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TILL GEOCHEMICAL SIGNATURES OF VOLCANOGENIC MASSIVE SULPHIDE DEPOSITS IN GLACIATED TERRAIN: A SUMMARY OF CANADIAN EXAMPLES

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ABSTRACT

Volcanogenic massive sulphide deposits are a significant source of Cu, Pb, Zn, and Ag in Canada. In the glaciated landscape of Canada, till geochemistry is an important exploration method for VMS deposits. This open file report provides an overview of the >50 year history of the application of till geochemical methods to VMS exploration in Canada, and also summarizes appropriate size fractions of till to analyze, analytical techniques, and pathfinder elements. Geochemical methods are now well developed and widely used, most commonly employing the <0.063 mm till fraction and an extensive suite of VMS pathfinder elements, including Cu, Pb and Zn, Ag, Au, Tl, Sn, Se, Hg, In, Cd, Bi, As, Sb, and Ge. In order to detect the clastic glacial dispersal signal down-ice of a VMS deposit, collection and analysis of unoxidized to weakly oxidized till is optimal, whereas B-horizon soil is not. Case studies and examples of glacial dispersal patterns associated with VMS deposits from major mining camps and deposits across Canada are highlighted, including Buchans, Bathurst, Timmins, Noranda, Manitouwadge, Flin Flon, Finlayson Lake, Hackett River, and Izok Lake.

INTRODUCTION

Volcanogenic massive sulphide (VMS) deposits are a significant exploration target in Canada. These deposits account for 27% of Cu, 49% of Zn, 20% of Pb, 40% of Ag, and 3% of Au production in Canada (Drake, 2011). Over 97% of Canada's land mass was covered by glaciers during the Quaternary (Nichol and Bjorklund, 1973) which eroded bedrock and deposited glacial sediments over large regions. As a result of glaciation, till geochemistry is an important exploration method for VMS deposits in Canada. The application of till geochemical methods to VMS exploration in Canada has a >50 year history (e.g. Ermengen 1957; Dreimanis 1958, 1960; Fortescue and Hughes 1965; Shilts, 1975; Kaszycki et al., 1996; Parkhill and Doiron, 2003). This report provides an overview of this history as well as an analysis of best practices, including recommendations on appropriate size fractions of till to analyze, analytical techniques, and pathfinder elements. Till geochemistry case studies of VMS deposits from mining camps across Canada are highlighted, including Buchans, Bathurst, Timmins, Noranda, Manitouwadge, Flin Flon, Finlayson Lake, Hackett River and Izok Lake (Fig. 1). This review considers the numerous published reports and scientific papers that describe surficial geochemical studies around VMS deposits in Canada. Many of the earlier case studies are listed in the *Exploration 77*, *87*, and *97* conference proceedings (Bolviken and Gleeson, 1979; Coker and DiLabio, 1989; McClenaghan et al., 1997, 2000) as well as exploration geochemistry reviews by Shilts (1975), Bradshaw (1975), and Brummer et al. (1987). The earliest soil and till geochemical case studies in Canada from the 1950s to 1970s were carried out before the VMS deposit genetic and exploration models were fully developed, as modern black smoker seafloor sulphide deposits were only discovered in 1979.

Table 1 summarizes and compares the pertinent information about the detailed surveys around VMS deposits that are described in this paper, including deposit location, pathfinder elements, sample media, size fraction analyzed, and analytical method. Some explanation of analytical methods used to extract metals from glacial sediments and soils is required before presentation and discussion of the case studies listed in Table 1.

The earliest determinations of the base metal content of till relied on "cold-extraction" techniques (abbreviated as cx, cx-THM, CxCu) that determine the content of readily soluble metal, or metals present as free ions or loosely bound ions on the surface of grains (Rose et al., 1979; Levinson, 1980). Cold extractions commonly use buffer solutions and dilute acids, such as nitric, hydrochloric, acetic, or Ethylenediaminetetraacetic (EDTA), and are commonly analyzed by colourimetric methods. These methods can be easily used in the field because no preliminary treatment, such as drying or sieving, is required.

One example of cold-extraction techniques widely used in the glaciated terrain of Canada in the 1950s and 1960s is that developed by Bloom (1955). This method extracts heavy metals (Cu, Zn, Pb, Co, Ni) in cold ammonium citrate in the presence of dithizone dissolved in xylene. The xylene floats on an aqueous surface and after a vigorous shake, the xyelene above the aqueous phase changes to a colour that reflects its metal content. Colours vary from green, blue, purple, red, to brown. If the colour is purple or red, more xylene-dithozone solution is added until the colour changes to a neutral blue-grey colour (referred to as the "endpoint"). Results are reported as milliliters of

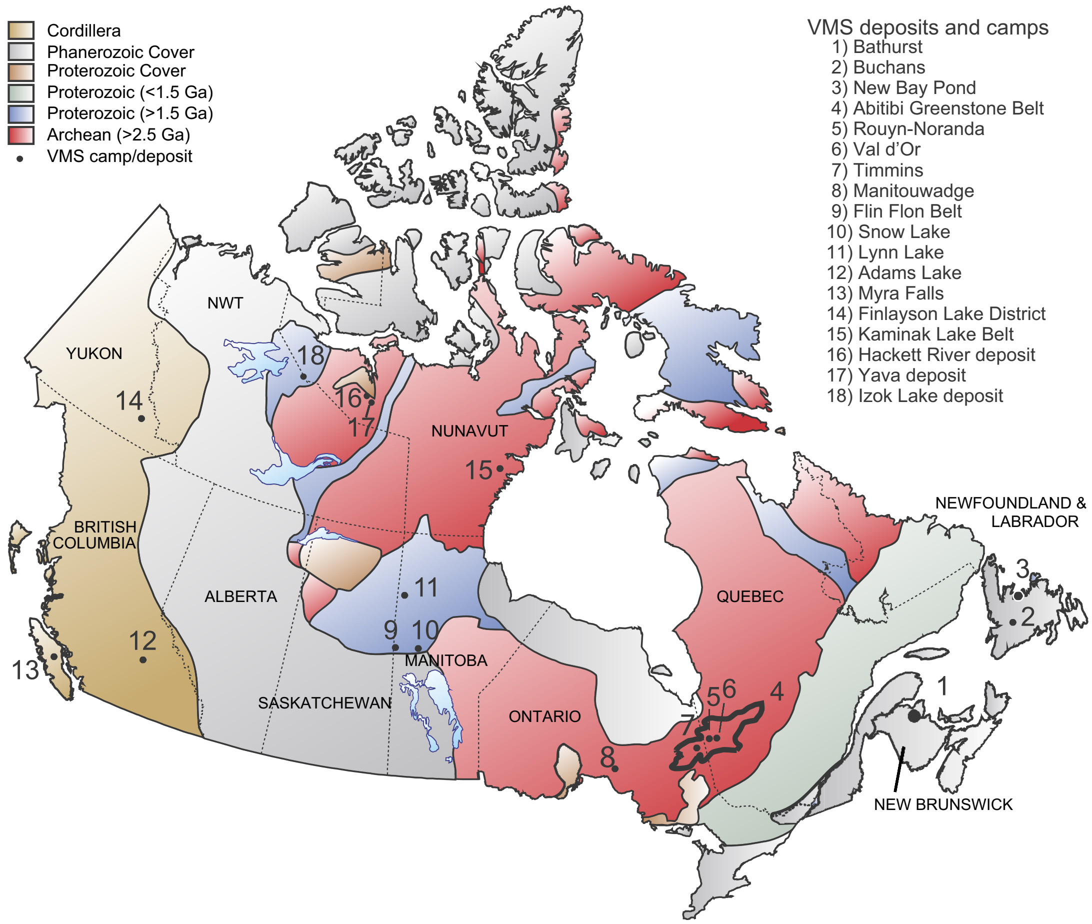

Figure 1. Location of volcanogenic massive sulphide camps and deposits in Canada that are discussed in this paper.

0.001% dithizone in xylene solution required to titrate to the blue-grey endpoint conditions. High metal contents are reflected in greater volumes of solution being added. Examples of its application to soils and glacial sediments are given by Byers (1956), Ermengen (1957), and Dreimanis (1960).

"Hot-extraction" techniques involve the use of one of more acid solutions at temperatures >60ºC and are performed in an analytical laboratory. The sample is dried and sieved prior to analysis. The main advantage of using hot acids is that more metal is extracted than with cold-extraction techniques. Early versions of hot extractions included the nitric acid method of Bloom and Crowe (1953) and the perchloric method used by Garrett (1971). Today, digestions can be "partial", such as those determined by aqua regia, or "near total", such as 3- or 4-acid digestions that include some combination of nitric, perchloric, hydrochloric, or hydrofluoric acids. Borate fusion followed by nitric acid digestion is a widely used total digestion method for determining the bulk composition of till (e.g. McClenaghan et al., in press).

BATHURST MINING CAMP

The Bathurst Mining Camp (BMC) in northern New Brunswick, Canada (Fig. 1) hosts 46 VMS deposits with known tonnage and grade data, as well as 95 occurrences. The BMC hosts some of the world's largest Zn deposits at Brunswick Number 12, Heath Steele B, and Caribou (Goodfellow and McCutcheon, 2003; Fig. 2). In the BMC, VMS mineralization has been weathered and oxidized prior to glaciation to form gold-rich gossans in some deposits and metal-rich secondary minerals such as beudantite and jarosite (Boyle, 2003).

