



**PROCEEDINGS OF THE 24TH
INTERNATIONAL APPLIED GEOCHEMISTRY SYMPOSIUM
FREDERICTON, NEW BRUNSWICK, CANADA**



JUNE 1ST-4TH, 2009

EDITED BY

DAVID R. LENTZ, KATHLEEN G. THORNE, & KRISTY-LEE BEAL



VOLUME II



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VOLUME II

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NEW FRONTIERS FOR EXPLORATION IN GLACIATED TERRAIN

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Glacial dispersal from the Mount Fronsac North massive sulfide deposit, Bathurst Mining Camp, New Brunswick, Canada

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ABSTRACT: Concentrations for 53 elements in till (C-horizon sediment) sampled over the Mount Fronsac North volcanogenic massive sulfide deposit were analyzed to determine whether geochemical concentrations were coincident with known glacial flow directions, and whether Hg could be used as a pathfinder element for massive sulfides. Based on data from these analysis, three patterns were observed in glacial till: palimpsest (Pb, Ag and Cu), related to local ice flow dispersal of mineralized gossan; ribbon (Ni, Co and Cr), related to flow of the Laurentide Ice Sheet over gabbroic intrusions and an arcuate pattern (Hg and Cd) related to post-glacial ionic mobility. Concentration gains of Mo, As, Sb and Hg in supergene gossan and gains of Zn, Au, Cd, Hg and Co in till were calculated using Sn as a conservative element. These results indicate that processes responsible for element signatures in till over the Mount Fronsac North deposit are: 1) pre-glacial weathering of primary sulfides resulting in gossan formation, 2) pre-glacial colluvial and hydromorphic redistribution of gossanous material, 3) west to east and southwest to northeast mechanical transport of mineralized bedrock by glaciers and 4) ionic migration of cations and anions due to electrochemical reactions between wall rock and sulfides.

KEYWORDS: *glacial, gossan, mobility, dispersal, till, geochemistry*

INTRODUCTION

Two hundred and fifty three till (C-horizon) samples were collected and analyzed to determine suitable analytical methods to delineate till geochemical signatures that reflect Zn-Pb-Ag mineralization and to determine possible pathways of element migration from the bedrock to till. Results of a study conducted at the Mount Fronsac North deposit are discussed here.

GEOLOGICAL SETTING

Location and Geology

The Mount Fronsac North (MFN) Zn-Pb-Ag deposit is located approximately 40 km southwest of Bathurst, in the Bathurst Mining Camp (BMC), New Brunswick. The MFN deposit lies stratigraphically in the Brunswick horizon between the Nepisiguit Falls Formation and the Flat Landing Brook Formation of the Ordovician Tetagouche Group (Figs. 1-3). Footwall

rocks consist of crystal tuffs, tuff lavas (ONFp), chloritic sedimentary and volcanic and volcanoclastic rocks (ONFs) of the Nepisiguit Falls Formation. The massive sulfides are enveloped by sericite-pyrite-chlorite schist alteration. Hanging wall units consist of ash and crystal tuff and interlayered sedimentary rocks (OFLBts), fine-grained crystal tuffs (OFLBft), rhyolites (OFLBr), mafic tuffs and flows (OFLbt) of the Flat Landing Brook formation. Late gabbroic intrusions intrude the hanging wall units (Gower & McCutcheon 1995; Walker & Graves 2006). Sulfide mineralization occurs in 2-20 m thick beds that dip to the east and plunge to the north with a high grade zone that grades 7.65% Zn, 2.18% Pb, 0.14% Cu, 40.3 g/t Ag and 0.40g/t Au (Walker & Graves 2006).

Host Rock & Sulfide Geochemistry

Massive sulphide chemistry used in this study were from from diamond drill hole (DDH) MF-00-31 (Walker & Graves 2006) with concentrations (geometric mean) of 3650.41 ppm Zn, 1091.32 ppm Pb, 1038.01 ppm As, 8.55 ppm Ag, 124.67 ppb Au, 159.51 ppm Cu, and 68.22 ppm Sb. Rhyolite (OFLBr) contains up to 8 ppb Au. The gabbro contains the highest values of Ni (77 ppm), Cr (293 ppm) and Co (47 ppm) and moderately high values of Cu (41 ppm).

PRE-GLACIAL ELEMENT CONCENTRATION IN GOSSANS

Pre-glacial weathering of BMC massive sulfide deposits during the Pliocene-Pleistocene (Boyle 2003; Symons *et al.* 1996) resulted in the formation of oxidized caps (gossans) that overlie many of the massive sulfide occurrences/deposits. Gossan occurs at MFN and outcrops on the northwest extent of the mineralized zone. Detailed studies on BMC gossans by Boyle (2003) showed that Sn volumetrically remained the same in the weathering process and thus could be used in mass balance calculations (1) to determine element mobility from the sulfide to the gossan.

% element gain / loss =

$$\frac{C_{\text{element in gossan}} \times \left(\frac{C_{\text{Sn Sulfides}}}{C_{\text{Sn Gossan}}} \right) - C_{\text{element in Sulfides}}}{C_{\text{element in Sulfides}}} \times 100$$

Calculations of gains and losses from the MFN deposit and gossan boulders on surface nearby show gains in Cu, As, Mo, V, Hg, Bi and Sb; which are consistent with other gossans in the BMC (Boyle 2003), with the exception of Cu.

GLACIAL DISPERSAL

Two main glacial events are responsible for glacial dispersal from the MFN deposit; a west to east Laurentide Ice Sheet flow (090°) and later local southwest to northeast (070°) ice flow. Both these glacial events were primarily erosive (Pronk *et al.* 1989; Parkhill & Doiron 2003)

leaving a thin layer (<1 m) of sandy lodgement till overlying deformation till.

METHODS

Bedrock samples were analyzed by aqua regia digestion/inductively coupled plasma mass spectrometry/emission spectrometry (ICP-MS/ES), 4-acid digestion/ICP-MS/ES (total digestion), INAA and XRF. The 253 till samples were collected at 25 m intervals along a grid extending 200 m outward from the mineralized zone. Gridlines with 50 m sample spacing were added to complete the survey and to cover approximately the 1 km x 1 km area over the deposit. Till samples were split, and the <0.063 mm fraction analyzed by aqua regia digestion - ICP-MS/ES. Splits (not sieved) were analyzed at the University of New Brunswick Forestry & Environmental Laboratories for cold vapor atomic fluorescence spectrometry (CVAFS).

TILL GEOCHEMISTRY AND DISTRIBUTION

Results for Hg from ICP-MS/ES and CVAFS showed excellent correlation ($r_s=0.87$) despite different sample preparation (sieving and pre-digestion for ICP-MS/ES; no sieving or digestion for CVAFS). Thresholds between anomalous and background populations were determined using methods of Sinclair (1974). Bubble plots of element distribution (Figs. 1-3) show four main geochemical patterns; 1) a slight arcuate pattern in the moderately anomalous (66-275 ppb) population for Hg and Cd contents, 2) a west to east ribbon-shaped train for Ni, Cr and Co concentrations, 3) a diffuse pattern for Zn content and 4) a southwest to northeast zone of elevated concentrations of Ag, As, Sb, Pb, Cu, Au, Hg and Mo.

Mass balance calculations were performed on till samples using Sn concentrations. Tin concentrations in till are sensitive to grain size partitioning and differing analytical methods, thus results from these calculations are qualitative. In the till, concentration gains relative to Sn in Zn, Au, Cd, Hg and Co were obvious after performing the calculations; all of

these elements show concentrations losses from the gossan.

DISCUSSION

Mechanical and chemical weathering is responsible for element transport in MFN till. The later northeastward – southwestward ice flow and resultant glacial dispersal (070°) is interpreted as palimpsest and defined by elements concentrated in the gossan along with Ag, Au and Pb. The ribbon-shaped train (090°) is defined by elements concentrated in the gabbroic intrusions. An arcuate concentration pattern is apparent for Hg and Cd in till surrounding the bedrock sulfide zone, thus it is thought that electrochemical mechanisms may be a factor in mobilizing these elements to the surface. The pattern for Zn (not shown) is diffuse and appears to be the result of down slope (hydromorphic) post-glacial transport.

CONCLUSIONS

Excellent correlation between ICP-MS/ES and CVAFS analysis of Hg ($r_s=0.87$) show that sieving does not affect anomalous concentrations of this element in till.

Element distribution patterns in till around the MFN deposit are most likely the result of concentration of anionic species in the gossan, glacial dispersal of metal-rich bedrock, and mobilization of

Fig. 1. Distribution of Hg (and Cd) in till at the MFN deposit. DDH MF00-31 and DDH MF00-29 are marked with an “X”; subcropping mineralization is marked by a dashed line. Arrows indicate ice flow directions, the youngest flow was northeastward.

elements by electrochemical mechanisms and hydromorphic dispersal. These conclusions are supported by qualitative mass balance calculations and variable geochemical distribution patterns in till, in the context of local and regional ice flow.

Till geochemical distribution patterns are coincident with known glacial dispersal directions; however post-glacial processes overprint the primary glacial dispersal

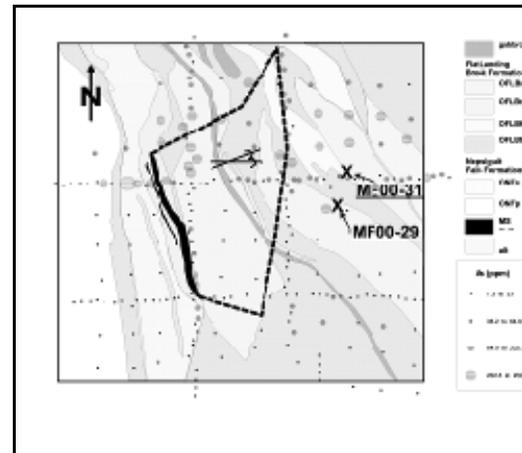
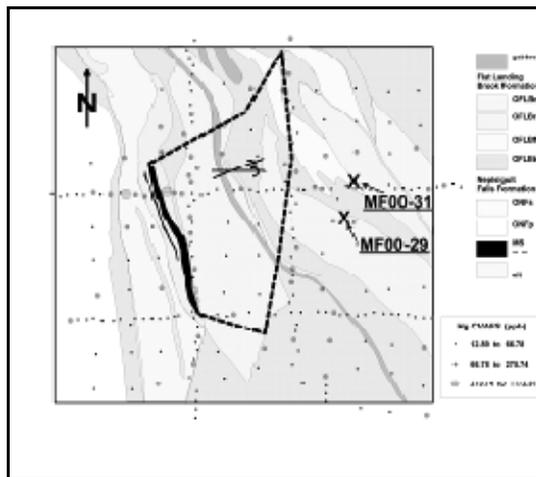


Fig. 2. Distribution of As (Ag, Sb, Pb, Cu, Au, Hg and Mo) in till at the MFN deposit. DDH MF00-31 and DDH MF00-29 are marked with an “X”; subcropping mineralization is marked by a dashed line. Arrows indicate ice flow directions, the youngest flow was northeastward.



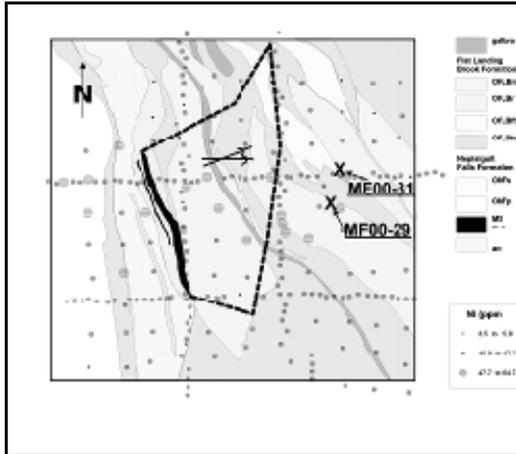


Fig. 3. Distribution of Ni (Cr, Co) in till at the MFN deposit. DDH MF00-31 and DDH MF00-29 are marked with an "X"; subcropping mineralization is marked by a dashed line. Arrows indicate ice flow directions, the youngest flow was northeastward. signature of the deposit. Thus both processes should be considered when using till geochemical methods in areas of thin till cover in the BMC.

