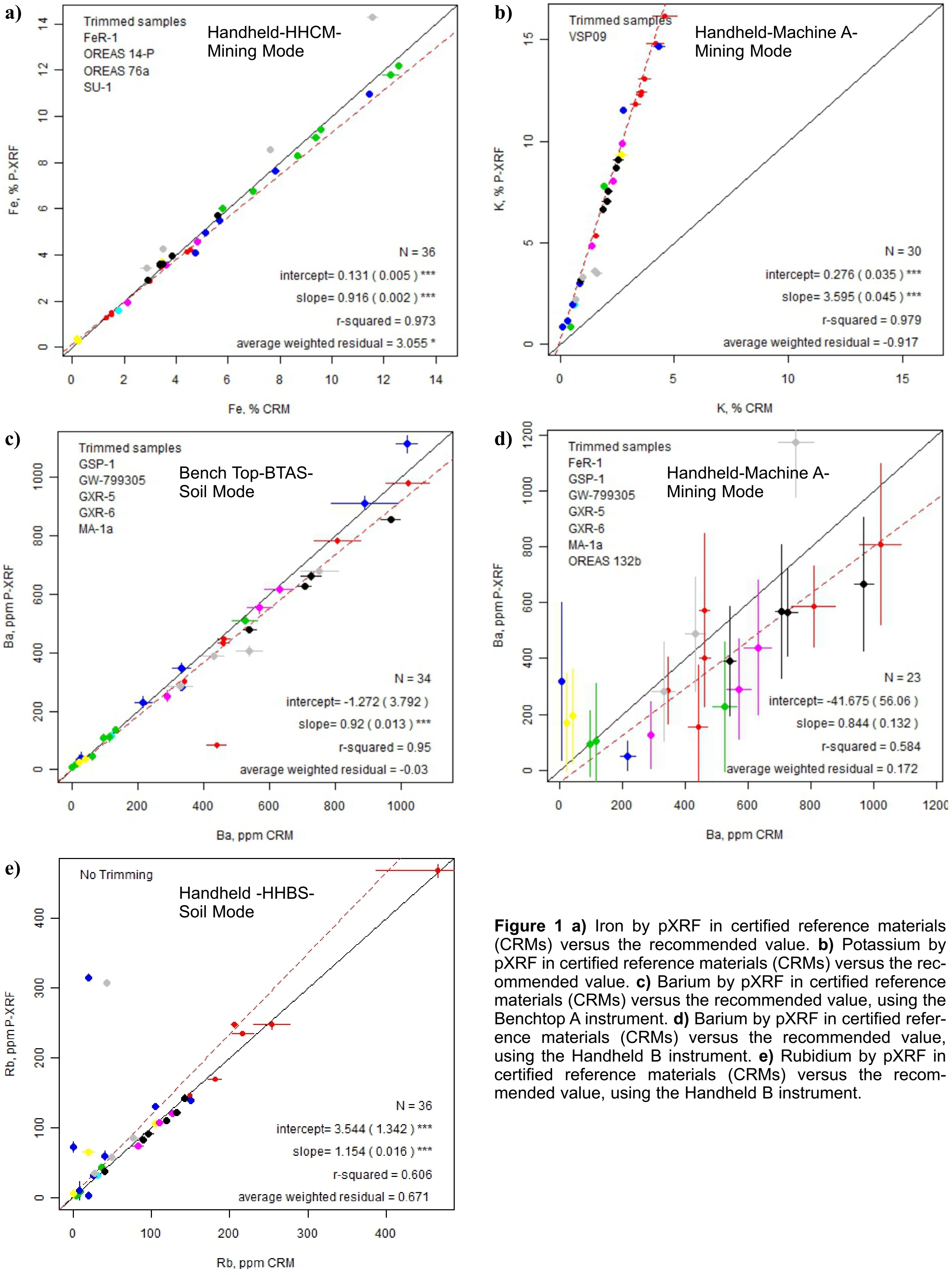

Figure 1 **a)** Iron by pXRF in certified reference materials (CRMs) versus the recommended value. **b)** Potassium by pXRF in certified reference materials (CRMs) versus the recommended value. **c)** Barium by pXRF in certified reference materials (CRMs) versus the recommended value, using the Benchtop A instrument. **d)** Barium by pXRF in certified reference materials (CRMs) versus the recommended value, using the Handheld B instrument. **e)** Rubidium by pXRF in certified reference materials (CRMs) versus the recommended value, using the Handheld B instrument.