Base metal mining in the camp commenced in 1965 at Brunswick Number 12, and this deposit and others (e.g. Halfmile Lake) are still being mined today. More than 99% of the BMC is covered by glacial and post-glacial deposits that are >3 m thick (Parkhill and Doiron, 2003). The first VMS deposits were discovered here in the 1930s by tracing mineralized boulders up-ice to what is now known as the Orvan Brook Zn-Pb-Ag-Au VMS deposit (Fig. 2) (Lundberg, 1948; Dreimanis, 1958; Tupper, 1969).

The earliest geochemical surveys of properties and orientation studies around VMS deposits in the BMC were carried out using soil as the sample medium. Soil is developed on till in the BMC, and therefore "soil sampling" can be used here to effectively detect elements mechanically dispersed by glaciers as well as

Table 1. Survey details for VMS deposits discussed in this paper.

Deposit/Occurrence	Location	Ore Elements	Pathfinder Elements	Size Fraction Analyzed	Analytical Method	Source of Information
Halfmile Lake deposit, Bathurst, NB	Bathurst Mining Camp	Zn-Pb-Cu	Cu, Pb, In, Sn, Ag, As, Au, Sb, Bi,	<0.063 mm	INAA + 4 acid/ ICP-ES,MS	Parkhill and Doiron (2003)
Halfmile Lake deposit, Bathurst, NB	Bathurst Mining Camp	Zn-Pb-Cu	Cu, Pb, Zn, Ag, As, Au, Bi, Hg, Sb, Se, Sn	<0.063 mm	aqua regia + borate fusion/ICP-MS,ES	Budulan et al. (2012)
Restigouche Deposit	Bathurst Mining Camp	Zn-Pb-Cu-Ag	Cu, Pb, Zn, In, Sn, As, Au, Sb, Bi	<0.063 mm	INAA + 4 acid/ ICP-ES,MS	Parkhill and Doiron (2003)
Mount Fronsac deposit, Bathurst, NB	Bathurst Mining Camp	Zn-Pb-Cu-Ag	Pb, Ag, Cu, Hg, Cd	<0.063 mm	Aqua regia/ICP-MS + cold vapour AAS	Campbell (2009)
Bog deposit, Bathurst, NB	Bathurst Mining Camp	Pb-Zn-Cu-Ag	Cu, Pb, Zn, Ag, As, Sb, Cd	not reported	not reported	Hoffman and Woods (1991)
CNE deposit, Bathurst, NB	Bathurst Mining Camp	Zn-Pb-Cu-Ag	Pb, Zn,Cu, Ag, Au, As, Sb, Hg	<0.063 mm	4 acid/ICP-ES + INAA + CV-AAS	Parkhill and Doiron (1995, 2003)
Buchans, Oriental, Lucky Strike, NL	Bathurst Mining Camp	Zn-Pb-Cu	Pb, Zn	<0.002 mm	LeForte/ICP-AES	Klassen and Murton (1996)
Buchans, Oriental, Lucky Strike, NL	Bathurst Mining Camp	Zn-Pb-Cu	Zn	<0.177 mm	nitric acid digestion	James and Perkins (1981)
New Bay Pond, NL	central Newfoundland	Cu-Zn	Cu, Zn, As, Hg	<0.063 mm; 0.063-0.297 mm HMC (SG >2.96)	$NHNO_3$+HCl/AAS, HNO_3+$HClO_4$/AAS, CV-AAS	Hornbrook et al. (1975)
Kidd Creek deposit, Timmins, ON	Timmins Mining Camp	Zn-Cu-Pb-Ag	Zn, Cu	<0.0177 mm	3 acid/colourimetric	Fortescue and Hughes (1965)
Kidd Creek deposit, Timmins, ON	Timmins Mining Camp	Zn-Cu-Pb-Ag	Zn, Cu	<0.0177 mm	total digestion	Fortescue and Hornbrook (1969); Hornbrook (1975a)
Kidd Creek deposit, Timmins, ON	Timmins Mining Camp	Zn-Cu-Pb-Ag	Zn, Cu, As	<1.7 mm HMC (SG >3.3)	aqua regia/ICP-ES	McClenaghan et al. (1998)
Kam Kotia deposit, Timmins, ON	Timmins Mining Camp	Cu-Zn	Cu, Zn, Ag, Cd, Sb, Se, Ga, Tl, V	<0.002 mm; <0.063 mm HMC (SG> 3.3)	aqua regia/ICP-MS & ES	Smith (1990, 1992)
Kam Kotia deposit, Timmins, ON	Timmins Mining Camp	Cu-Zn	Cu-Zn	<0.063 mm; <0.25-0.063 mm HMC (SG >3.3)	not reported	Skinner (1972a); Shilts (1976)
Jameland despoit, Tmmins, ON	Timmins Mining Camp	Cu-Zn-Au-Ag	Cu-Zn	<0.063 mm; <0.25-0.063 mm HMC (SG >3.3)	not reported	Skinner (1972a); Shilts (1976)
Horne deposit, Noranda, QC	Noranda Mining Camp	Cu-Au-Ag	Cu, Zn, Pb	<0.0177 mm	not reported	Dreimanis (1958, 1960)
MacDonald deposit, Noranda, QC (Gallen)	Noranda Mining Camp	Zn-Cu-Au-Ag	Cu, Zn, Pb	<0.177 mm	not reported	Dreimanis (1958, 1960)
Magusi River deposit, Noranda, QC	Noranda Mining Camp	Zn-Cu	Cu, Zn, Ag, Hg	whole till; >0.177 mm HMC (SG >2.96); <0.177 mm	not reported	Gleeson (1975b)
Mogador (Vendome), Val d'Or, QC	Val d'Or Mining Camp	Zn-Cu-Pb-Ag-Au	Cu, Zn, Ag	<0.177 mm; >0.177 mm HMC	not reported	Dreimanis (1958); Gleeson (1975a)
Louvem deposit, Val D'Or, QC	Val d'Or Mining Camp	Zn-Cu-Ag-Au	Cu, Zn	<0.177 mm; >0.177 mm HMC (SG >2.96)	not reported	Gleeson and Cormier (1971)
Louvem deposit, Val D'Or, QC	Val d'Or Mining Camp	Zn-Cu-Ag-Au	Cu, Zn	<0.177 mm; 0.064-0.177 mm HMC (SG >3.3)	pyrosulphate fusion + colourimetry	Garrett (1969a,1971)
Geco, Willroy, Nama Creek deposits, Manitouwadge, ON	Manitouwadge Mining Camp	Zn-Cu-Ag	Cu, Zn, Ag	<0.063 mm	aqua regia	Kettles et al. (1998)
Chisel Lake, Lost Lake, Ghost Lake deposits, Snow Lake, MB	Snow Lake Mining Camp	Zn-Cu	Cu, Hg, Pb, As, Au, Sb	<0.002 mm; <0.063 mm	INAA + aqua regia AAS and ICP-ES	Kaszycki et al. (1996)
Kudz Ze Kayah deposit, Finlayson Lake, YU	Canadian Cordillera	Zn-Pb-Cu-Ag-Au	Zn, Pb, Ag, Au	<0.063 mm	aqua regia/ ICP-MS	Bond and Plouffe (2002)
Broken Ridge occurrence, Adams Lake, BC	Canadian Cordillera	Cu-Pb-Zn-Ag	Cu, Hg, Bi	<0.063 mm	aqua regia/ICP-ES + INAA	Lett et al. (1998)
Harper occurrence, Adams Lake, BC	Canadian Cordillera	Cu-Pb-Zn-Ag-Au	Cu, Au, Bi, Hg, Se	<0.063 mm	aqua regia/ICP-ES + INAA	Lett et al. (1998)
Samatosum and Rea deposits, Adams Lake, BC	Canadian Cordillera	Ag-Pb-Zn-Cu	Pb, Zn, As, Hg, Sb, Au	<0.063 mm	aqua regia/ICP-ES + INAA	Bobrowksy et al. (1997); Lett (2001); Paulen (2001)
Lynx, Myra, H-W, Prince deposits, Myra Fall, BC	Canadian Cordillera	Cu-Zn-Pb-Au-Ag-Cd	Cu, Pb, Zn	<0.002 mm	total digestion/AAS	Hicock (1986)
Yava (Agricola Lake) deposit, NU	Canadian Arctic	Zn-Cu-Pb-Ag-Au	Cu, Pb, Zn, Ag, Au, Hg	<0.177 mm	HNO_3 + HCl/AAS + CV- AAS+ FA-AAS	Cameron and Durham (1975); Cameron (1977)
Hackett River deposit, NU	Canadian Arctic	Zn-Pb-Cu-Ag	Pb	<0.177 mm	HNO_3 + $HClO_4$ + HCl /AAS	Miller (1979)
Spi Lake occurrence, NU	Canadian Arctic	Zn, Pb,Cu	Cu, Zn	<0.002 mm	HCl-HNO_3/AAS	Shilts (1975)
Izok Lake deposit, NU	Canadian Arctic	Zn-Cu-Pb-Ag	Zn, Cu, Pb, Fe, Ag, Cd Cd, Sb, Bi, Hg, Se, In, Tl	<0.063 mm	aqua regia/ICP-Ms + borate fusion/ICP-MS	Hicken et al. (2012)

those subsequently dispersed by hydromorphic processes. Morris (1966) was one of the first to test soil geochemical methods as an exploration tool in the BMC. He demonstrated that compositional analyses of soil using both Cx-THM and total Zn, Cu, and Pb outlined the area of mineralization on a property that later became known as the Stratmat Zn-Pb-Ag-Cu VMS deposit (Fig. 2).