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Geochemical and mineral dispersal patterns related to drift-covered copper-gold mineralization in central British Columbia, Canada

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ABSTRACT: Commercial selective extraction methods, such as Enzyme LeachSM, MMISM, and Bio LeachSM have become increasingly popular for geochemical soil surveys in areas where the mineralization is buried beneath unconsolidated sediments. A soil (B horizon soil) and till (C horizon soil) orientation survey on the Shiko Lake copper-gold porphyry mineral occurrence in central British Columbia reveals asymmetric soil geochemical profiles typical of mineralised bedrock entrained in till. Abundant, fresh gold grains in till samples close to a copper anomaly peak suggest a local source for the anomalous soil. A close association of MMISM and Bio LeachSM B horizon soil anomalies with metal extracted by aqua regia from C horizon soil samples suggests that the selective extractions reflect till rather than bedrock composition.

KEYWORDS: *till, copper, gold, MMI, Bio Leach, aqua regia.*

INTRODUCTION

Mesozoic volcanic rocks and coeval intrusive complexes within the Quesnel geotectonic terrain of central British Columbia host several major porphyry copper-gold mines. Exploration for new deposits in this region has been met with limited success, because prospective bedrock is mantled by Late Pleistocene glacial sediment (e.g., till) and Late Oligocene to Pleistocene plateau basalt. However, subcropping mineral deposits can be found by detecting the geochemical signature of mineralized bedrock in till. These down-ice dispersal trains are typically ribbon-shaped and are areally more extensive than their bedrock target. For example, Levson (2001) reports anomalous Cu values in the <0.063 mm till fraction up to 4 km down-ice from the Bell Cu-Au mine. In these trains, metal values typically decreased exponentially in the down-ice direction (Klassen 2001).

This paper documents a soil and till survey of the Shiko Lake porphyry copper-gold mineral occurrence near Quesnel Lake, British Columbia, and the comparison of Cu, Au, and other elements by partial extraction geochemical analysis with the distribution of gold and other heavy mineral grains (Lett & Doyle 2009).

BEDROCK AND SURFICIAL GEOLOGY

At Shiko Lake (Fig. 1) a Jurassic complex composed of diorite, monzonite, and syenite intrudes basalt and volcanoclastic rocks. Chalcopyrite, bornite, and gold occur disseminated and in veins mainly within the syenite (Fig. 2).



Fig. 1. Location of the Shiko Lake mineral property in western Canada.

Much of the bedrock is covered with up to 3 m of a sandy till deposited during a southeast to northwest ice-flow event. Soil formed on the glacial sediment is typically a well-drained brunisol.

Sampling and analysis

Samples from the B and C soil horizons, collected from profiles exposed in pits dug along traverses crossing the mineralized zone (Fig. 2) were prepared and analysed for 63 elements by a combination of aqua regia digest-inductively coupled plasma-mass spectrometry (ICPMS) and neutron activation (INAA). Analyses were carried out on the <0.063 mm fraction of the C horizon and the <0.177 mm fraction of the B soil horizon. The B horizon samples were also analysed for by SGS's propriety Mobile Metal IonSM (MMI) and Activation Lab's propriety Bio LeachSM and Enzyme LeachSM techniques and for hydrocarbons by the soil gas hydrocarbonSM (SGH) method. Gold and other heavy mineral grains were identified and counted in a heavy mineral concentrate of the C soil horizon (till) sample.

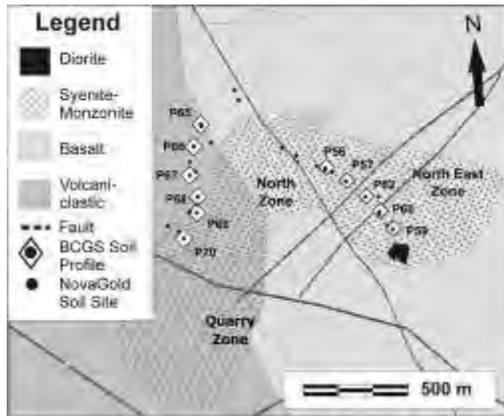


Fig. 2. Shiko Lake bedrock geology and soil sample locations. Geochemical data described here were compiled from BC Geological Survey studies by Lett & Doyle (2009) and a Novagold Resources till survey (Petsel 2006).

Results

A strong positive correlation exists between Cu, Ag, Co, Au, W, and Se in the B and C horizon soil and suggests that these elements are geochemical pathfinders for sulfide mineralization at the Shiko Lake mineral occurrence. Glacial dispersal of Cu and Co in C horizon soil samples is characterized by the shape of geochemical profiles. These typically

show a sharp up-ice peak and exponential down-ice decay curve of metal values.

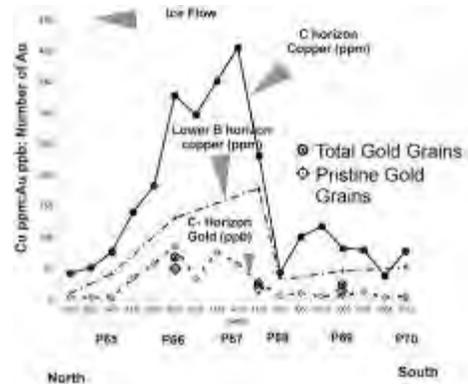


Fig. 3. Distribution of Cu and Au in B and C horizon soil west of the north zone, Shiko Lake. C horizon geochemical data are from BCGS studies by Lett & Doyle (2009) and a Novagold Resources till survey by Petsel (2006). Gold abundance in the C horizon samples was determined by an aqua regia digestion and instrumental analysis.

Figure 3 shows an example of this dispersal curve for Cu concentration along one traverse west of the North East zone. In addition to Cu, there are also abundant Au grains in the same C horizon sample suggesting a local bedrock source for both Cu and Au-rich debris in the till. The greater anomaly contrast for Cu, Au, and Co in the C horizon sample, compared to the lower B, may be explained by the fact that in this case analyses were conducted on the -0.063 mm fraction of the C horizon sample compared to the -0.180 mm fraction of the B horizon soil.

Two commercial partial extraction techniques improve anomaly contrast in B horizon soil samples compared to aqua regia-ICPMS for Cu and Au. However, whereas the MMISM and Bio LeachSM Cu profiles are similar, the MMISM Au signal is much larger than that for Bio LeachSM. Analysis of samples at different depths down the B soil horizon profile indicates that the geochemical response from these methods is depth dependant.

An exact source for the anomalous metal content and the gold grains in the samples presented here cannot be

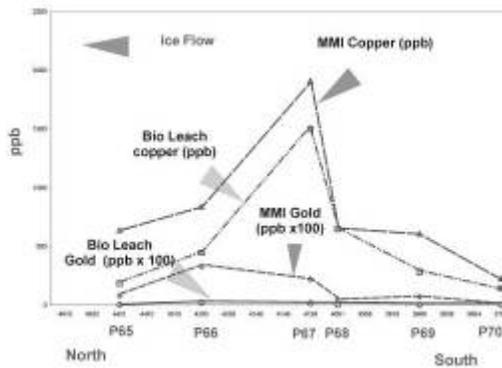


Fig. 4. Distribution of Cu and Au in B horizon soil west of the north zone, Shiko Lake, by MMISM and Bio LeachSM.

confirmed, but a most likely source is mineralized bedrock close to the syenite – volcaniclastic contact, near Profile Site 68. A close relationship between the aqua regia-ICPMS, MMISM and Bio LeachSM determined element patterns suggests that the partial extraction methods reflect metal-rich debris in till mechanically dispersed x m from a mineralized source rather than metal dispersion to surface directly from underlying mineralized bedrock.

CONCLUSIONS

A study of soil geochemistry and gold grain mineralogy over the Shiko Lake porphyry copper-gold mineral occurrence in central British Columbia has revealed:

- (1) That an asymmetric soil Cu profile and abundant fresh gold grains in C horizon soil samples most likely reflects mineralised bedrock entrained in till from a local source.
- (2) MMISM and Bio LeachSM selective extract anomalies most likely reflect till geochemistry.

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Heavy mineral and till geochemical signatures of the NICO Co-Au-Bi deposit, Great Bear magmatic zone, Northwest Territories, Canada

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ABSTRACT: To establish a practical guide to geochemical and mineralogical exploration for iron oxide copper-gold deposits in glaciated terrain, an orientation study around the NICO Co-Au-Bi deposit in the Great Bear magmatic zone of Northwest Territories was initiated in 2007. Bedrock and till samples, collected up-ice (background), proximal and down-ice from mineralization and host rocks, were analyzed to characterize their heavy mineral and geochemical signatures. Heavy mineral analysis demonstrates that, apart from gold and magnetite, few mineral species present at NICO have some clear potential as indicator minerals in surficial sediments. The non-ferromagnetic heavy minerals are either not chemically stable in surface glacial sediments (arsenopyrite, chalcopyrite, pyrite), not sufficiently coarse-grained (bismuthinite, tourmaline), not abundant enough in the mineralized bedrock (scheelite, molybdenite, cobaltite), or not sufficiently heavy (ferroactinolite). Although the Co-rich composition of arsenopyrite is possibly the strongest vector to Au-rich polymetallic mineralization in the study area, arsenopyrite is completely oxidized in surface tills. Iron oxide composition using preliminary discriminant diagrams shows some potential, namely with the Ni/(Cr+Mn) versus Ti+V plot. Till geochemistry reflects major differences in composition between the country/barren host rocks versus the mineralized rocks, and several elements (As-Bi-Co-Au-Cu-Sb-W-Cd) are identified as pathfinders for IOCG mineralization.

KEYWORDS: *indicator minerals, till geochemistry, IOCG, NICO, arsenopyrite*

INTRODUCTION

The Great Bear magmatic zone (GBMZ) in the Northwest Territories (NWT) is now considered the most prospective setting for iron oxide copper-gold (IOCG) deposits in Canada (Corriveau 2007) and hosts two economic IOCG deposits: the magnetite-group IOCG NICO Co-Au-Bi deposit and the nearby hematite-group IOCG Sue-Dianne Cu-Ag-Au deposit (Fig. 1). Moreover, many past-producing vein-type uranium, silver and copper mines and Kiruna-type showings are now recognized to be parts of large polymetallic IOCG systems (Mumin *et al.* 2009). As part of a joint government-industry-academia research project taking place under the government Targeted Geoscience Initiative 3, Geo-mapping for Energy and Minerals, and Strategic Investments in Northern Economic Development programs, the Co-Au-Bi NICO deposit was selected as a first test site to characterize the heavy mineral and geochemical

signature of IOCG±U deposits and derived glacial sediments and assess if some heavy minerals have a potential as indicator minerals for IOCG deposits. The mineralogy and chemistry of heavy minerals from bedrock and C-horizon till samples collected in 2007, as well as till geochemistry, are summarized below.

REGIONAL SETTING

The NICO deposit is located at the south end of the GBMZ in the Proterozoic Bear Structural Province of the Canadian Shield, about 160 km northwest of Yellowknife, Northwest Territories (Fig. 1). It represents an economically significant source of Co-Au-Bi-Cu-Fe with calculated reserves of 21.8 Mt with 1.08g/t Au, 0.13%Co and 0.16% Bi (Fortune Minerals 2008). Mineralization at NICO consists of a number of mineral showings predominantly hosted in brecciated and altered siltstone and wacke of the 1.88 Ga



Fig. 1. The Great Bear magmatic zone in the Wopmay orogen and known mineralization. The NICO deposit is located in the southern part of the GBMZ.

Treasure Lake Group, overlain by felsic ignimbrite sheets of the Faber Group (Goad *et al.* 2000). Ore minerals mainly consists of Fe-, As-, Co- and Cu-sulphides, native Au and Bi. Intense, pervasive, polyphase iron-oxide (magnetite-dominant)-hornblende-biotite-tourmaline-K-feldspar-carbonate replacive alteration occurs in the upper metasedimentary sequence below the volcanic-sedimentary unconformity (Corriveau *et al.* 2009; Mumin *et al.* 2009).

Ice-flow indicators indicate the area was influenced primarily by the Laurentide Ice Sheet flowing to the WSW during the last Wisconsinan glaciation. Pebble lithology data show that surface till composition reflects local provenance of the underlying

bedrock. The area is underlain by extensive discontinuous permafrost with mixed deciduous and conifer open forest vegetation.