f)

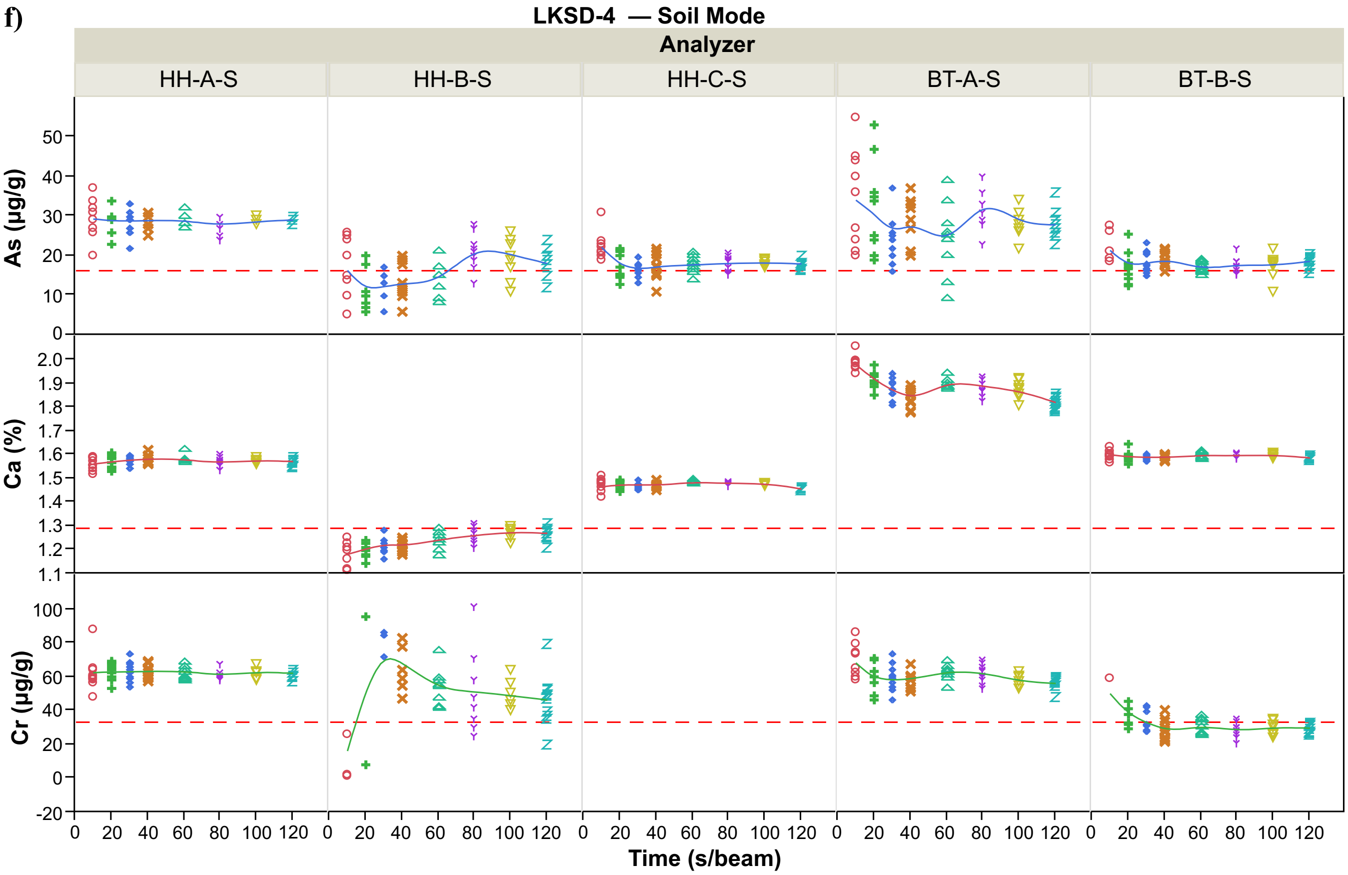

Figure 1 continued. f) Beam time optimization study for As, Ca, and Cr across five instruments using the lake sediment CRM LKSD-4.