Klassen's (2003) study of metal partitioning in till from around nine VMS deposits in the BMC concluded that mineralized bedrock is reflected in till by elevated contents of Cu, Pb, Zn, Ag, Bi, As, Cd, Co, Hg, Sb, and

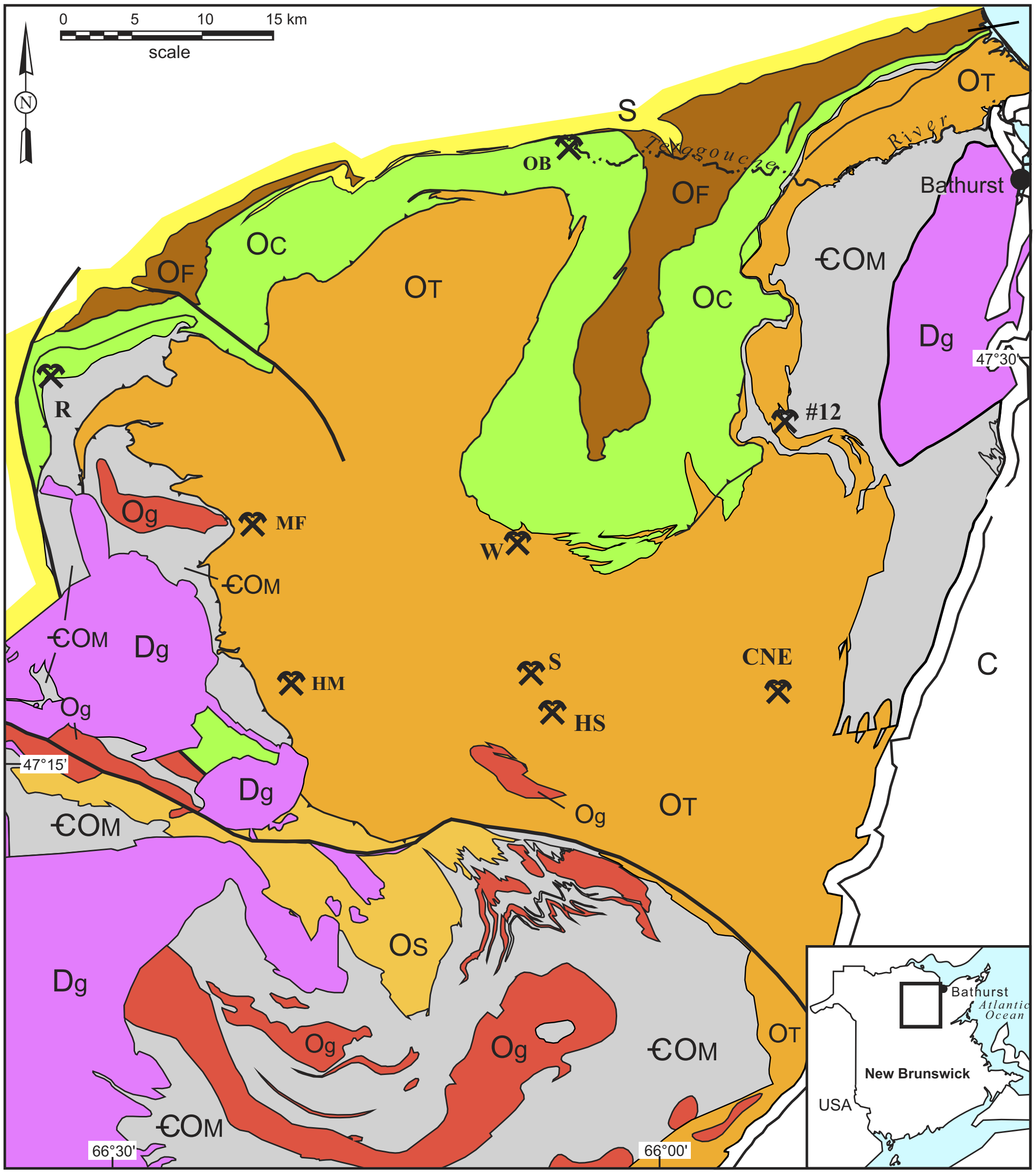

Figure 2. Location of volcanogenic massive sulphide deposits in the Bathurst Mining Camp in north-central New Brunswick and regional bedrock geology (modified from Parkhill and Doiron, 2003). Bedrock legend: C = Carboniferous sedimentary rocks; Dg and Og = Devonian and Ordovician (mainly felsic) intrusive rocks, respectively; Є-OM = Cambrian-Ordovician sedimentary rocks of the Miramichi Group; OF = Ordovician mafic volcanic and sedimentary rocks of the Fournier Group; OT, OC, and OS = Ordovician sedimentary and felsic and mafic volcanic rocks of the Tetagouche, California Lake, and the Sheephouse Brook groups, respectively; S = Silurian and younger rocks. Crossed hammer symbol indicates significant VMS deposit: CNE = Captain North Extension, HM = Halfmile Lake, HS = Heath Steele, #12 = Brunswick 12, MF = Mount Fronsac North, OB = Orvan Brook, R = Restigouche-C4-C5, S = Stratmat, W = Wedge/BOG.

Sn that are elevated above background. He demonstrated that metal contents are highest in the clay (<0.002 mm) fraction of till, but that clay-sized material is a minor component (<4%) of local BMC till. He also observed that glacial transport of metal-rich debris in the BMC was short (<1 km); therefore, glacial comminution of ore minerals to the finest, clay-sized fraction was limited. Because of these factors, Klassen (2003) concluded that analyzing the slightly coarser silt + clay (<0.063 mm) fraction of till for base metal exploration in the BMC is effective for detecting glacial dispersal.

In addition to comparing size fractions, Klassen (2003) also compared Pb, Zn, and Ag contents in till as determined by 4-acid (total) versus aqua regia digestions. Both digestion methods display similar abundances of base metals, indicating that the elements occur in mineral forms that are readily soluble in aqua regia (i.e. sulphides). Bismuth, Co, Sb, and Sn were reliably detected in metal-rich till only by use of a total digestion, indicating that these elements occur in refractory minerals such as cassiterite (Sn) and tetrahedrite (Sb), or within minerals such as pyrite (Co), galena

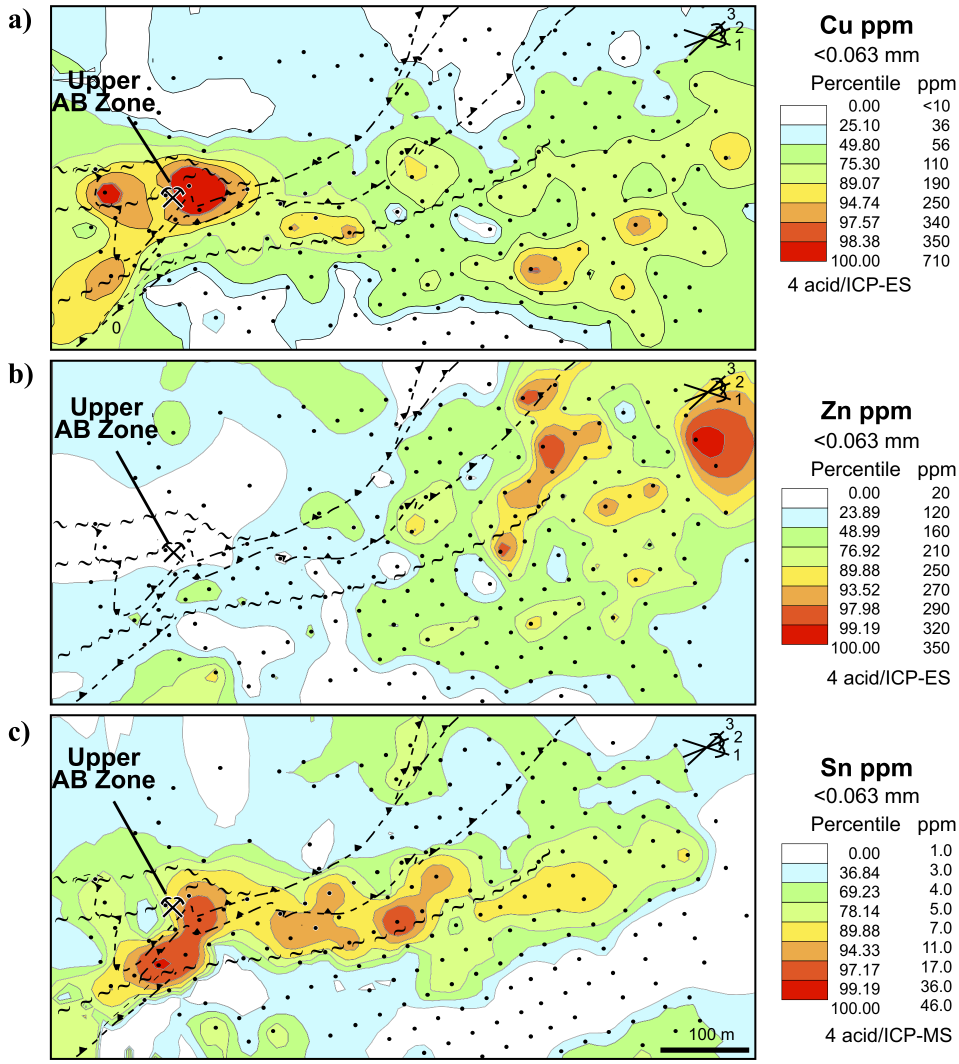

Figure 3. Distribution of **(a)** Cu, **(b)** Zn (4 acid/ICP-ES), and **(c)** Sn (4 acid/ICP-MS) in the <0.063 mm fraction of till around the Halfmile Lake VMS deposit, Bathurst Mining Camp, showing a well developed east-northeast-trending dispersal train (modified from Parkhill and Doiron, 2003).