METHODS

Thirteen till samples were collected over or immediately down-ice (<100 m) from known mineralized zones, offset from mineralization (barren), and up-ice (NE) from the NICO deposit area (background). The samples were collected from hand dug pits in the upper C horizon, at an average depth of 50 cm. Twenty-seven representative bedrock samples were collected from both mineralized and unmineralized host rocks and from regional rocks. Till and bedrock samples were processed to separate a heavy mineral fraction (specific gravity > 3.2 g/cm³), indicator mineral picking (0.25-2 mm) and gold grain counts. Selected mineral grains considered to have possible IOCG affinities were hand picked, mounted and microprobed. Till samples (<2 and <63 µm fractions) were analysed geochemically for trace and major elements using ICP-ES+MS (aqua regia) and INAA. Analysis of duplicate and analytical standards were used to monitor analytical precision and accuracy of geochemical results.

RESULTS AND DISCUSSION

Heavy mineral signature

Six sulphide species were observed in the non-ferromagnetic heavy mineral concentrates (NFM-HMCs) of bedrock samples: arsenopyrite >> pyrite > chalcopyrite > bismuthinite = molybdenite = cobaltite. Chalcopyrite, pyrite and bismuthinite do survive in near-surface till but only in minor amounts (<8 grains/sample). Although the Co-rich composition of arsenopyrite is possibly the strongest vector to Au-rich polymetallic mineralization in the study area, sand-sized arsenopyrite is absent in C-horizon tills, suggesting that arsenopyrite more readily oxidizes than chalcopyrite and pyrite in till, and therefore is an impractical indicator mineral to detect mineralization using surficial sediments at NICO.

Tourmaline occurs in three bedrock samples in considerable amounts (up to 650 grains/sample) but in two of these samples, both from barren brecciated porphyry, tourmaline occurs as very small grains (<0.05 mm) intercalated with quartz so that few grains are heavier than 3.2 g/cm³ in the 0.25-0.5 mm fraction. The fragmental nature of the tourmaline grains in crackle breccias hampers the use of tourmaline as an indicator mineral for the NICO deposit.

Ferroactinolite, although forming a pervasive alteration mineral in mineralized bedrock at NICO, is present only in minor amounts in several bedrock concentrates. The grains are not sufficiently heavy to be concentrated in the NFM-HMCs, except where they contain inclusions of magnetite (Fig. 2). Ferroactinolite also typically occurs as loose, silt-size aggregates of prismatic crystals in mineral grains of several bedrock samples (Fig. 3). These mineral inclusions are likely destroyed during glacial transport and comminution.

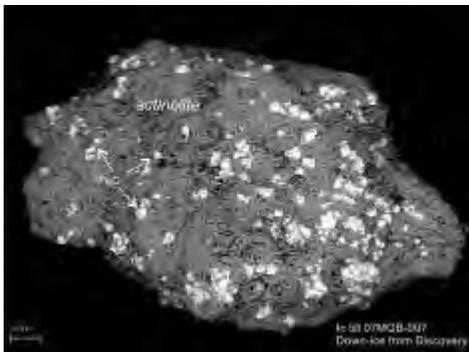


Fig. 2. Fe-oxide grains occurring as small inclusions in an actinolite grain from a till sample collected near the Discovery outcrop. Scale bar is 100 µm in length.

Relatively high concentrations of gold grains are found in surface tills collected over and near mineral showings of the NICO deposit area (up to 39 grains/10 kg sample) in comparison with those collected over barren host rocks (up to 10) and background terrain (up to 4). Pristine gold grains indicating a local source and a short distance of glacial transport are mostly abundant close to mineralized

zones indicating that documenting gold grain abundance, size, shape and fineness remains a valuable surface exploration method for gold-bearing IOCG deposits in the GBMZ.

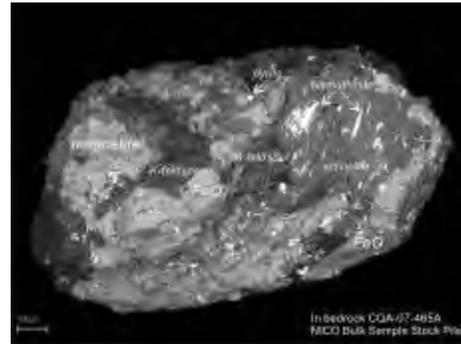


Fig. 3. Magnetite grain from a sub-surface bedrock sample occurring in association with a mixture of other minerals common to the mineralization zones. Scale bar is 100 µm in length.

Magnetite occurs in all bedrock and till samples in varied concentrations, as individual grains but also disseminated in bedrock fragments (Fig. 3) or as inclusions in mineral grains (Fig. 2). Variations in Fe-oxide composition are such that they fall within distinct fields in discriminant diagrams and can fingerprint a range of mineral deposit types (Beaudoin & Dupuis 2009). In the Ni/(Mn+Cr) vs. Ti+V diagram (Fig. 4), most grains from background till have higher Ti+V compositions compared to grains from till collected over NICO and a similar composition to grains collected in nearby metasediments at the Tan Fe-U showing. There is a good correspondence between the composition of grains from NICO metasediments and that of grains from till collected over NICO, and a reasonable differentiation between NICO metasediments and background metasediments. These preliminary results indicate the potential use of discriminant diagrams for iron oxides to fingerprint IOCG deposits.

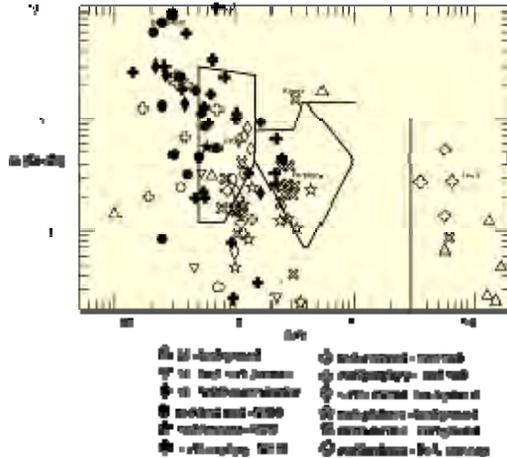


Fig. 4. Ni/(Cr+Mn) vs. Ti+V for magnetite grains from all till and bedrock samples.

Till geochemistry

Several trace elements show anomalous concentrations in the fine fractions of till. Increasing metal concentrations from background to mineralization for As-Cu-Bi-Co-Au-Sb-W-Cd are observed, by over three orders of magnitude for As (up to 1512 ppm in <63 µm). This geochemical signature reflects major differences in composition between the country/barren host rocks versus the mineralized rocks.

CONCLUSIONS

Study of the heavy mineral signature of the NICO deposit area and overlying glacial sediments demonstrates that gold grain abundance, size and shape, as well as magnetite composition, have the best potential to fingerprint the IOCG mineralization. Till geochemistry re-mains a useful and effective exploration tool for IOCG deposits in the GBMZ with As-Cu-Bi-Co-Au-Sb-W-Cd as the most effective pathfinder elements. The de-velopment of indicator mineral methods, together with till geochemistry, will be further tested with detailed bedrock and drift sampling around the Sue-Dianne deposit in 2009.

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We are grateful to Fortune Minerals for logistical support at NICO, K. Venance (GSC) for microprobe analysis, the DIVEX research network for supporting the iron

oxide mineral chemistry studies, and Overburden Drilling Management for heavy mineral processing. R. Paulen is thanked for providing a careful review.

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Base metal exploration using indicator minerals in glacial sediments, northwestern Alberta, Canada

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ABSTRACT: An indicator mineral survey in northwest Alberta has discovered a glacial dispersal train containing highly elevated concentrations of sphalerite grains and minor galena within the sand-sized fraction of glacial sediments. High concentrations of dark grey to black, angular, brittle grains of sphalerite were found (100 to >1000 grains) in nine bulk till samples (~30 kg). The presence of high sphalerite grain counts in nine samples situated within a geographically restricted area argues against long-distance glacial transport, comminution, and deposition of erratic material from the carbonate-hosted Pine Point Zn-Pb deposits, located 330 km to the northeast. The Pb isotopic composition of the galena grains recovered from till is similar to values obtained from other Mississippi Valley-type deposits in the Cordillera and Pine Point suggesting the galena is derived from sulphide occurrences situated along the Great Slave Lake Shear Zone. However, sphalerite grains from the till have a sulphur isotopic composition much different from values recorded from Mississippi Valley-type deposits in the northern and southern Cordillera; $\delta^{34}\text{S}$ values are interpreted to indicate bacterial reduction of coeval seawater sulphate. These results highlight the prospect of base metal deposits hosted within the Cretaceous shale bedrock of northern Alberta.

KEYWORDS: *indicator minerals, sphalerite, galena, Great Slave Lake Shear Zone*

INTRODUCTION

The Cretaceous sedimentary rocks of the Western Canada Sedimentary Basin (WCSB), renowned for their hydrocarbon resources, are seldom considered to have potential to host base metal sulphide mineralization. These sedimentary rocks have also discouraged those who presumed that the Precambrian rocks of the Canadian Shield to the east and north are more favourable hosts of base metal mineralization (*cf.*, Macqueen 1997).

In northwestern Alberta, Canada, the Alberta Geological Survey (AGS) and the Geological Survey of Canada (GSC) conducted reconnaissance-scale sampling of glacial sediments to assess the potential occurrence of economic minerals (Fig. 1). This sampling program represents the first systematic regional geochemical and mineralogical survey of northwestern Alberta (Plouffe *et al.* 2006; 2008).

REGIONAL SETTING

The uppermost bedrock in northwest Alberta consists of a Cretaceous succession of nearly horizontal and poorly-indurated marine shales of the Fort St. John Group (Loon River and Shaftesbury formations) and Smoky Group, separated by deltaic to marine sandstones of the Dunvegan Formation (Okulitch 2006). A large structural feature, the Great Slave Lake Shear Zone (GSLSZ) cuts across the study area (Eaton & Hope 2003).

Northwest Alberta is mantled by an extensive cover of unconsolidated glacial and nonglacial sediments of varying thicknesses. During the Late Wisconsin, the Keewatin-sourced Laurentide Ice Sheet flowed west and southwest across northern Alberta towards the Rocky Mountains (Paulen *et al.* 2007).

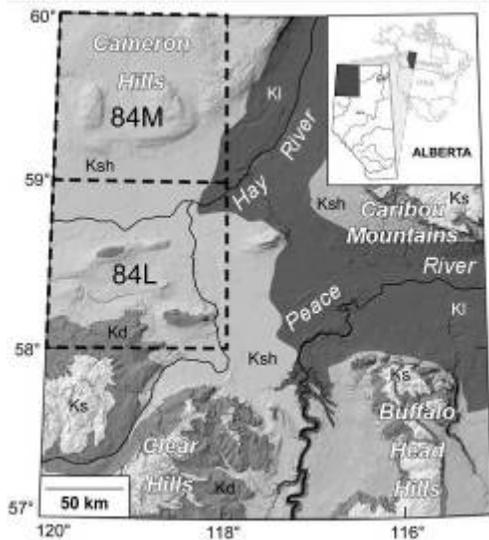


Fig. 1. Physiography and bedrock geology of northwest Alberta in which the sampling survey (National Topographic System sheets 84M and 84L) was undertaken. Cretaceous bedrock units listed from oldest to youngest (after Hamilton *et al.* 1998): Loon River Formation (Kl), Shaftesbury Formation (Ksh), Dunvegan Formation (Kd) and Smoky Group (Ks).

METHODS

Bulk sediment samples (~30 kg) of till (n=63) and glaciofluvial sediments (n=7) were collected in C soil-horizon (>1 m depth) from hand-dug pits, natural bluffs, and man-made exposures. Samples underwent heavy mineral separation ($SG \geq 3.2 \text{ g/cm}^3$) using a shaking table and heavy liquid separation. Heavy indicator minerals were visually identified and picked from the sand-sized fraction (0.25 – 2.00 mm).

Selected sphalerite grains (n=15) were mounted and analyzed by electron microprobe. Isotopic analyses of Pb were conducted on galena and sphalerite grains at Carleton University. Sulphur isotope analyses were performed on sphalerite powders at the University of Ottawa.

RESULTS AND DISCUSSION

Heavy Mineral Signature

A sphalerite dispersal train occurs in the centre of the study area (Fig. 2). Dark grey to black, brittle grains of sphalerite were found in high concentrations (>100 grains)

in nine till samples including one sample with 1047 sphalerite grains (normalized to 30 kg sample weight; (Plouffe *et al.* 2006). Background concentration in local till is zero grains. Grains exhibit pristine morphology with angular to sub-angular edges. The mineralogical anomaly extends over an area of approximately 4000 km². One to four angular to sub-angular galena grains were recovered in eight of the till samples from the anomalous region.