based on the <63 µm fraction. Though the referee method may be based on an aqua regia digest, rather than a fusion for some elements, it can be considered close to total for elements such as Zn, Pb, As, etc. in tills. Agreement for Si between the two data-sets is excellent (r^2=0.9), with most values in the range of ~7 to 9% Si. The six samples outside this tight range are evident in both data-sets and agree reasonably well (e.g. the highest Si is 30.2% by fusion ICP-ES and 22.7% by pXRF). Similarly, agreement is very good for Fe (see Fig. 2a; r^2=0.8), K and Ti (most values are <150 ppm), though calibration is clearly required for K where the majority of values by pXRF cluster around ~ .2%, whereas those by fusion ICP-ES are close to ~1%. The three extreme lows in Ca by fusion are well matched by pXRF analysis, but there is much more variability amongst the majority of the samples by pXRF (in the range of 15-21%), whereas this range is much tighter by fusion (17-19%; Fig. 2b); the error bars on the pXRF data are small and do not explain this variability.

The commodity elements at Pine Point, Pb and Zn, show excellent agreement in their concentration trends, though not necessarily in their absolute concentrations, as is shown in Figure 2c-d. The two samples with high Zn concentrations (not plotted), which were reported as >1% by aqua regia ICP-ES, were determined to be 13.8±1.8% and 9.7±0.5% by pXRF. Aqua regia, a strong 'partial' digestion, appears to be close to total for these elements. Figure 2e illustrates the interference of Pb on As: samples containing >1% and 0.91% Pb are erroneously reported by pXRF at 131 ppm As (cf 1.9 ppm by aqua regia ICP-MS) and 103 ppm As (cf. 2.9 ppm by aqua regia), respectively; Pb at a few hundred ppm is seen to enhance the As pXRF values also, up to ~20 ppm As (cf ~2-3 ppm As by referee method). Interference from the shoulder of the Kα line of Zn on the Kα line of neighbouring Cu is evident in the two high-Zn (>1% Zn) samples: Cu is reported by pXRF as 105 ppm (cf 7.6 ppm by aqua regia) and 61 ppm (cf 10.7 ppm by aqua regia) (Fig. 2f). The high Cu concentration reported by pXRF for Sample 22 (41±49 ppm vs 6.5 ppm), however, is not due to an interference; rather, its noisy signal, which is also evident for Cr, Ni, and V, is probably an indication of heterogeneity and different mineralogy in the 'as is' sample. With the several exceptions (the two high Pb-Zn samples and sample 22), agreement between the two data-sets for Mn, Rb, Sr, Th, U, and V is excellent, the concentration ranges being quite restricted (e.g. 20-50 ppm for V). Furthermore, the standard deviations shown in the three measurements per sample by pXRF are, for the