(Bi), and bismuthinite (Bi) that were incompletely dissolved by digestions other than 4-acid. In addition to Klassen's (2003) general studies of base metal glacial dispersal in the BMC, several deposit-specific studies have been carried out over the past 30 years. Highlights from these case studies are described below.

Halfmile Lake Deposit

The Halfmile Lake Zn-Pb-Cu deposit, in the westernmost part of the BMC (Fig. 2), was discovered in 1952 using soil geochemical and geophysical surveys (Adair, 1992; Parkhill and Doiron, 2003). The deposit is capped by a preglacial massive sulphide gossan that is enriched in Pb, Cu, In, Au, Ag, Sn, As, Sb, Bi, and Se (Boyle, 2003). A well developed, ribbon-shaped glacial dispersal train extending up to 1 km down-ice (east-northeast to east-southeast) is best defined by Cu, Sn (Fig. 3), Pb, In, Ag, As, Au, Sb, and Bi in the <0.063 mm till fraction. Although Zn is the most abundant base metal in the deposit, it is not a pathfinder element in till immediately down-ice. The low Zn contents in till down-ice likely reflect the Zn depletion of the gossan cap (Parkhill and Doiron, 2003). Budulan et al. (in press) collected additional till samples around the Halfmile Lake deposit to document the indicator mineral signatures in till down-ice. This additional sampling confirms the till geochemical dispersal patterns in the <0.063 mm till fraction first identified by Parkhill and Doiron (2003) and identifies a similar suite of pathfinder elements, including Cu, Pb, Zn, Ag, As, Au, Bi, Hg, Sb, Se, and Sn. Both of these studies of till dispersal around the Halfmile Lake deposit demonstrate the broad multi-element signature of this VMS deposit, which likely reflects mainly the subcropping gossan cap.

Certain VMS deposits can contain Pb (as galena) whose Pb isotopic composition can be distinctly different from that of the surrounding country rocks (e.g.

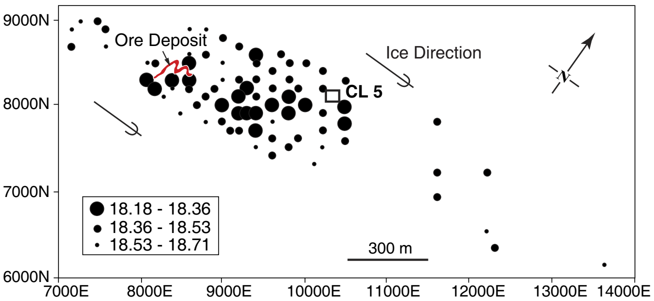

Figure 4. Spatial plan distribution of $^{206}Pb/^{204}Pb$ ratios in the <0.063 mm fraction of surface till around the Halfmile Lake VMS deposit, Bathurst Mining Camp (modified from Hussein et al., 2003).

Sangster et al., 2000). This difference in compositions allows for isotopic fingerprinting of Pb in the deposits (e.g. Bell and Murton, 1995). A relatively recent application of Pb isotopic analysis is its determination in glacial sediments to identify signatures that may be indicative of VMS mineralization in source rocks up-ice. One example of this application is the analysis of till down-ice of the Halfmile Lake deposit using Pb isotopic ratios and Pb abundance in the till matrix (<0.063 mm fraction). Hussein et al. (2003) determined Pb isotope compositions of surface till up to 1600 m down-ice of the Halfmile Lake deposit and demonstrated that Pb isotope compositions could be used to map out the dispersal train for at least 600 m (Fig. 4). In vertical till sections down-ice from the deposit, the Pb isotopic signature of the ore is generally found in the lowest part of the section, overlying bedrock (Fig. 5).

Restigouche, C-4, and C-5 Deposits

The discovery holes for the Restigouche Zn-Pb-Cu VMS deposit and nearby C-4 and C-5 VMS deposits (Fig. 2) were drilled in 1958 to follow-up a soil geochemical anomaly (Parkhill and Doiron, 2003). Similar to the Halfmile Lake deposit, the Restigouche deposit is, in part, capped by preglacial gossan. This gossan is likely preserved because the deposit is on the lee side (down-ice side) of a hill. The C4 and C5 zones, which outcrop and subcrop on the top of a hill, are not covered by gossan. Till around the three deposits has elevated contents of Cu, Pb, Zn, In, Sn, As, (Fig. 6), Au, Sb, and Bi in the <0.063 mm fraction up to 2 km down-ice. Dispersal patterns for Pb and As (Fig. 6a,d) reveal there are separate trains sourced from the Restigouche deposit and from the C-4 and C-5 zones trending north-east. Glacial dispersal patterns associated with the C-4 and C-5 zones are at least 3 km down-ice, 750 m wide, and are best defined by Pb, In, Sn, and As. The C-4 and C-5 zones consist of unweathered sulphides outcropping on topographic highs. As a result, the deposits have been deeply eroded and thus material dispersed from these deposits extends farther down-ice than that from the main Restigouche deposit.

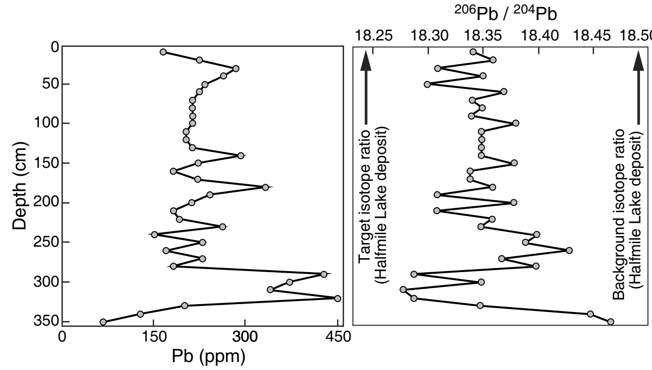

Figure 5. $^{206}Pb/^{204}Pb$ ratios and Pb abundance in the <0.063 mm fraction of till in a vertical section in pit CL-5 at the Halfmile Lake VMS deposit. The lowest ratios correspond to the highest Pb contents in the lowermost till (modified from Hussein et al., 2003).

In addition to till samples, humus and B-horizon soil samples were collected over the Restigouche deposit in the 1990s. Comparison of these samples to underlying till samples indicates that where anomalous metal contents are present in B-horizon soil, they are also generally present in the underlying till upon which the soil has formed (Hall et al., 2003; Parkhill and Doiron, 2003). Copper, Pb, and Zn anomalies in the <0.063 mm fraction of till cover a much larger area than anomalous B-horizon soil (<0.177 mm), indicating that till provides a larger exploration target than the soil, and that soil developed on till can reflect clastic glacial dispersal signals. These observations demonstrate that old soil geochemical surveys conducted in the BMC between 1950 and the 1980s likely reflect underlying till compositions and thus soils around VMS deposits reflect clastic dispersal signals derived from erosion of base metal mineralization.

Mount Fronsac North Deposit

The Mount Fronsac North Zn-Pb-Cu-Ag-Au VMS deposit is the most recently discovered (1999) VMS deposit in the BMC (Fig. 2). It was discovered by diamond drilling after a reassessment of geophysical data in the area led to the discovery of a previously unknown gossan outcrop. Similar to some of the other BMC deposits, it is covered in places by a preglacial gossan (Walker and Graves, 2007). Glacial dispersal from the thin till-covered deposit and its gossan cap is best defined by Pb, Ag, Au, Cu, As, Sb, and Bi in the <0.063 mm fraction of till (Campbell, 2009). Distribution patterns in till reflect glacial dispersal to the east-northeast, together with post-glacial weathering and hydromorphic remobilization of some elements.