Sphalerite Chemistry

The average composition of the 15 sphalerite grains analyzed is 33.4 wt.% S, 65.4 wt.% Zn, 0.7 wt.% Fe and 0.43 wt.% Cd with trace amounts (0.3 to 0.1 wt.%) of Cu, Ag, Se, and In (Plouffe *et al.* 2007). Compared to the composition of sphalerite from the world class Pine Point Mississippi Valley-type Zn-Pb deposit, 330 km to the northeast (Kyle 1981), sphalerite from this study contains lower levels of Pb and Fe and higher Cd concentrations.

Isotopic Fingerprinting

Of the ten galena grains recovered from the till, nine cluster into one population which exhibit very small variations in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{206}\text{Pb}$. These nine galena grains lie within the “Pine Point lead” cluster that includes data from the Pine Point orebodies (Cumming *et al.* 1990), other Zn-Pb occurrences in the Pine Point district (Paradis *et al.* 2006), and subsurface sulphide occurrences in drill cores from carbonate sequences of the WCSB located along the GSSLZ. One galena grain is more enriched in $^{206}\text{Pb}/^{204}\text{Pb}$ and plots below the “shale curve.” The only two sphalerite grains analyzed for Pb isotopes plot below the “shale curve” away from the “crustal evolution curve” (Fig. 3).

The “Pine Point lead” isotopic signature is quite distinctive (Fig. 3). It shows remarkable homogeneity, with $^{206}\text{Pb}/^{204}\text{Pb}$ values in a narrow range of 18.167 - 18.189, indicating either a homogeneous source or a thorough mixing of Pb during extraction, transport, and precipitation (Cumming *et al.* 1990; Paradis *et al.*

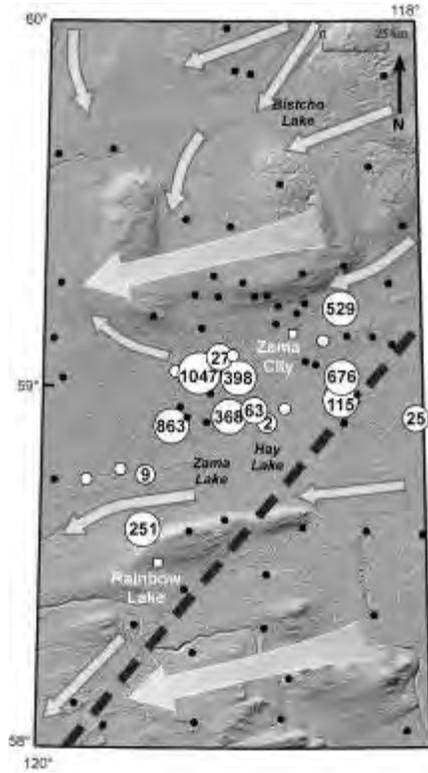


Fig. 2. Sphalerite grains recovered from glacial sediments, normalized to 30 kg sample weights, plotted on a Shuttle Radar Topography Mission (SRTM) generated digital elevation model. Small white circles represent a single grain count; small solid black circles indicate samples with no recovered sphalerite. The GSLSZ, projected to surface (Eaton & Hope 2003), is shown as the thick dashed line. Large arrows depict ice flow during glacial maximum and smaller arrows indicate local lobes of flow during deglaciation.

2006). Modelling of U and Pb concentrations and ratios suggest a depleted lower crustal source consistent with Pb derivation from basement rocks (Nelson *et al.* 2002; Paradis *et al.* 2006).

Sphalerite from the till displays a range of $\delta^{34}\text{S}$ values from -14.1 to -6.0 per mil with a mean value of -9.0 per mil. These low values are interpreted to be the result of bacterial reduction of coeval seawater sulphate. These values are different than those reported for Mississippi Valley-type deposits in the northern and southern Cordillera, which are dominantly much heavier (Fig. 4). Sulphur isotope values

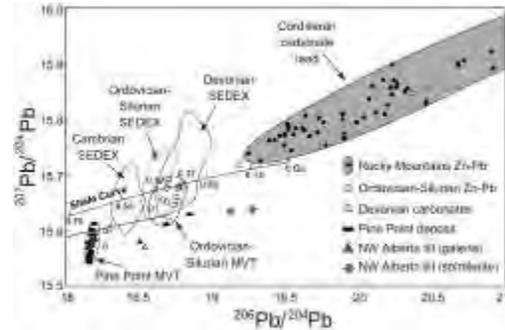


Fig. 3. Lead isotopic data ($^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$) from till of northwest Alberta compared with data from the Pine Point district, Cordilleran Zn-Pb deposits, and known WCSB occurrences (Paradis *et al.* 2006).

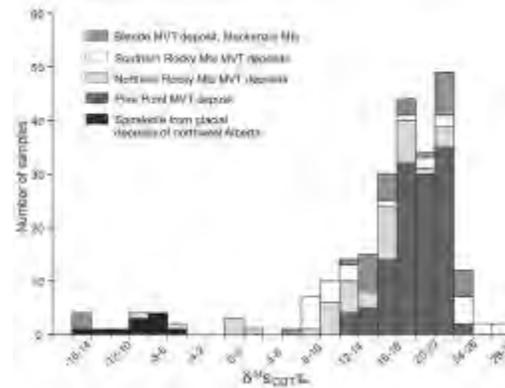


Fig. 4. Histogram of $\delta^{34}\text{S}$ values for sphalerite grains from NW Alberta till samples, the Pine Point Pb-Zn deposit and other Pb-Zn deposits in the Rocky and Mackenzie mountains (Paradis *et al.* 2006).

from the Pine Point deposits range from 12.2 to 27.0 per mil (Evans *et al.* 1968).

CONCLUSION

The bedrock source(s) of the sphalerite and galena grains recovered from till in northwest Alberta remains unknown. Data presented here indicate that this mineralogical anomaly in till is not derived from the nearest known Zn-Pb deposit, Pine Point. The anomaly occurs in close proximity to the GSLSZ (Eaton & Hope 2003). The Pb isotopic values of the galena samples from the till samples in northwest Alberta are identical to those of the Pine Point district and other occurrences along the GSLSZ. Therefore,

we suggest that the bedrock source(s) for the sphalerite and galena grains in the till is probably local sulphide occurrence(s) situated along the GSSLZ, hosted in Cretaceous sediments of the WCSB.

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Imaging a buried diamondiferous kimberlite using conventional geochemistry and Amplified Geochemical ImagingSM Technology

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ABSTRACT: Accurate mapping of mineral deposits buried by tens to hundreds of meters of overburden will focus an exploration program, minimizing costs and time expended. Traditional surface geochemical techniques often focus on measuring and mapping metal ions in the soil or vegetation, water/soil chemical properties, and by-product gases such as oxygen and carbon dioxide. A new technique, Amplified Geochemical ImagingSM Technology, focuses on high sensitivity measurements of volatile compounds emanating from the mineral deposit itself, its contact zone, or associated redox systems. Compounds ranging from light sulphur species to organics with 18 carbon atoms, which are found at the surface, are collected and analyzed using a sensitive and sophisticated analytical technique. Differentiation of compounds associated with the mineralization and a robust image of the buried deposit are then obtained by processing the data using advanced modelling systems and multivariate statistical methods. This new technique works well with high content sulphur minerals such as those deposits hosted in Volcanogenic Massive Sulphide, porphyry Cu, Mississippi Valley-type, and some gold systems. In this paper, Amplified Geochemical ImagingSM Technology, along with conventional surface geochemical analysis, was used to image a kimberlite.

KEYWORDS: *diamond, kimberlite, soil geochemistry, imaging, volatile*

INTRODUCTION

In regions where bedrock is covered by thick sediments, application of surficial geochemical exploration methods has led to a great deal of success. This paper identifies responses of Gore Amplified Geochemical ImagingSM (GAGI) compounds ranging from light sulphur species to organics with 18 carbon atoms (Anderson 2006) over kimberlites, which correlate well with geochemical responses in soil.

GEOLOGICAL SETTING

The Honerat kimberlite is approximately 45 km east of the town of Ville-Marie, western Quebec, Canada (Fig. 1). Gravity surveys and drilling have indicated that the kimberlite was emplaced along a normal fault structure trending NW-SE. Kimberlites in this region are of Jurassic age. The Honerat kimberlite is approximately 85 m in diameter, based on company drill logs. The subcropping

surface of the kimberlite consists of hypabyssal facies kimberlite. Country rocks are dominantly Archean felsic to intermediate metavolcanics and the surficial sediments sampled at Honerat consisted of clay with minor silt to silt with minor clay. Continental-scale glaciation has affected the region several times during the Quaternary. The most recent glaciation retreated from the study area approximately 8000 years BP (Veillette 1994), during which time thick deposits (45 to 90 m) of unconsolidated glacial, glaciofluvial and glaciolacustrine sediments were deposited over the Honerat kimberlite.

A second location approximately 5 km south of the Honerat kimberlite was also studied (named Unknown) (Fig. 1).

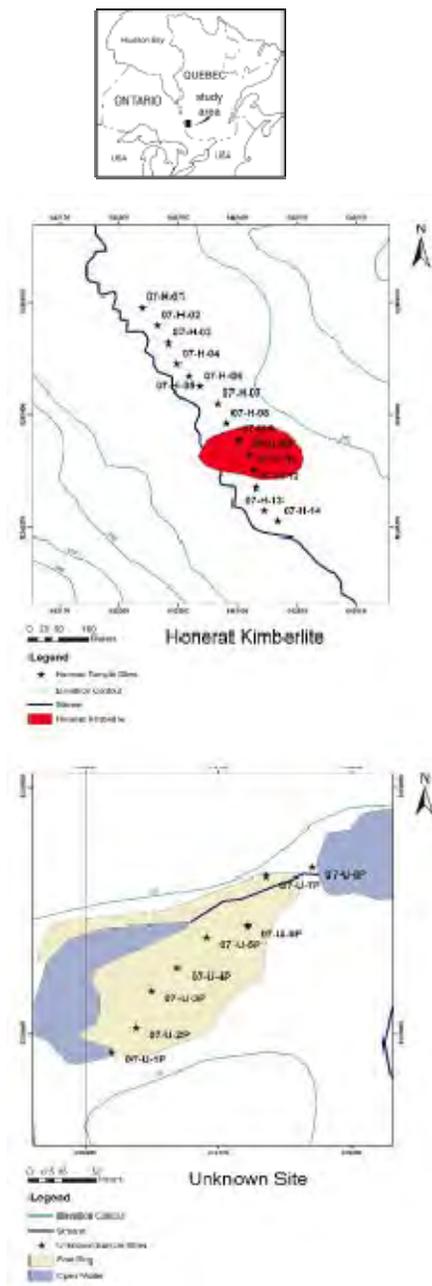


Fig. 1. The Honerat kimberlite and the Unknown Site are located in western Quebec, Canada. The labeled points represent sample collection sites along transects at Honerat and Unknown.

Although no kimberlite is known of in this second area, kimberlite boulders and elevated kimberlite indicator mineral counts in glacial sediments have been

found within 300 m of the Unknown site. This location was also interpreted to be a possible site for a kimberlite pipe because it is along a NE-SW trending graben structure. The terrain at Unknown is saturated peat, between 1 and 4 m deep, which overlies fine gravel. Depth to bedrock at this test site is not known.

METHODS

Soil samples were collected along a traverse over the Honerat kimberlite and extended off the kimberlite approximately 75 m SE and 225 m NW from the pipe's centre (Fig. 1). Although it is common practice to collect samples from upper B-horizon soil (Levinson 1980; Bajc 1998; Mann *et al.* 2005) our samples were collected from C-horizon soil because GAGI samplers were placed at a depth of 60 cm (well below the B horizon). Within 8 hours of sampling, a portion of each soil sample was mixed with Milli-Q water (1:1) to create a slurry. The values of pH and oxidation-reduction potential (ORP) were determined in each slurry. Ammonia acetate leach of the soil samples were performed at Acme Analytical Laboratories, Vancouver, where 20 ml of ammonium acetate was mixed with 1 g soil sample and elements were determined by inductively coupled plasma-mass spectrometry. The GAGI samplers installed at Unknown were placed in piezometers and submerged in water at a depth of approximately 1 m below ground surface.