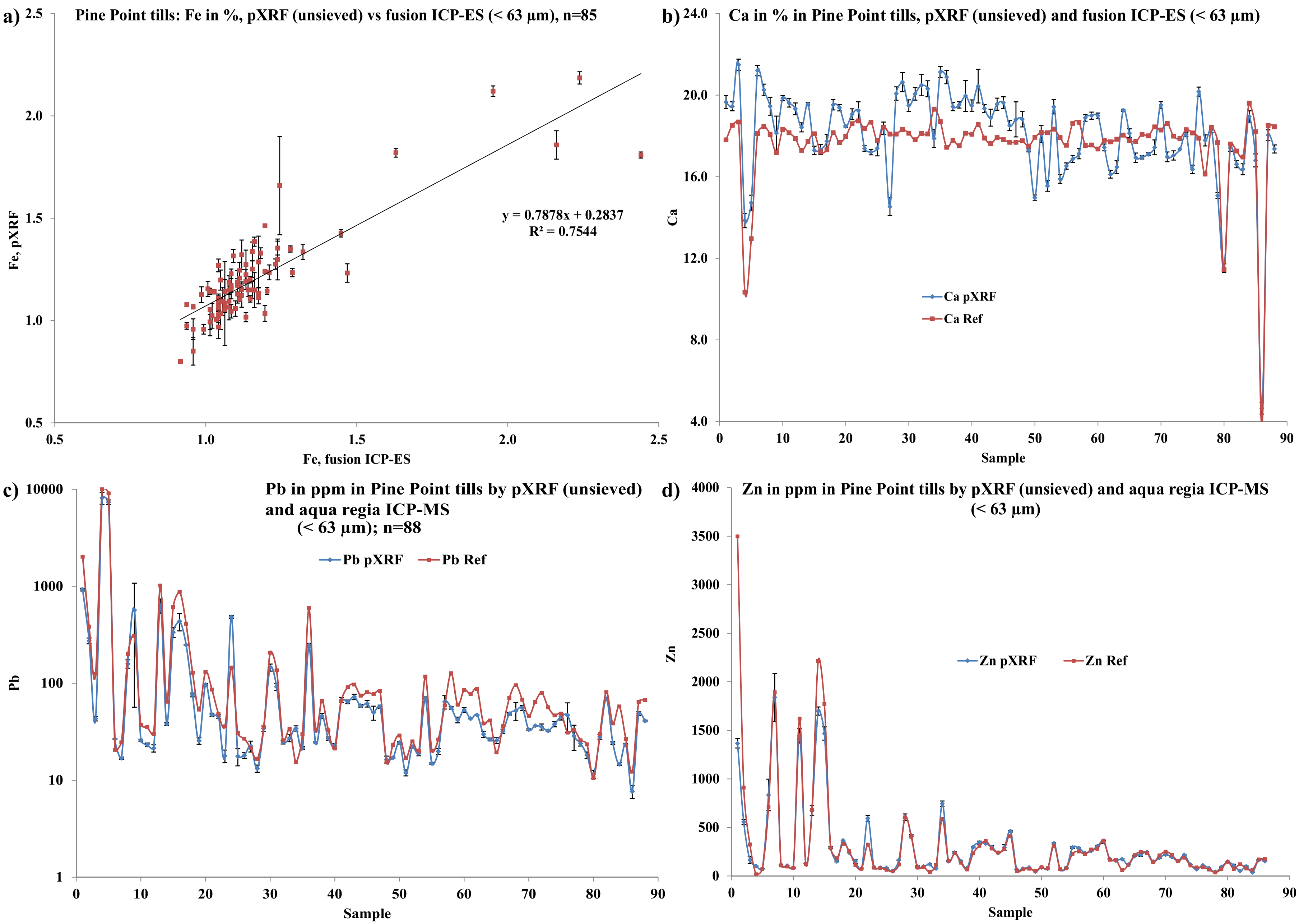

Figure 2 a) Iron by pXRF vs Fe by fusion ICP-ES in tills. **b)** Calcium by pXRF and fusion ICP-ES in tills. **c)** Lead by pXRF and aqua regia ICP-MS in tills. **d)** Zinc by pXRF and aqua regia ICP-MS in tills.