BOG Deposit

Hoffman and Woods (1991) have documented the role of till sampling in the discovery of the BOG Pb-Zn-Cu-Ag VMS deposit, 3 km northwest of the Wedge Cu-Pb-

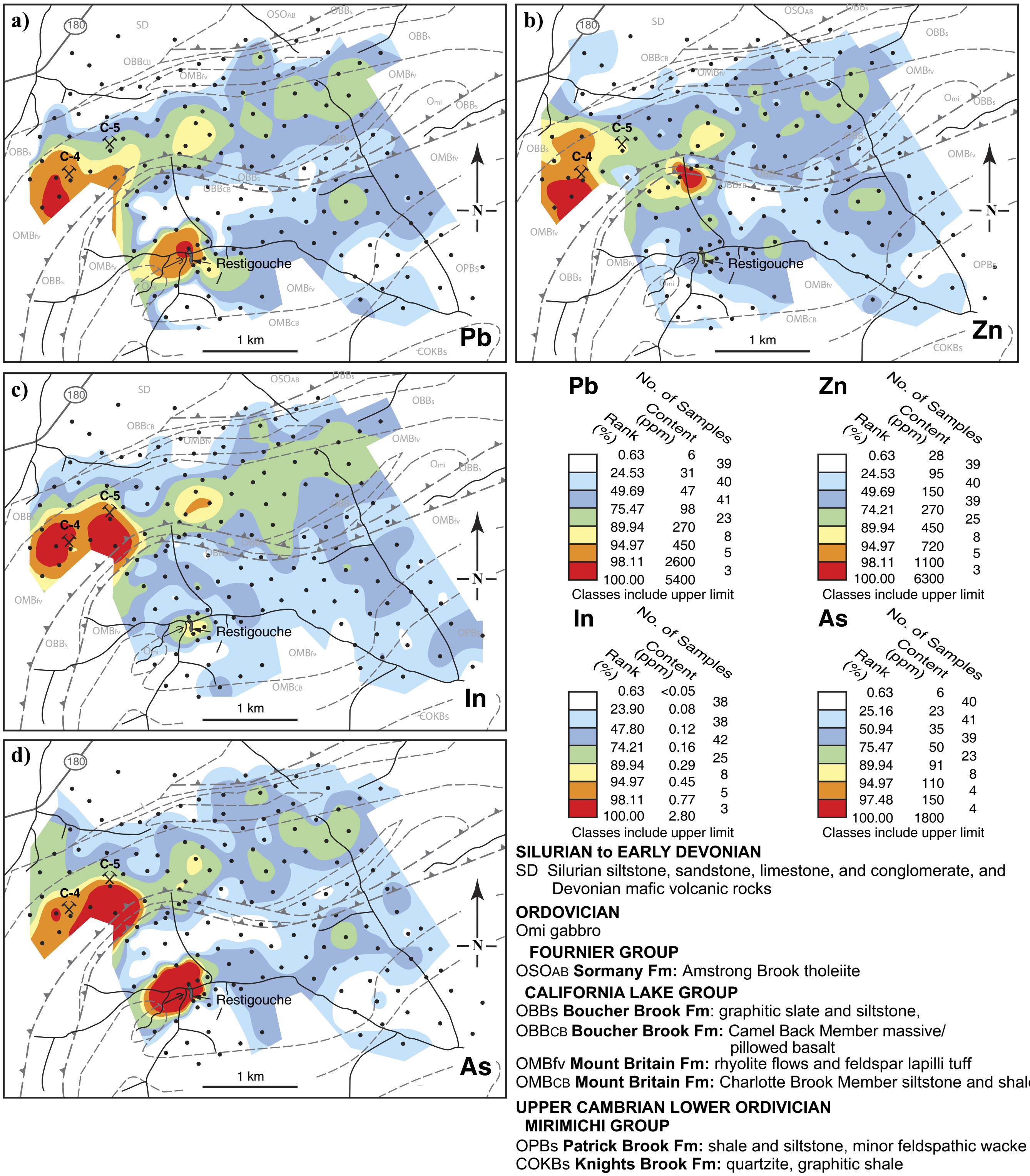

Figure 6. Distribution of **(a)** Pb, **(b)** Zn, **(c)** In, and **(d)** As (4 acid/ICP-MS, /ES) in the <0.063 mm fraction of till around the Restigouche, C-4, and C-5 VMS deposits, Bathurst Mining Camp, New Brunswick (modified from Parkhill and Doiron, 2003).

Zn-Ag VMS deposit in the central part of BMC (Fig. 2). One of first indications of the presence of the Bog deposit was the elevated metal contents in surface [A-horizon?] soil reported in the 1960s. Hoffman (1985, 1986, 1989) outlines the reasons why earlier exploration of the property, as far back as the 1950s, failed to discover the BOG zone. The early geochemical surveys collected soil developed on alluvium and till, as well as organic matter in bogs. The genesis and geochemical characteristics of these early soil surveys were not taken into account when interpreting the data. In 1982, resampling the soils over part of the earlier soil survey

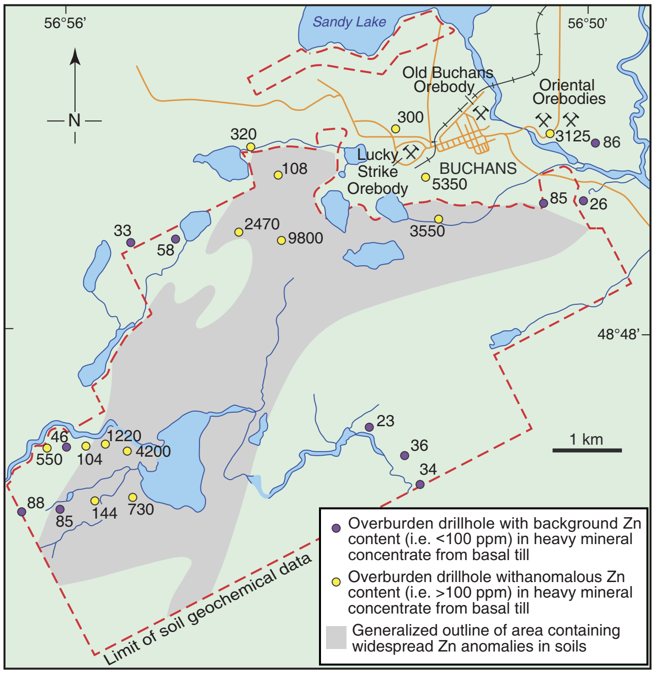

Figure 7. Zinc content (ppm) in the 0.074-0.177 mm (fine sand) non-magnetic heavy mineral concentrates (SG > 2.95) from selected basal till samples around the Buchans VMS deposits showing a well developed zone of Zn-rich till southwest of the deposits (modified from James and Perkins, 1981).

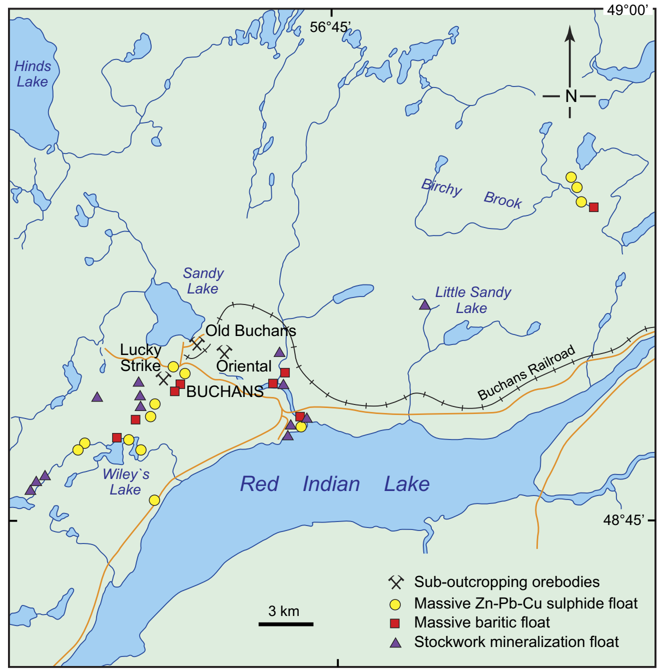

Figure 8. Location of float (boulders, cobbles) of massive sulphide, massive barite, and stockwork mineralization found at surface around the Buchans VMS deposits (modified from James and Perkins, 1981).

grid, with renewed focus on soils developed on till and sufficient sample depth (consistent B-horizon sampling), identified elevated contents of Cu, Pb, and Zn in samples from parts of the grid area. The deposit was subsequently discovered in 1983 through the use of geophysics and deep overburden drilling to sample till and bedrock. Hoffman and Woods (1991) reported that till overlying the deposit is enriched in Cu, Pb, Zn, Ag, As, Sb, and Cd and this suite of metals in the till is likely also represented in the bulk soil compositions. Thus, soils formed on the metal-rich till also record glacial dispersal of mineralization from the deposit.

CNE Deposit

The CNE Zn-Pb-Cu-Ag VMS deposit (Fig. 2) in the southern part of the BMC was discovered in 1978 using stream sediment geochemistry (Whaley, 1992). The deposit is relatively small (331,000 tonnes), but was open pit mined in the early 1990s; reserves remain and there are current goals to recommence mining. Parkill and Doiron (1995, 2003) carried out detailed till sampling around the deposit and found elevated of Pb, Zn, Cu, Ag, Au, As, Sb, and Hg contents in the <0.063 mm fraction of till up to 1000 m down-ice. Dispersal distances from this deposit are short because it is situated in a topographic depression and was protected from multiple ice-flow events by a thick (up to 5 m) cover of till deposited by early east-flowing ice (Parkill and Doiron, 1995, 2003).