The GAGI samplers, installed along traverses at both Honerat and Unknown, were left in place for 5 months before being retrieved. Retrieved samplers from both locations were sent to Gore Laboratories where they were heated, and compounds were thermally desorbed and analyzed with a gas chromatograph/mass spectrometer (GC/MS).

RESULTS AND DISCUSSION

Soil slurry ORP values are lower over the Honerat kimberlite (near 0 mV) compared to other locations along the sampling traverse (up to 100 mV). Over this kimberlite there is also a marked depletion

in concentrations of a variety of elements such as Ni, Mg, Co, K, and total REEs in soil directly over the kimberlite (Fig. 2). Conversely, enrichments of these elements at the margin(s) of the kimberlite are evident. The elemental results are similar to the soil geochemical signature over the 95-2 kimberlite, approximately 60 km to the west (McClenaghan *et al.* 2006).

Reduced ions from the Honerat kimberlite are accumulating in the surface soil producing low ORP values. Low ORP values over the kimberlite with high values near the margins suggest the presence of a “reduced chimney” (Hamilton *et al.* 2004a, 2004b), where reduced species (such as Fe²⁺) are migrating from the underlying kimberlite through glacial sediments to surface.

The partial leach results from soil samples identify the location of the buried Honerat kimberlite. The depletion of Ni, Mg, Co, K, and total REEs in C-horizon soils over the Honerat kimberlite suggests that numerous kimberlite pathfinder elements are not adsorbed on to soil particles. Instead, they are remaining in the dissolved phase in solution due to the more reducing environment inside compared with outside the kimberlite. However, as elements migrate out of the kimberlite “reduced chimney” environment into a more oxidizing environment, they may adsorb to soil particles, possibly oxyhydroxide complexes and produce elevated element responses at the margins of the kimberlite.

The data obtained by GAGI correlate well with soil geochemical data for the Honerat kimberlite. Individual components of the Gore analysis such as elevated dimethyl sulfide, and lower concentrations of methyl butane (Fig. 3a & b) are found at the same locations as low relative element concentrations and more reducing conditions. The spatial correlation between changes in the redox conditions, the depletion of metals, and some GAGI compounds suggests either the upward migration of GAGI compounds from the kimberlite or their formation/depletion in soil due to changing redox conditions. We suggest the latter interpretation based on

the variation of $\delta^{13}\text{C}$ for dissolved inorganic carbon (DIC) in peat groundwaters from Unknown. The values of $\delta^{13}\text{C}$ compared with concentrations of sulfide and hydrocarbons suggest biogenic reactions with inorganic carbon.

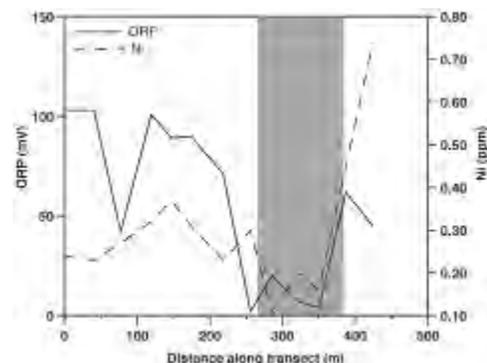


Fig. 2. Low relative ORP values correlate with low Ni values in soils over the Honerat kimberlite (depicted as the grey zone).

CONCLUSIONS

This paper demonstrates that, in addition to soil geochemical exploration techniques, Gore Amplified Geochemical ImagingSM is another tool for the exploration geochemist.

- 1) Kimberlite bodies can be identified at ground surface using soil geochemistry where 90 m of glacial sediment overlies a kimberlite. This is based on variations in element concentrations of pathfinder elements such as Ni, Mg, Co, K, and total REEs over versus off a kimberlite.
- 2) The Gore Amplified Geochemical ImagingSM technique, like soil geochemistry, shows anomalous concentrations of sulfides and hydrocarbons in soils over the kimberlite.
- 3) Values of $\delta^{13}\text{C}$ -DIC correlate with some hydrocarbons at the Unknown Site and suggest that Amplified Geochemical ImagingSM responses could be the result of surficial bacterial communities that thrive over kimberlites.

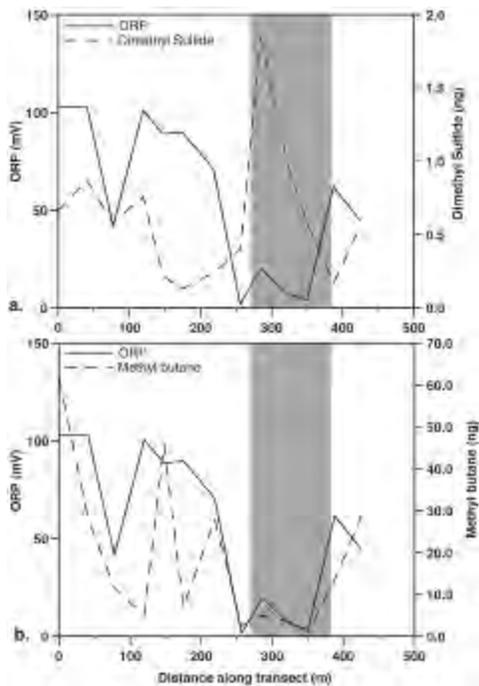


Fig. 3. High concentrations of dimethyl sulfide (a) and depleted concentrations of methyl butane (b) correlate with reducing soils over the kimberlite (depicted as the grey zone).

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We thank Dr. Thomas Morris, President and CEO, and Mr. Matthew Sooley of Northern Superior Resources for providing information on, and access to the site. Field expenses and analytical costs were supported by an NSERC Discovery Grant. Funding for this project was also provided in part by an Ontario Graduate Scholarship (support for Jamil Sader's Ph.D.) and a student research grant from the Society of Economic Geologists.

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New advances in geochemical exploration in glaciated terrain – examples from northern Finland

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ABSTRACT: New geochemical sampling and analysis methods were tested in northern Finland. The purpose was to test new applications for regional and/or target-scale exploration by using surficial till as a sample material. The tests were carried out as part of a gold, nickel and PGE exploration project. One of the tested methods was mobile metal ion method of which results were compared with the results of enzyme leaching, soil gas and partial leaching methods. Sampling was carried out using small, hand-dug test pits. Another method tested was using an on-line XRF method, using continuous, 5 to 20 m long till and weathered bedrock samples from test excavations, and at the second stage from 0.5 km to 3 km long sampling lines (50 m interval) with percussion drilling. Based on these results, all methods have potential for exploration purposes in glaciated terrain, although the detection limits can cause some limitations. For example, using on-line XRF methods it is possible to find out elevated contents of trace elements in till as a mark of mineralization or mineralized alteration zones in the bedrock, and to direct target-scale sampling and research.

KEYWORDS: *geochemical methods, weak leach, XRF, till, exploration*

INTRODUCTION

Till geochemistry is a widely used method in regional- and target-scale exploration and mineral potential mapping in Finland. Sampling is usually carried out by using percussion drilling and/or test pit surveys with following partial leaching and analyses of inductively coupled plasma atomic emission spectrometry (ICP-AES) and/or graphite furnace atomic absorption spectrometry (GAAS). However, this sampling procedure is often expensive and time-consuming.

Based on this background new sampling and analytical methods have been tested in northern Finland to seek new applications for exploration by using surficial till as a sample material with emphasis on decreasing analytical costs and increasing sample efficiency. This study was carried out as a part of on-going Au, Ni and PGE exploration project of the Geological Survey of Finland.

METHODS

In the first test phase, several weak leach methods were tested. Samples were collected from the small hand-dug test pits

(Fig. 1) for mobile metal ion (MMI), enzyme leaching and soil gas analyses. The results were compared against known results of analyses based on partial leaching. MMI sampling procedure as outlined by SGS Group Laboratories (http://www.geochem.sgs.com/sampling_f_or_mmi_geochem). Trace element analyses were completed in the ALS Chemex laboratory.

In the second test phase, the application of a new on-line XRF-scanner was tested for 1) continuous till and weathered bedrock samples and 2) till profiles with sampling interval of about 100 m. Continuous samples were taken from the tractor excavated test trenches both from the surface of the pre-Quaternary weathered bedrock and from the till about 0.5 m above the weathered bedrock surface.

For the profile (length from 0.5 to 3 km, point interval of 50 m) sampling, both small hand-dug test pits (depth about 50 cm) and percussion drilling (sampling depth 1 to 1.5 m) have been used. Measurements were made using the ScanMobile system which is a moving



Fig. 1. Sampling point for the weak leach analytical samples, northern Finland.

scanning unit produced by the Mine On-line Services Limited. New sample handling methods were developed for the XRF scanning process. After removing pebbles >1 cm, till samples with natural moisture were put into the wooden boxes: continuous samples, 6 m per box (Fig. 2), and profile samples, 48 pieces per box (Fig. 3).

RESULTS

The test of weak leach methods shows that glacial till and stratified sediments are usable material for mobile metal ion tracing. The thickness of overburden is not an essential factor for affecting the mobile ion concentrations in the upper soil horizon. However, the influence of complex till stratigraphy is not clear for ion mobilization from the bedrock source of surface.

The large number of trace elements available in weak leach analytical packages is effective for many types of ore exploration. In surveys for Au, Ni and PGE deposits, many anomalies in surficial sediments have been found, and detailed studies have shown that these anomalies reflect bedrock (source) mineralization. As an example, Figure 4 shows a Ni anomaly

in surface sediment with a mineralized zone sourced in the bedrock at the contact



Fig. 2. Continuous pre-Quaternary weathered bedrock sampling, placed into core boxes that allow for 6 m of continuous length.

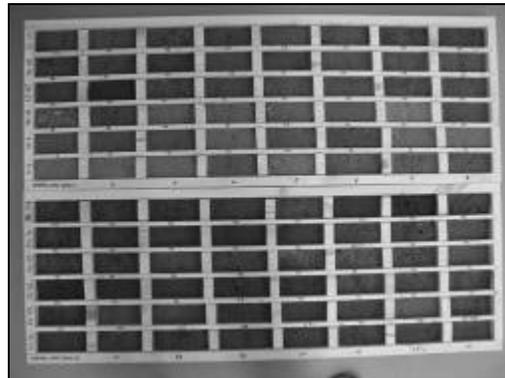


Fig. 3. Profile till samples placed into the wooden boxes ready for XRF-scanning.

of metakomatiitic volcanic rocks and quartzite (Fig. 4).

Mobile, on-line XRF methods have been tested in the Au exploration targets. Analysis of continuous till and weathered bedrock samples shows clear variation of the contents of pathfinder elements of hydrothermal alteration. Particularly, in the weathered bedrock, the presence of narrow mineralized veins is seen (Fig. 5). One interesting feature is that the indication of the weathered bedrock sources can be traced 2 to 5 m down-ice in the till. These results suggest very short glacial transport of mineralized debris from the bedrock sources. Information on

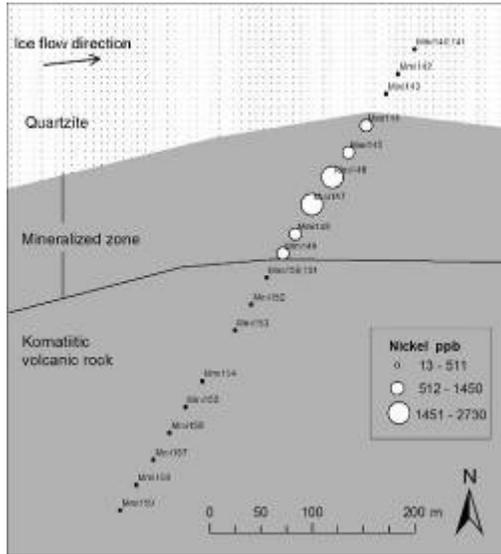


Fig. 4. An example of Ni (MMI) anomaly in till indicating mineralization in the bedrock.