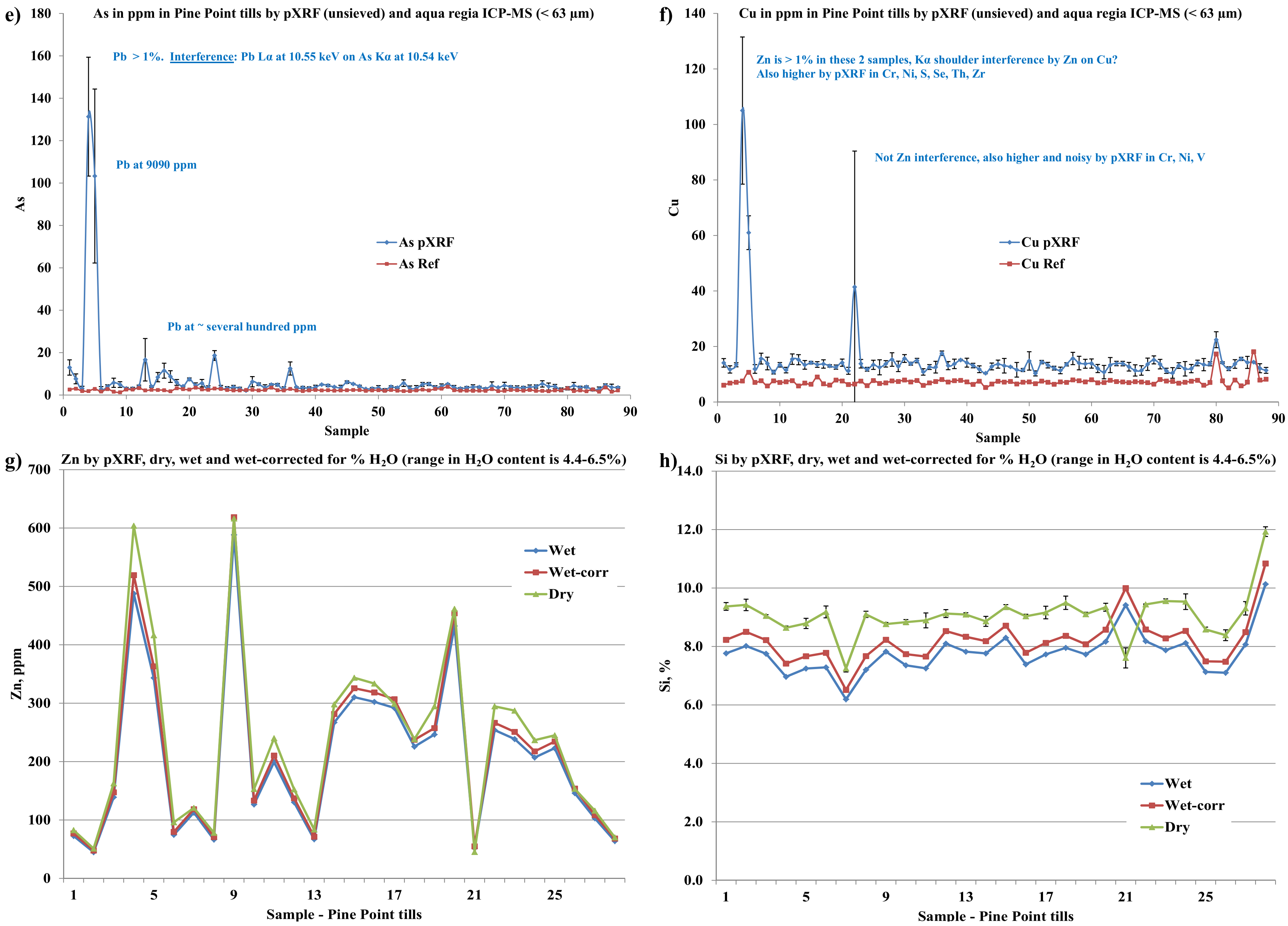

Figure 2 continued. e) Arsenic by pXRF and aqua regia ICP-MS in tills. **f)** Copper by pXRF and aqua regia ICP-MS in tills. **g)** Zinc by pXRF in a till subset, analysed wet, dry and corrected for moisture content. **h)** Silicon by pXRF in a till subset, analysed wet, dry and corrected for moisture content.