BUCHANS MINING CAMP

The Buchans Zn-Pb-Cu VMS deposits in central Newfoundland (Fig. 1) were discovered in the early 1900s (Neary, 1981) and were some of the richest and most productive VMS deposits in Canada, with average grades of 14.5% Zn, 7.6% Pb, and 1.3% Cu (Klassen and Murton, 1996). Till and soil sampling, in combination with geological mapping and geophysical surveys, were used by the Buchans Mine exploration staff to identify several sulphide deposits in the area (James and Perkins, 1981). They identified an area of elevated Zn in soil developed on till southwest of the Oriental, Lucky Strike, and Buchans VMS deposits (Fig. 7), in concert with mapping the distribution of massive sulphide, massive barite, and stockwork boulders that were glacially dispersed from the deposits (Fig. 8).

Klassen and Murton (1996) documented the complex ice-flow history of the Buchans area, which includes four phases of flow: north, south, northeast, and southwest. These varied ice-flow events are responsible for the distribution of mineralized boulders both southwest and northeast of the deposits, as shown in Figure 8. The area is covered by thick glacial sediments. In places, the till is covered by >40 m of glaciolacustrine clay and silt. Similar to the Abitibi Greenstone Belt (described below), till in this area is best sampled by overburden drilling below the glaciolacustrine and glaciofluvial deposits. Klassen and

Murton (1996) identified a Pb-Zn dispersal train in till extending up to 10 km from the deposits in a southwest direction, which coincides with the dispersal train first documented by James and Perkins (1981) (Fig. 7). They concluded that the geochemical dispersal pattern for the Buchans deposits reflects both southwest glacial transport and later redistribution of mineralized debris within debris-flows and glaciolacustrine deposits.

A second example of the application of Pb isotopes to till geochemistry and glacial dispersal is documented by Bell and Murton (1995), who studied till samples adjacent to the Oriental and Lucky Strike deposits at Buchans. They demonstrated that Pb derived from the VMS deposits can be differentiated from Pb derived from country rocks down-ice of the two deposits on the basis of radiogenic Pb isotopic compositions.

NEW BAY POND VMS DEPOSIT

In the mid-1970s, Hornbrook et al. (1975) conducted a multimedia surficial geochemical study of the undisturbed New Bay Pond Cu-Zn VMS deposit 40 km north of Grand Falls, in north-central Newfoundland (Fig. 1). The deposit, discovered in 1971, is a bimodal felsic-type deposit hosted by rhyolite that contains 18.1 Mt grading 2 wt.% Zn and 0.5 wt.% Cu. The study included till, B- and C- horizon soil developed on till, stream sediments, and lake sediments. Both the 0.063-0.297 mm heavy mineral concentrate (HMC) (SG > 2.96) and the <0.063 mm fractions of "basal" till sampled at depths below the weathering and soil development were analyzed. The two fractions were found to contain elevated Zn (Fig. 9), Cu, As, and Hg at least 500 m down-ice (northeast and east) dispersed in a fan shape that appears to reflect redistribution by both phases of ice flow. The metal contents in the HMC fraction are greater than in the <0.063 mm fraction.

The authors assumed that the geochemical composition of the HMC fraction of till reflects clastic dispersal, whereas the <0.063 mm fraction of till reflects clastic as well as some hydromorphic dispersion via groundwater. Metal contents in both fractions reflect the underlying mineralized bedrock (Fig. 9), although elevated values in the HMC fraction extend farther down-ice than values for the <0.063 mm fraction. Based on these assumptions and observations, the authors concluded that the HMC fraction of unweathered till is better suited to till geochemical surveys in support of base metal deposit exploration.

NORANDA MINING CAMP

The Abitibi Greenstone Belt (AGB) in western Quebec and eastern Ontario is one of the largest greenstone belts in the world, covering an area approximately 300 x 700 km (Fig. 1). It hosts several world-class VMS deposits (Fig. 10): the Horne VMS deposit in the Noranda Mining Camp, as well as Bousquet-LaRonde in the Doyon-Bousquet-LaRonde mining camp and the giant Kidd Creek VMS deposit in the Timmins mining camp. The challenges of exploring the AGB, compared to other VMS mining camps in glaciated terrain, are the thick deposits of till (up to 10 m) and, in places, even thicker (up to 40 m) overlying glaciolacustrine clay and silt that cover prospective rocks and hinder geophysical surveys and till sampling. The Abitibi region is also referred to as the 'Clay Belt" because of the thick cover of glaciolacustrine silt and clay.

Bischoff (1954), Ermengen (1957), and Dreimanis (1958, 1960) carried out some of the earliest case studies around VMS deposits in the AGB, sampling around deposits in the Noranda, Timmins, and Chibougamau regions (Fig. 10). They tested the metal content of soils using both cold and hot acid extraction methods. In this early work, the authors recognized the glacially transported nature of the material (i.e. till) on which the soil was developed and the importance of understanding ice-flow direction(s) for the interpretation of geochemical patterns.

The Horne Cu-Au VMS deposit, discovered in 1923, underlies the City of Rouyn-Noranda in the central AGB (Fig. 10). It is the second largest VMS deposit (after Kidd Creek) and one of the largest Au deposits in the AGB. Using extensive surface till sampling and mapping of the locations of mineralized pebbles and cobbles down-ice (south to southwest) of the Horne deposit (Fig. 11), Dreimanis (1958, 1960) demonstrated that the Horne deposit has a well defined glacial dispersal train that extends at least 2400 m down-ice and that till geochemical sampling and analysis (Cu and Zn) was an effective exploration tool.

A second case study was carried out in the Noranda Mining Camp, at the MacDonald (Gallen) Cu-Zn-Au VMS deposit located 6 km northeast of Rouyn-Noranda (Fig. 10). Here Dreimanis (1958, 1960) collected surface till samples and mapped the location of mineralized pebbles and cobbles to document the presence of Cu- and Zn-mineralized clasts or debris up to 900 m down-ice (Fig. 12). From his early studies, Dreimanis (1958, 1960) concluded that because Canada is a glaciated landscape, the application of till geochemical and boulder tracing methods, in combination with geophysical and other prospecting methods, would lead to new discoveries of ore deposits.

At the Magusi Cu-Zn-Ag-Au VMS deposit, 32 km northwest of Rouyn-Noranda (Fig. 10), three overburden holes were drilled above and up- and down-ice of the deposit to test the geochemical signatures in three size fractions of till; whole till, >0.177 heavy mineral concentrate (HMC), and <0.177 mm (Gleeson, 1975a). Metal-rich till over the deposit was found to contain metal contents elevated above background in all three

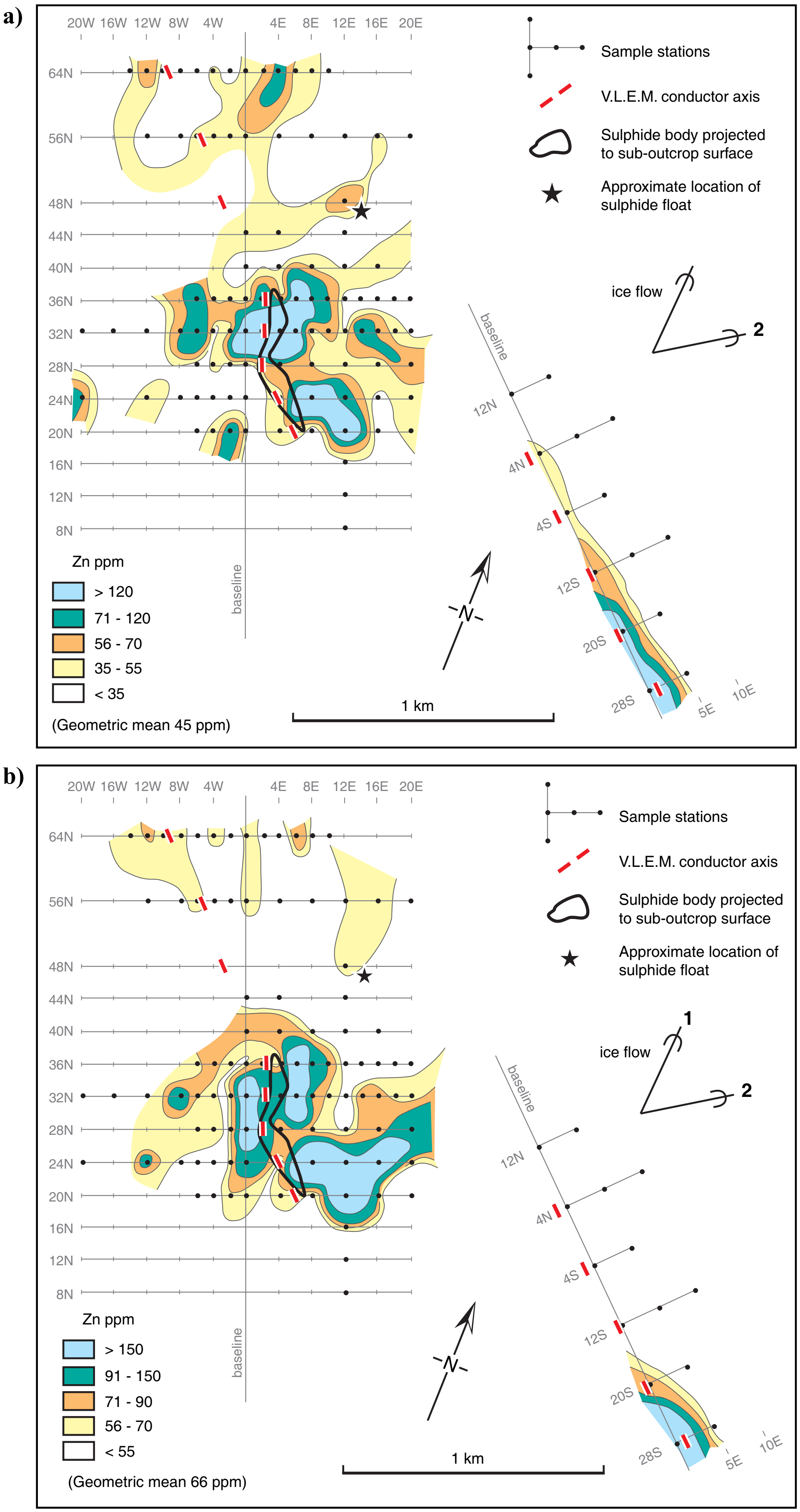

Figure 9. Zinc content (ppm) in unweathered basal till samples collected around the New Bay Pond VMS deposit, Newfoundland using overburden drilling: **a)** <0.063 mm fraction; **b)** 0.063-0.297 mm (SG > 2.96) heavy mineral fraction (modified from Hornbrook et al., 1975).