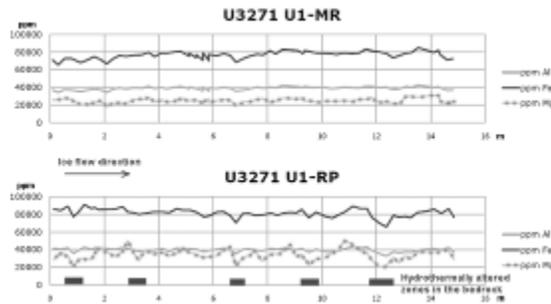


Fig. 5. An example of Al, Fe and Mg contents in continuous weathered bedrock and till samples analyzed with on-line XRF method. MR = till, RP = weathered bedrock.

transport distance and is very important for planning other till geochemistry sampling within the region.

XRF analyses of the profile till sampling reflects lower variation of trace element content. However, it is possible to see indications of mineralized bedrock as relatively higher element concentrations particularly, if overburden is thin.

CONCLUSIONS

Use of weak leach methods shows that mobile ion concentrations in the upper soil horizons can be used for tracing mineralization or mineralized structures in

the bedrock. Au, Ni and PGE type deposits have been found based on the studies carried out in northern Finland. This method is also usable for bedrock mapping in the areas of thick glacial overburden.

Mobile, on-line XRF-scanning is a new tool for exploration when using till and weathered bedrock samples. Detailed geochemical mapping is possible if continuous samples are taken. The most prospective regional- or target-scale zones in the bedrock can be traced with long till sampling profiles using light-weight sampling methods (e.g., shallow hand-dug test pits or percussion drilling). The benefit of this method is low analytical costs and faster turn around time for results.

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Regional geochemical soil data as aid to the reconstruction of Mid-Pleistocene ice flows across central and eastern England

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ABSTRACT: Principal component analysis of high-density, regional soil geochemical data was used to reveal element associations within Mid-Pleistocene glacial till deposits across Central and Eastern England. Results have helped to characterise tills by their geochemical composition at a regional scale, leading to a better understanding of, (i) which parent materials tills have been derived from, (ii) sediment transportation paths and flow trajectories of the British Ice Sheet, and (iii) the evolution of the British Ice Sheet during the Mid-Pleistocene.

KEYWORDS: *Soil geochemistry, glacial till deposits, PCA, ice flow reconstruction*

INTRODUCTION

Tills are the most difficult superficial deposits to interpret and classify, but are crucial to the reconstruction of former glaciations and understanding the coupling between ice sheet behaviour and climate change (Evans 2007). Geochemical surveys of tills in Finland and Canada have successfully demonstrated that geochemical data contain vital information for refining glacial stratigraphy, determining till sediment provenance, and reconstructing ice flow trajectories (McClenaghan *et al.* 1992; Klassen 2001; Sarala 2005). Anglian-age (c. 450 ka) glacial deposits of Central and Eastern England are complex and have been studied in various detail, but studies have not yet utilised the vast resource of high-density soil geochemical data held by the British Geological Survey (BGS). The aim of this study was to investigate the potential of this regional soil geochemical data help to characterise and classify glacial till deposits as well as to reconstruct glacial flow trajectories and its sediment sources. This was tested by using multivariate principal component analysis (PCA), which is a helpful means to manipulate and interpret multi-element geochemical data as shown by Grunsky and Smee (1999) and Ali *et al.* (2006).

MATERIALS AND METHODS

Study area and data

The study benefits from access to a geochemical database containing analytical data from ~ 27,500 soil samples collected since 1986 by the Geochemical Baseline Survey of the Environment (G-BASE) (Johnson *et al.* 2005). The area presented in this study covers more than 40,000 km² of Central and Eastern England (Fig.1). Soils were collected at a density of one sample every two km² of the British National Grid (BNG). At each site, samples were collected, from (5-20 cm) and (35-50 cm), of which latter were used in this study. Each sample comprising a composite of material of five sub-samples collected at the corners and centre of a 20 m square. A more detailed account on the sampling procedures used and sample preparation can be found in Johnson *et al.* (2005). Major and trace element determinations were carried out by X-ray fluorescence spectrometry (XRFS) giving a range of up to 53 elements. However, this study used only 25 elements (Ba, Ca, Co, Cr, Cu, Fe, Ga, K, La, Mg, Mn, Mo, Nb, Ni, P, Pb, Rb, Sn, Sr, Ti, U, V, Y, Zn and Zr) as some elements were excluded on quality issues. Prior to PCA, analytical data were log-transformed, as investigated by Reimann *et al.* (2002).

A spatial join of the analytical data with BGS DiGMapGB-50 Superficial Geology returned data for ~ 4,700 soil samples, which had been collected over glacial till deposits (Fig.1) of Mid-Pleistocene, Anglian age.

Geological setting

Central and Eastern England is almost entirely underlain by sedimentary rocks that young from west to east. Four major geological sub-divisions are presented in Figure 1. Permian and Triassic mudstone and sandstone dominate the East Midlands and parts of Yorkshire; Jurassic clays crop out within the centre of the study area and Cretaceous chalk underlies most of Central East Anglia.

Figure 1 shows the distribution of sample sites located directly over Anglian till deposits, covering approximately a quarter of the study area. North of the Devensian limit (also known as Dimlington re-advance) occur younger till deposits of the Devensian glaciation. More than half of the sample sites were located over diamictons of the Lowestoft Formation (LOFT) of East Anglia. The remaining tills are classified as Mid-Pleistocene diamictons (TILMP), and the Oadby Till (ODT) and Thrussington Till (THT) members of the Wolston Formation in the Midlands. Several possible ice flow scenarios could account for the spatial and lithological distribution of these tills (Perrin *et al.* 1979).

Ice trajectory scenarios are A) ice flowing southwards from the North Sea Basin and into northern East Anglia, B) ice flowing into East Anglia and East Midlands through The Wash Basin radiating to the east and C) west. The fourth scenario (D) describes ice moving down from northern Central England into the Midlands in southerly direction and then radiating into East Anglia.

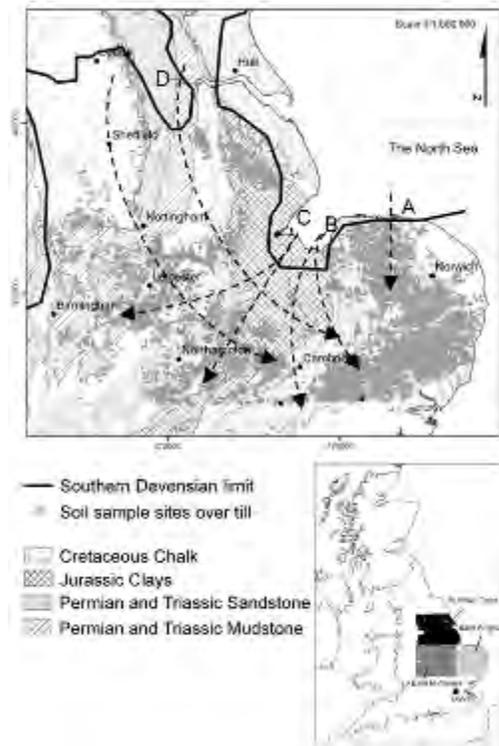


Figure 1. Distribution of soil sample sites collected over glacial till deposits, ice flow scenarios (A to D) and main bedrock strata of the study area.

RESULTS

PCA is a popular approach for analysing large multi-element datasets for two reasons. Firstly, the reduction of the number of variables to form a small number of independent principal components and secondly, the creation of more interpretable combined variables (Ali *et al.* 2006). The analysis was carried out using a correlation matrix in order to reduce the effects of magnitude that are attributed to elements such as Ca, Fe, K and Mg (Grunsky & Smee 1999). A total of 15 principal components were calculated until 95 % of the variance was explained. Eigenvalues returned from PCA were plotted in a scree plot (Fig. 2), which gives an indication as to the significance of the derived PCs (Grunsky & Smee 1999).

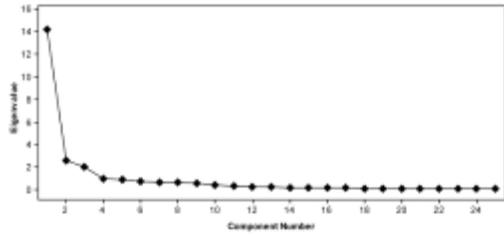


Fig. 2. Scree plot of eigenvalues

PCs with high eigenvalues are assumed to best represent the geochemical variability and characteristics of the data. Components 4 and higher returned Eigenvalues below 1.0 and were excluded from further interpretation, as discussed by Mandal *et al.* (2008).

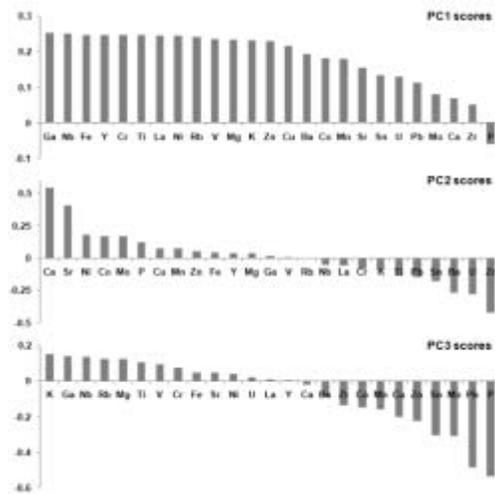


Fig. 3. Score loadings for PC1 to 3

PC1 represents 57% of the total variance of the data with an eigenvalue of 14.2. PC2 accounts for a further 10 % and PC3 for 8.0% of the total variance with eigenvalues of 2.6 and 2.0 respectively.

Element loadings of the first three PCs are displayed in Figure 3. PC1 includes all selected elements with only P being inversely related. Loadings of PC2 present a much clearer variation in the data and correspond to Ca-Sr association, thought to be related to limestone and chalk bedrock.

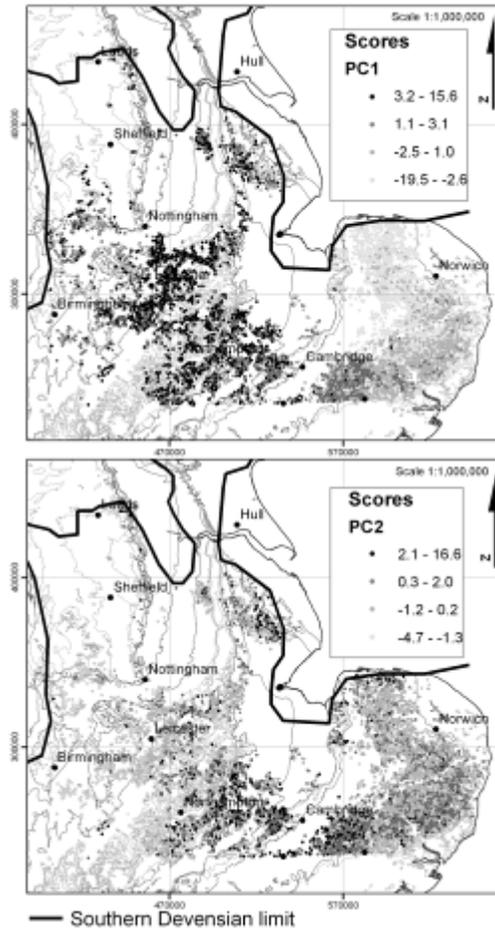


Fig. 4. Spatial distribution of PC1 and PC2 loading scores across Central and Eastern England.

Positive loadings of K, Ga and Nb in PC3 are indicators for clay rich soils. Negative loadings correspond to heavy metals and may indicate an anthropogenic component. Figure 4 displays spatial distribution of scores of PC1 and PC2. High scores of PC1 are mainly located over the East Midlands area, whilst the northern half of East Anglia, with low or negative scores, appears relatively deficient in these elements. High scores of PC2 are located between Northampton and the east of Cambridge, south of the Humber estuary at Hull and along the northern coastline of East Anglia. Tills in these areas were derived from calcareous and Sr-bearing strata, most likely Cretaceous Chalk (Fig. 1).

CONCLUSIONS

This study is in progress and gives only preliminary results. However, the application of multivariate analysis has already highlighted various geochemical characteristics and associations within soils collected over Mid-Pleistocene tills. Findings can be summarised as follows:

(1) Regional geochemical soil data can provide vital information on the composition and provenance of glacial till deposits in Central and Eastern England.

(2) PCA has highlighted some clear regional divisions within the tills, especially between the East Midlands and East Anglia

(3) Ice flow scenario A is unlikely. Scenarios B and C have occurred mainly in a southerly direction, carrying chalky material and possibly overriding earlier ice flow D.