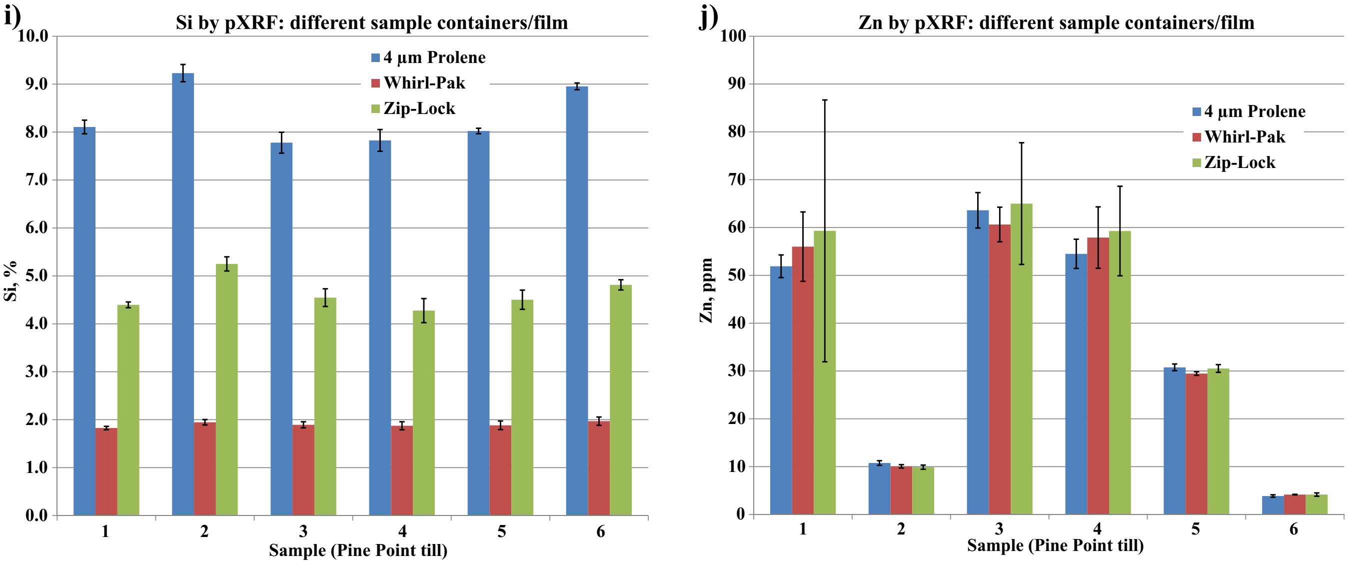

Figure 2 continued. i) Silicon by pXRF using different sample containers/film. **j)** Zinc by pXRF using different sample containers/film.

most part, reasonably low (e.g. ~<10% at levels a decade above detection level), as shown in the figures. Calibration to suit this matrix is clearly required for elements such as Ni (majority in the range by pXRF ~40-50 ppm, 9-12 ppm by the referee method) and Sn (~15-26 ppm by pXRF and ~0.2-0.9 ppm by fusion).

The generally good agreement between pXRF and the referee method is quite surprising given that the samples analysed are the unsieved 'as is' material. A contributing factor may be that, in tapping the sample upside down in the cup prior to measurement by pXRF, the finer grains are collected on the film and the coarser remain above. This observation is consistent with previous studies of pXRF analyses on glacial till samples (Knight, pers. comm., 2011; Kjarsgaard et al., 2012). These authors prepared till samples by inducing granular convection prior to pXRF analysis. These authors (Knight, pers. comm., 2011; Kjarsgaard et al., 2012) noted that the glacial till analysed is closer in grain size (clay – silt – fine-sand) to clay - silt than to unsieved till, and hence the good agreement between 'shaken' pXRF data on till and laboratory data on the clay-silt fraction of the till. This explanation would account for the similarity in compositions observed in this study.

Twenty-eight till samples were analysed 'wet' or 'as received' after placing them in the pXRF cups. They were then dried in an oven overnight, the moisture content calculated, and finally reanalyzed in their dry state. Results for Zn, shown in Figure 2g, are typical of the trace elements: the 'wet' data corrected for the moisture content (only ~4-6% moisture) agree well with the 'dry' data, an indication that simple correction for dilution is effective. A moisture meter in the field would be useful for this purpose. Results for several major ele-ments, such as Si and Ca, however, show that the data for the 'dry' samples are considerably higher than those for the 'wet', higher than would be accounted for by this relatively low-moisture content (Fig. 2h). This may be a result of a physical phenomenon, a coalescing of particles on drying; it is interesting to note that Sample 21 behaves in an opposite manner (also for Ca).

The plots in Figure 2i and 2j show the results for Si and Zn in six tills, which were analysed in three ways: in the usual cups with 4-µm Prolene film, in Whirl-Pak® bags, and Zip-Lock (Ziploc®) bags. Clearly, the WhirlPak® material absorbs about 75% of the Si low-energy photons or signal, whereas Zip-Lock bag absorb ~50%. The other light elements, K and Ca, are affected in a similar, though less drastic, manner (e.g. Ca in Sample 1 reports at 19.5, 18.3, and 15.0% using Prolene, Zip-Lock, and Whirl-Pak, respectively). Zinc behaves like most elements, showing no pattern and no contamination from the bags. It is interesting that the standard deviations for Zn are generally lower using the cups compared to the bags, perhaps a reflection of concentrating the finer material on the film by tapping the cup.

The results for these till samples suggest that careful analyses of the unsieved samples by pXRF in the field could well provide trends similar to the more conventional approach of laboratory analysis of the <63 µm fraction. The user should be aware of possible interferences, especially prevalent when analysing samples enriched in 'trace' or commodity elements.

A moisture meter should be used to correct for dilution. Zip-Lock bags are preferable to Whirl-Pak® bags, but the partic-ular stock used should be checked for their transmis-sion and contamination properties.

ACKNOWLEDGEMENTS

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