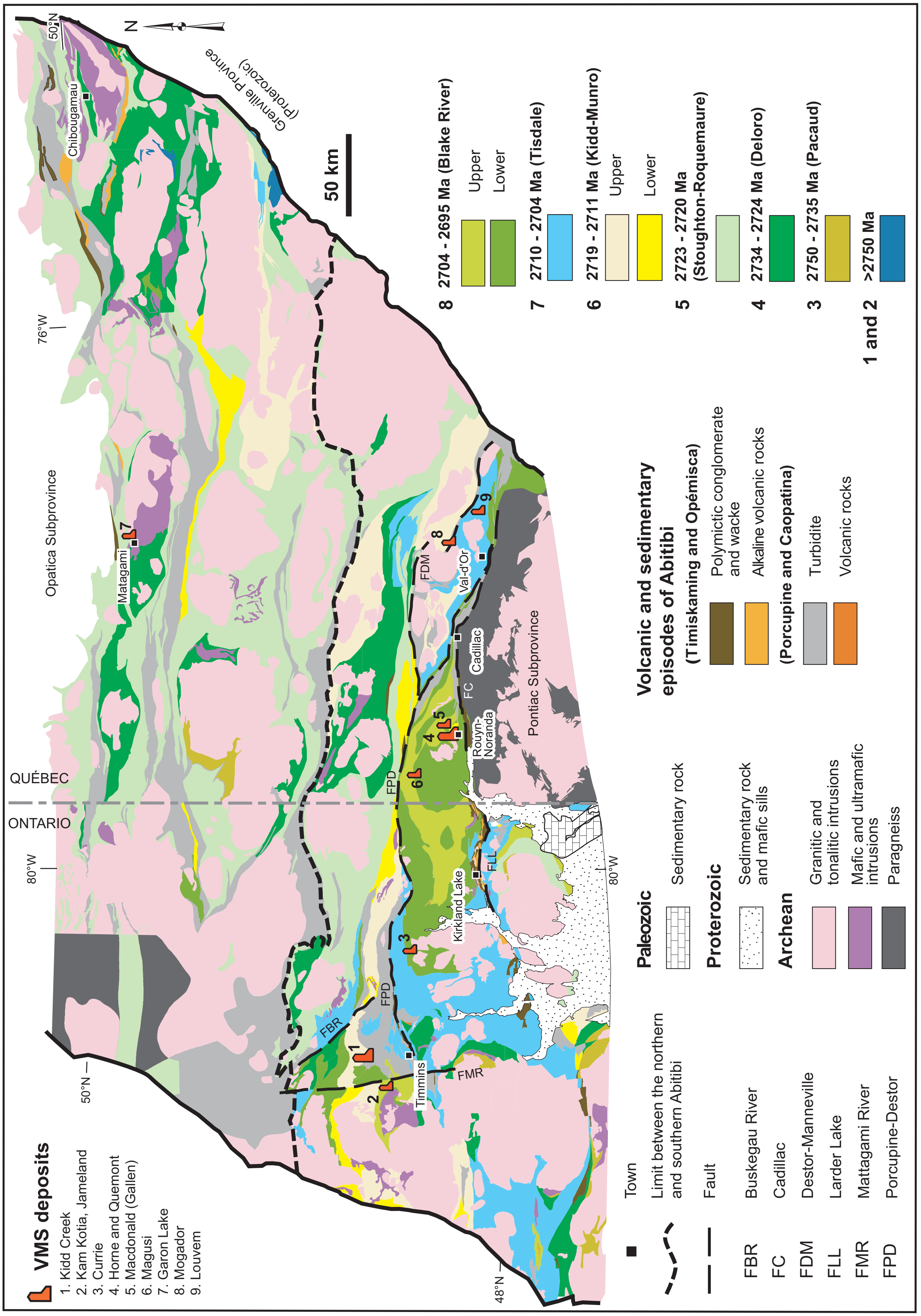

Figure 10. Location of VMS deposits in the Abitibi Greenstone Belt, Ontario and Quebec that are discussed in the paper (modified from Mercier-Langevin et al., 2011b).

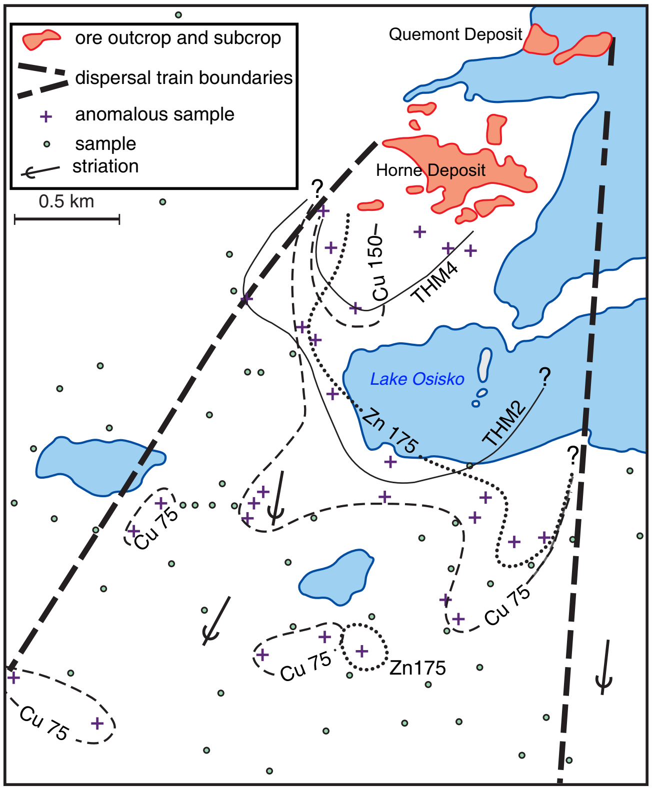

Figure 11. Glacial dispersal train base metal-rich till down-ice (south to southwest) of the Horne and Quémont Cu-Zn-Au VMS deposits in Noranda, Quebec in central Abitibi Greenstone Belt (modified from Dreimanis, 1958). THM = total heavy metals.

size fractions, but only the HMC fraction in till 30 m down-ice contained elevated metal contents. Gleeson (1975b) concluded that this example demonstrated the importance of analyzing the HMC fraction for detecting base metal mineralization.

VAL D'OR MINING CAMP

Tracing of Pb-Zn sulphide boulders in the late 1930s and onward contributed to the discovery in the 1950s of the Mogador (Vendome) Cu-Pb-Zn-Au-Ag VMS deposit (Dreimanis, 1958) (Fig. 10), 40 km northeast of city of Val d'Or, in the Val d'Or mining camp. This was one of the first examples of the application of drift prospecting to VMS exploration in the AGB. Subsequent sampling of till overlying the Mogador deposit by Gleeson (1975b) included analysis of the <0.177 mm and the <0.177 HMC fractions of till. The HMC fraction of the till contained elevated Cu (1600 ppm), Zn (612 ppm), and Ag (3.7 ppm) contents, but the strong geochemical signature is confined to a localized area immediately above the mineralization (Fig. 13).

Other early studies to document till geochemical signatures of VMS deposits in the AGB include those of Garrett (1969a, 1971) and Gleeson and Cormier (1971) around the Louvem Zn-Cu-Ag-Au VMS deposit in the central AGB, east of Val d'Or (Fig. 10).