(4) To classify tills, most significant indicator elements are Ga, Mg, K, Rb, Ca, Sr and P.

(5) Further investigation should involve the integration of lithological and grain-size data as well as other methods of data analysis.

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Till geochemical and indicator mineral methods in mineral exploration: history and status

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ABSTRACT: Detection of clastic debris transported from mineralized sources is the basis of mineral exploration methods ranging from boulder tracing to elemental and indicator mineral methods. Essential to successful application of these methods to tracing of mineralized debris to bedrock sources in recently glaciated environments are an understanding of glacial process and history, combined with sound survey design and interpretation. In North America and Fennoscandia, advances in mineral exploration and glacial geology were mutually supportive in the latter 20th century, concurrent with a shift in exploration to overburden-covered regions. Developments during this time began with recognition of the relevance of glacial process and history to prospecting, and progressed with increased comprehension of the textural and mineralogical tendencies of glacial sediments. Development of logistics suited to glaciated environments such as reverse circulation drilling followed, and in the 1990s, the discovery of diamonds in Canada resulted in much progress in application and awareness of drift prospecting methods. As a result, the discipline now centres on intricate indicator mineral and elemental methods that bring together the most current insights into glacial geology, mineral deposit geology, and mineral chemistry, in the search for a full range of commodities.

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

INTRODUCTION

In glaciated terrain, 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

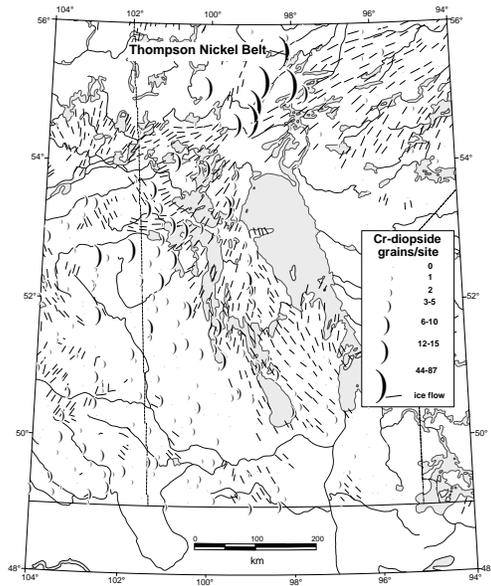


Fig. 1. An indicator mineral plume consisting of Cr-diopsides glacially dispersed from the Thompson Nickel Belt in Manitoba, Canada, detected in ~20 litre till samples at a 30-km spacing (Thorleifson *et al.* 1994; Thorleifson & Matile 1997).

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

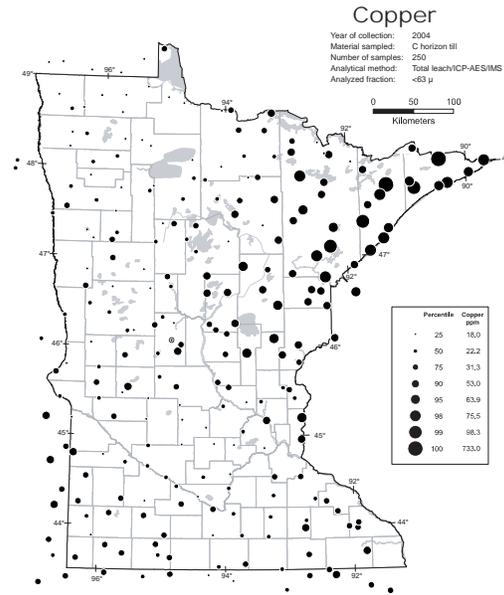


Fig. 2. Mapping of sediment composition by government agencies provides a reference for exploration by mapping background, identifying problematic areas, and by providing examples of anomalies (Thorleifson *et al.* 2007).

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 be used to detect elements diagnostic of specific mineral grains or their weathering products, typically 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 size fractions may also be analyzed to trace provenance, in order to assist interpretation.

Several syntheses have reviewed the application of till geochemical and indicator mineral methods to mineral exploration in glaciated terrain (Coker & DiLabio 1989; DiLabio & Coker 1989; Kujansuu & Saarnisto 1990; Kauranne *et al.* 1992; Bobrowsky *et al.* 1995; Shilts 1996; McClenaghan *et al.* 1997, 2001; Thorleifson & McClenaghan 2003, 2007;

McClenaghan 2005; Paulen & McMartin 2009).

HISTORY

Pre-20th century literature includes reference to glacially transported boulders and mineral grains being recognized as indicators of mineral potential (e.g., Tilas 1740), 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 of its principles 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 (Skinner 1972).

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 & 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 (Averill 2001).

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Numerical Evaluation of Partial Digestions for Soil Analysis, Talbot VMS Cu-Zn Prospect, Manitoba, Canada

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ABSTRACT: To enhance the subtle geochemical expression of ore deposits in surface soils developed on exotic sediment cover, various partial digestions and selective extraction methods have been developed, targeting specific phases in the soil or cation sorption sites. Eleven extraction methods were assessed for their exploration performance on soil samples from a 1000 m transect across the Paleoproterozoic Talbot VMS deposit, hosted by metavolcanic and metasedimentary sequences of the Flin Flon – Snow Lake terranes that are overlain by 100 m of Paleozoic dolomite and 0 to 2 m of Holocene glacial and glaciolacustrine sediments. As a numerical screening tool for exploration performance, Student's *t* test and *t* probability (P_t) statistics were applied to evaluate the magnitude and spatial accuracy of anomalies in each data set. In the surface soils that were analyzed, Zn anomalies have the highest contrast for most methods, followed by P and Cd. Extraction methods by which Zn anomalies were identified within the >95% confidence interval (i.e. $P_t < 5\%$) were ranked numerically, in decreasing order of exploration performance (increasing P_t): Enzyme Leach (0.3%), deionized water (0.8%), sodium pyrophosphate (0.9%), MMI (1.6%), clay fraction aqua regia (2.2%), and ammonium acetate at pH 7 (2.3%).

KEYWORDS: soil geochemistry, partial digestion, Student's *t* distribution, VMS Cu-Zn

INTRODUCTION

Soil geochemistry is widely applied in mineral exploration, and with advancing knowledge of speciation and residence phases of trace elements in soils, a variety of partial and selective extractions for chemical analysis have been developed over the past decades. Each of these methods has been designed to target and dissolve only those elements that are adsorbed onto labile phases in soil, from carrier fluids and gases that transported them from a deposit to the surface (e.g. Hall *et al.* 1996).

In this case study, 11 different extraction methods (Table 1) were applied to a 1000 m line of 15 B/C-horizon soil samples (<0.25 mm) across the Talbot VMS Cu-Zn deposit in northern Manitoba, Canada (Fig. 1), followed by ICP-MS analysis. Student's *t* test and minimum *t* probability statistics provide a tool to rank the 'exploration performance' of each method (Stanley 2003; Stanley & Noble 2008). By

comparing the means and standard deviations of the anomalous and background sub-populations of the soil data set, the probability that they are derived from the same parent population can be calculated as a percentage (P_t). The greater the contrast between the anomalous and background sub-populations, the smaller P_t , and the better the element indicates the anomaly. T probability was calculated for all elements in each extraction method, with Zn showing the strongest anomalies for most extraction methods.

GEOLOGICAL SETTING

The Talbot VMS Cu-Zn prospect is situated in the eastern extension of the Paleoproterozoic Flin Flon Belt (1.92 – 1.88 Ga), north-western Manitoba (Stern *et al.* 1999). The prospect is located just northeast of Lake Talbot, about 160 km SE of Flin Flon (Fig. 1). Mineralization is hosted by medium to high-grade

Table 1. Partial digestions and selective extractions applied to Talbot soil samples (<250 µm fraction)

Method (ICP-MS)	Target Phases	Laboratory
Deionised water	Soluble components ¹	GSC
Ammonium acetate at pH 7	Exchangeable cations, soluble ¹	GSC
Ammonium acetate at pH 5	Fine carbonates, exchangeable cations ¹	GSC
Sodium pyrophosphate	Organic complexes ¹	GSC
Hydroxylamine hydrochloride	Amorphous Fe-Mn oxides ¹	GSC
1% Nitric acid	Carbonates, adsorbed components ¹	GSC
Aqua regia	All but silicates and stable oxides ²	ACME Labs
Aqua regia clay fraction (<2 µm) [†]	All but silicates and stable oxides ²	ACME Labs
Enzyme Leach SM (proprietary)	Enzymatic, bio-available ³	Actlabs
Bioleach (proprietary)	Bio-available ³	Actlabs
MMI TM (proprietary)	"Mobile metal ion" ⁴	SGS

¹Hall 1996a & b, Geological Survey of Canada (GSC); ²ACME Labs 2009; ³Actlabs 2009; ⁴SGS 2009

[†]Physical extraction by suspension and centrifugation in deionized water



Fig. 1. Location of the Talbot prospect (inside black circle), Manitoba, Canada .

metamorphic arc assemblages (Syme & Bailes 1993) and occurs as coarse grained, massive to semi-massive and disseminated sulphides: chalcopyrite + sphalerite + pyrite ± pyrrhotite (Bailes & Galley 1999). The Proterozoic rocks are overlain by 100 m of Palaeozoic carbonate sequences of the Western Interior Basin and 0 to 2 m of Quaternary glacial and glaciolacustrine sediments.

Minor intra-plate tectonics and isostatic rebound after glaciation have fractured the

carbonate cover (Elliott 1996). Normal faulting of the carbonate cover with vertical offsets over 5 m has been observed in the Talbot area. These fractures, as well as many smaller cracks and joint sets, may allow fluids and gases to migrate upward and transport elements from the basement to the surface.

The soil in the study area is developed in clays and fine grained till (clay to sand - rich matrix), and soil horizons are poorly developed in the boreal climate. Vertical relief around the prospect is minimal, less than 10 m in general, and standing water occupies low-lying areas most of the year. The area was glaciated between 13 ka and 10 ka, after which it was covered by the large water body of Lake Agassiz, until ~8 ka (Teller & Leverington 2004) in which glaciolacustrine sediments were deposited. The local vegetation consists mostly of sphagnum moss and coniferous trees.

RESULTS

Student's *t* test statistics and *t* probability were calculated to quantify the contrast between 'anomalous' and 'background' populations in each extraction method data set (Student 1908; Stanley & Noble 2008). Sample sites were designated 'anomalous' based on the projection of mineralization and a fault zone in the cover rocks. For most methods, Zn

Table 2. Numerical ranking of extractions, based on *t* probability distribution of Zn

Method, Zn <i>t</i> probability	%
Enzyme Leach	0.3
Deionized water	0.8
Sodium pyrophosphate	0.9
MMI	1.8
Aqua regia clay fraction (<2 μm)	2.2
AA7	2.3
AA5	6.5
Aqua regia	11.7
Hydroxylamine hydrochloride	17.6
1% Nitric acid	46.8
Bioleach (negative <i>t</i> , as $\mu_a < \mu_b$)	(-)80.0

anomalies have the greatest contrast between anomaly and background, followed by P (if detected) and Cd (Fig. 2). Enzyme Leach produces the greatest contrast for Zn (Table 2), Bioleach the weakest.

CONCLUSIONS

Although the number of samples in this case study is small, *t* probability analysis provides a robust screen for comparing and ranking different geochemical methods applied to the same soil samples. High contrast anomalies of Zn, Cd, and P in most methods, including sodium pyrophosphate and Enzyme Leach, may indicate an affinity with organic phases in the <250μm soil fraction. The proprietary nature of the Enzyme Leach, Bioleach, and MMI restricts the geochemical interpretation of the results. From an exploration point of view, clay separation with aqua regia digestion gives the most reproducible and interpretable results for the Talbot soils (*in progress*).

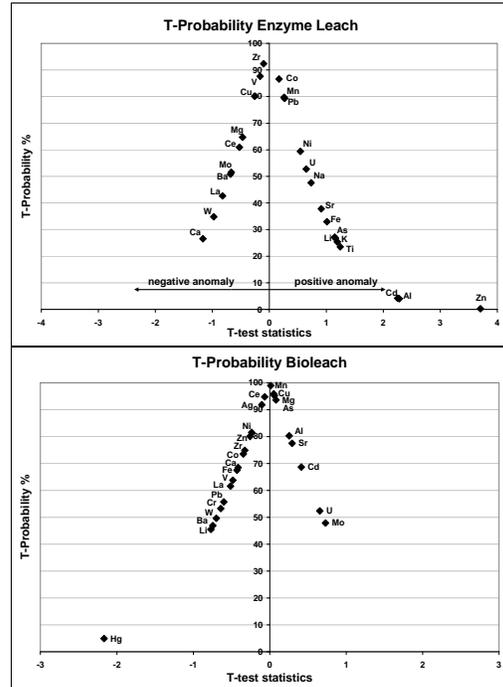


Fig. 2. *t* probability as a function of Student's *t* statistics for Enzyme Leach (a; "best case") and Bioleach (b; "worst case")

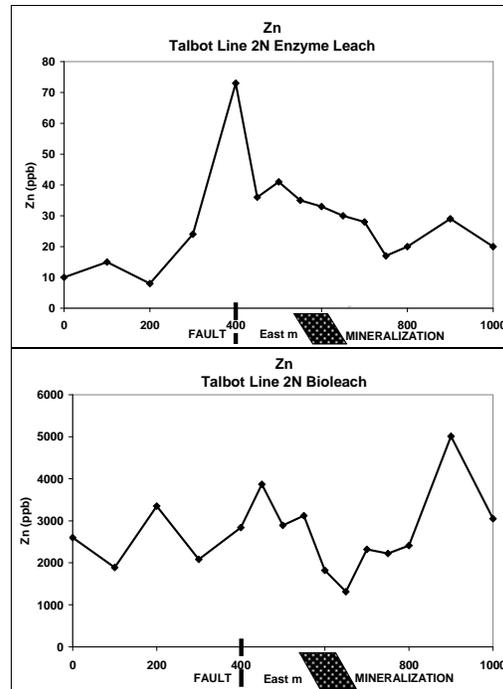


Fig. 3. Line plots of Zn concentration (ppb) in soils determined by Enzyme Leach (a) and Bioleach (b), with respective *t* probabilities of 0.3% and (-)80% ($\mu_a < \mu_b$).

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Multi-element soil geochemistry above the Talbot Lake VMS Cu-Zn Deposit, Manitoba, Canada

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ABSTRACT: Future discoveries of economic mineral deposits increasingly rely on the identification of secondary expressions of deeply buried, metal bearing systems. The Talbot VMS prospect, located in the Paleoproterozoic Flin Flon belt in northern central Manitoba, hosts Cu-Zn mineralization in meta-volcanic sequences that are overlain by 100 m of Paleozoic sandstone and dolomite formations of the Western Interior Platform, that are covered by a thin (0 to 2 m) blanket of Quaternary glacial and glaciolacustrine sediments. Soil profiles up to 50 cm depth were sampled at 50-100 m intervals over a 1000 m transect across the deposit. Trace element chemistry of the clay fraction (<2 µm) of soils displays a strong geochemical signature of the underlying deposit. Anomalous concentrations of Ag, Cu, Au, Cd, Co, Bi, Se, and Mn in clay separates are related to the presence of the underlying Talbot ore body, showing that deposits at considerable depths of allochthonous cover can be detected using a multi-element approach, at low cost and small environmental impact.

KEYWORDS: soil geochemistry, deep cover exploration, VMS Cu-Zn, Manitoba, Canada

INTRODUCTION

Most major ore deposits that intersect the earth's surface have probably been identified. To satisfy the increasing demand for metals, buried deposits lacking primary surface expressions have become targets for exploration. Future discoveries of economic mineral deposits increasingly rely on the identification of subtle, secondary expressions of deeply buried metal bearing systems (Govett 1976; Kelly *et al.* 2006).

Novel geochemical methods that can indicate the presence and composition of deep seated mineralization are therefore essential. In this study, the multi-element geochemistry of soils and their clay-sized fractions are compared for the deeply buried Talbot VMS Cu-Zn prospect, northern Manitoba, Canada.

GEOLOGICAL SETTING

The Talbot VMS Cu-Zn prospect is situated in the eastern extension of the Paleoproterozoic Flin Flon Belt (1.92-1.88 Ga), northwestern Manitoba (Stern *et al.* 1999). The prospect is located just

northeast of Lake Talbot, about 160 km SE of Flin Flon and 200 km SW of Thompson (Fig. 1). Mineralization is hosted by medium to high-grade metamorphic arc assemblages (Syme & Bailes 1993; Lucas *et al.* 1996) and occurs as coarse grained, massive to semi-massive and disseminated sulfides: chalcopyrite + sphalerite + pyrite ± pyrrhotite (Bailes & Galley 1999). The Proterozoic rocks are overlain by 100 m of Palaeozoic carbonate sequences of the Western Interior Platform (Stern *et al.* 1995). The deposit was first discovered through diamond drilling in 2003, and is currently in an advanced stage of exploration by Hudson Bay Exploration and Development. Diamond drilling has indicated significant mineralization, including a major intersection of massive sulphide, containing 11.2 ppm Au, 184 ppm Ag, 12.4% Cu and 3.50% Zn, over 9.65 m (HudBay Minerals Inc. 2006).

The crystalline host rocks are covered by Palaeozoic sediments of the Western Interior Basin. These consist of Ordovician



Fig. 1. Location of the Talbot prospect (inside black circle), Manitoba, Canada.

sandstones (Winnipeg Fm) and sequences of dolomite and limestone (Red River, Stonewall, and East Arm Fms) that contain chert and small pyrite-marcassite accretions (Bezys 2000). Minor intra-plate tectonics and isostatic rebound after glaciation have fractured the carbonate cover rocks (Elliott 1996). Acids produced by sulfide oxidation in the basement are interpreted to have caused partial dissolution of the basal limestone, in a manner similar to that described for rocks in eastern Brazil (Auler & Smart 2003). Increased void space and glacial loading may have caused the carbonate cover to collapse locally, and normal faulting of the carbonate cover with vertical offsets over 5 m has been observed in the Talbot area. These fractures, as well as many smaller cracks and joint sets, may allow fluids and gases to migrate upward and transport elements from the basement to the surface.

The area was glaciated between 13 ka and 10 ka, after which it was covered by the large water body of Lake Agassiz, until ~8 ka (Teller & Leverington, 2004), in which up to 2 m of fine grained glacial and glaciolacustrine sediments were deposited. The Talbot soil is developed on inhomogeneous glacial sand and clay,

and soil horizons are poorly developed. Vertical relief around the prospect is minimal, less than 10 m in general, and standing water occupies low-lying areas most of the year, forming swamps. The local vegetation consists mostly of sphagnum moss and coniferous trees.

METHODS AND RESULTS

At 15 sites along a 1000 m transect across the Talbot deposit, soil profiles were sampled in 10 cm depth intervals, up to 50 cm. The <250 μm (silt + clay) and <2 μm (clay) fractions of the soil samples were analysed using an aqua regia digestion and ICP-MS measurement of 53 elements.

Most elements of interest in the Talbot 250 μm and <2 μm separates are well above analytical detection limits, except PGEs. Clay separates have, on average, 50% higher concentrations of most elements than silt + clay fraction of the soils.

The clay content (wt. %) (Fig. 2) shows a strong positive correlation with most element concentrations in the <250 μm soil analyses, e.g. Cu (Fig. 3), with distinctly low values at 400 m east. In contrast, the clays show a well defined anomaly at the bottom of the profile at 400 m east (Fig. 4), with high concentrations of Ag, Cu, Au, Cd, Co, Bi, Se, and Mn.

CONCLUSIONS

The results of this research have implications for the application of exploration geochemistry in boreal forest terrains, especially when soils developed on glaciolacustrine sediments are used as the main sample medium. The choice of sampling depth, or soil horizon, can greatly impact the geochemical results, and the optimum should therefore be established in orientation surveys, by describing and sampling depth profiles. Separation of the clay fraction from the soil reduces the variability in the mineralogy of the sample medium, and subtle geochemical anomalies are not obscured by variations in the silt content of the bulk soil. Although the locations of anomalies are partly controlled by

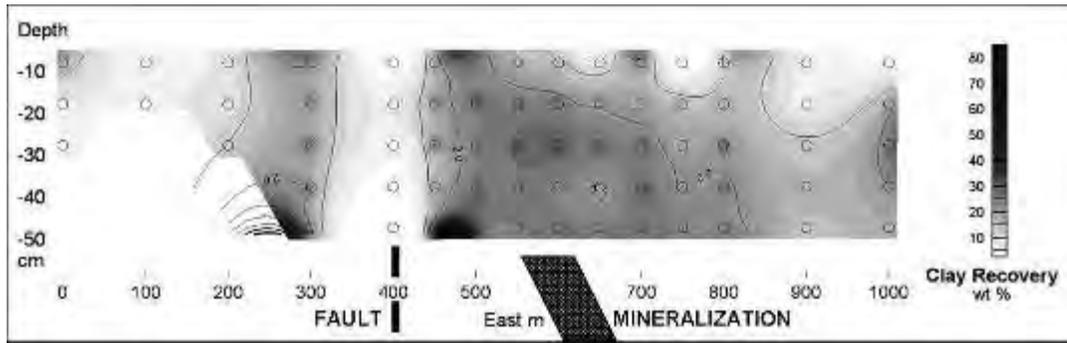


Fig. 2. Clay recovery (wt %) from soils, depth profile (vertical scale 500 x exaggerated).

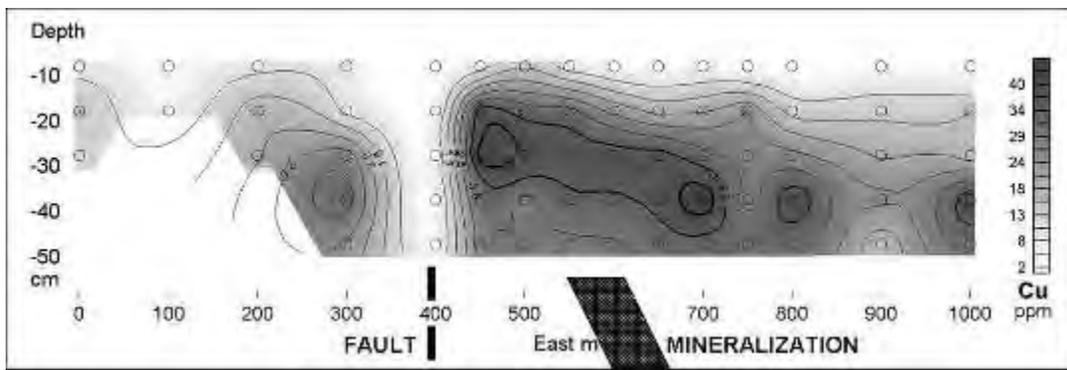


Fig. 3. Cu concentrations (ppm) in bulk soil, depth profile.

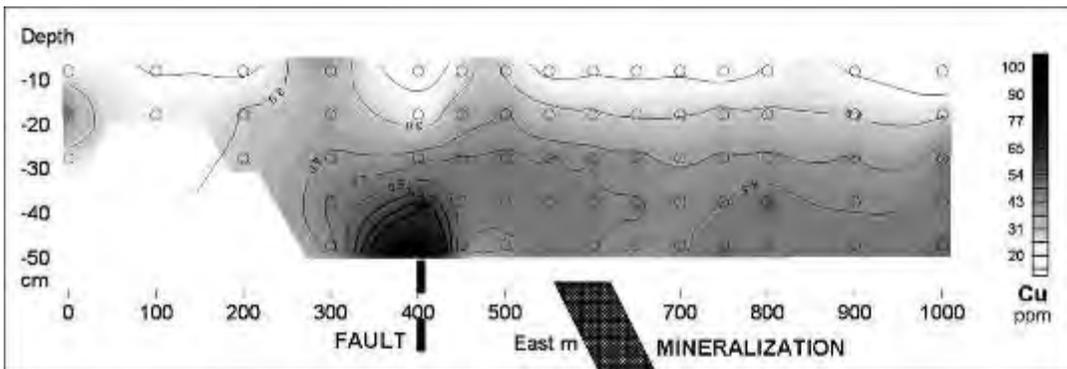


Fig. 4. Cu concentrations (ppm) in clay fraction, depth profile.

structures in cover rocks, the presence of the Talbot ore body is evident in the geochemistry of the clay sized fraction of soils through more than 100 m of cover rocks and glacial sediments.

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