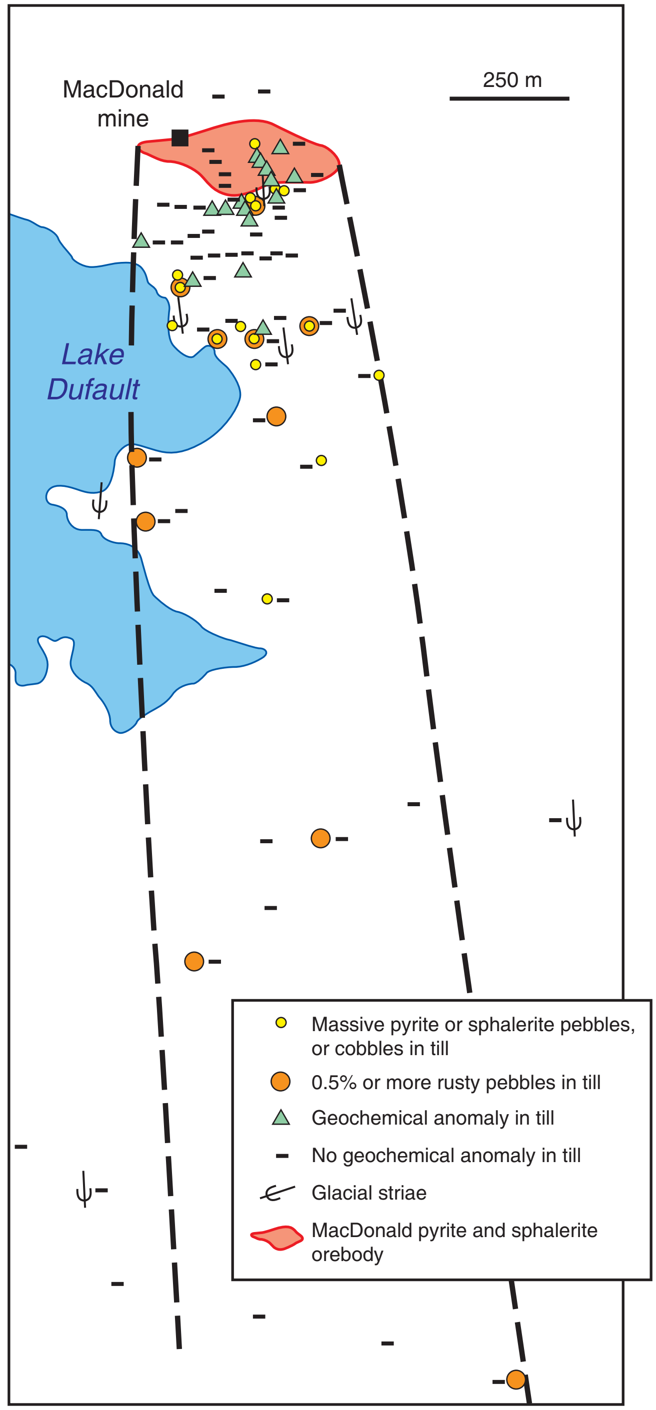

Figure 12. Glacial dispersal train of mineralized clasts and metal-rich till down-ice (south) of the MacDonald (also known as Gallen) Zn-Cu-Ag-Au VMS deposit in the Abitibi Greenstone Belt, Quebec (modified from Dreimanis, 1958).

The study by Gleeson and Cormier (1971) was one of the first to demonstrate that till samples could be collected by drilling at depth. They analyzed the <0.177 mm and >0.177 mm HMC (SG = 2.96) fractions of till. Both till fractions display elevated Cu and Zn contents in samples collected over the deposit as well as down-ice from it (Fig.14); however, the greatest contrast between background and anomalous values is in the

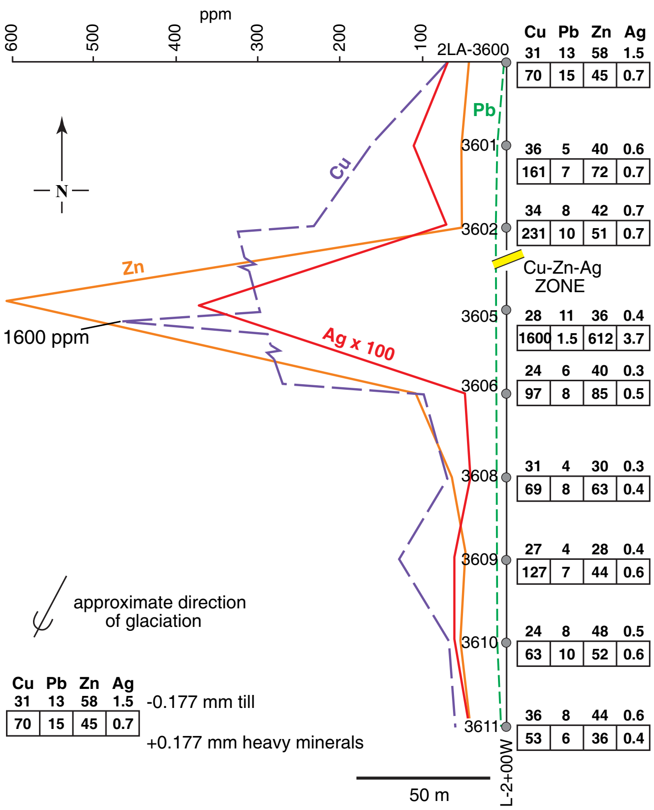

Figure 13. Copper, Pb, Zn, and Ag contents of the <0.177 mm and the >0.177 mm heavy mineral fraction of till along line 2+00 W across the Vendome (Mogador) VMS deposit, in the central Abitibi Greenstone Belt (modified from Gleeson, 1975b).

HMC fraction. Garrett (1969a, 1971) sampled till in 34 overburden holes drilled up to 200 m down-ice of the Louvem deposit and analyzed both the <0.177 mm fraction and the 0.063-0.177 mm HMC fraction (SG = 3.3). Both size fractions of till reflect dispersal of metal-rich till at least 200 m down-ice (southwest) of the deposit; however, the contrast between background and anomalous contents is much greater for the HMC fraction (Fig. 15). Garrett (1971) recommended the use of the HMC for future till geochemical sampling programs. Base metal-rich till immediately down-ice of the deposit is at the bedrock surface and occurs stratigraphically higher in the till section with increasing distance down-ice (Fig. 16). Garrett's (1971) work is one of the first studies by a government geological survey on the geochemical signatures of VMS deposits.

TIMMINS MINING CAMP

Kidd Creek Deposit

In the 1960s, till geochemical methods for base metal exploration were still being developed. One important test site was the giant Kidd Creek Zn-Cu-Pb-Ag deposit, in the Timmins mining camp of the western AGB, 25 km north of Timmins (Fig. 10) (Fortescue and Hughes, 1965; Fortescue and Hornbrook, 1969; Hornbrook, 1975a). These studies aimed to determine if till geochemistry was useful in the evaluation of geophysical anomalies in the "Clay Belt". These Kidd Creek case studies by the GSC were among the first to demonstrate the value of deep (20-40 m) overburden drilling to collect till samples in an area of thick till and clay (Brummer et al., 1987). The first study by Fortescue and Hughes (1965) made use of till samples collected for civil engineering investigations of the mine property. Their analysis of the <0.177 mm fraction of lower till resting on bedrock showed that the VMS deposit imparted a strong Cu-Zn signature to the till.

Subsequently, Fortescue and Hornbrook (1969) conducted one of the first tests using reverse circulation (RC) overburden drilling to collect till samples for mineral exploration. Since their study, tens of thousands of RC overburden holes have been drilled across the AGB to collect till samples in the search for base metal and gold deposits. Fortescue and Hornbrook's (1969) RC drilling showed that elevated Cu (up to 1000 ppm) and Zn (up to 2000 ppm) contents in the <0.177 mm fraction of till outline a south-trending dispersal fan more than 2 km down-ice (Fig. 17) from the deposit (Fortescue and Hornbrook,1969; Hornbrook, 1975a). Skinner (1972a,b) conducted additional RC drilling farther down-ice of the Kidd Creek deposit to further document the dispersal of metal-rich till. Till south of the deposit has high Cu (up to 4300 ppm) and Zn (up to 13,000 ppm) contents in the sand-sized heavy mineral (SG > 3.3 gm/cc) fraction of till at least 8 km down-ice (Fig. 18).

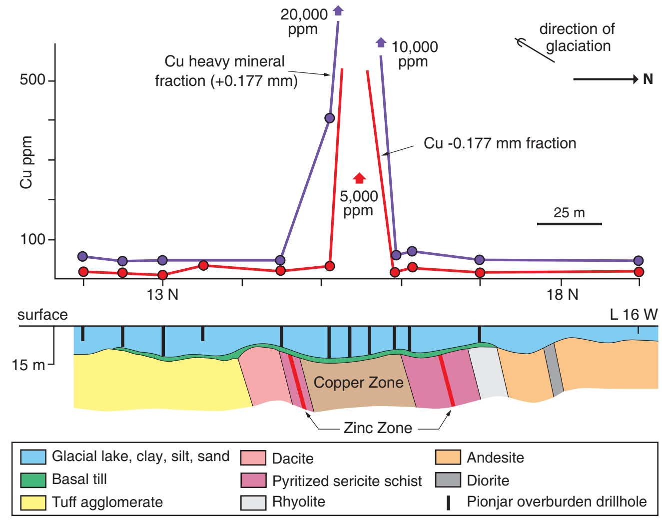

Figure 14. Abundance of Cu (ppm) in the <0.177 mm and >0.177 mm fractions of till overlying and down-ice (southwest) of the Louvem Zn-Cu-Ag-Au deposit in the Abitibi Greenstone Belt, Quebec (modified from Gleeson and Cormier, 1971).

More recently, McClenaghan et al. (1998) conducted a regional surface till sampling survey of the western part of the Timmins mining camp, which

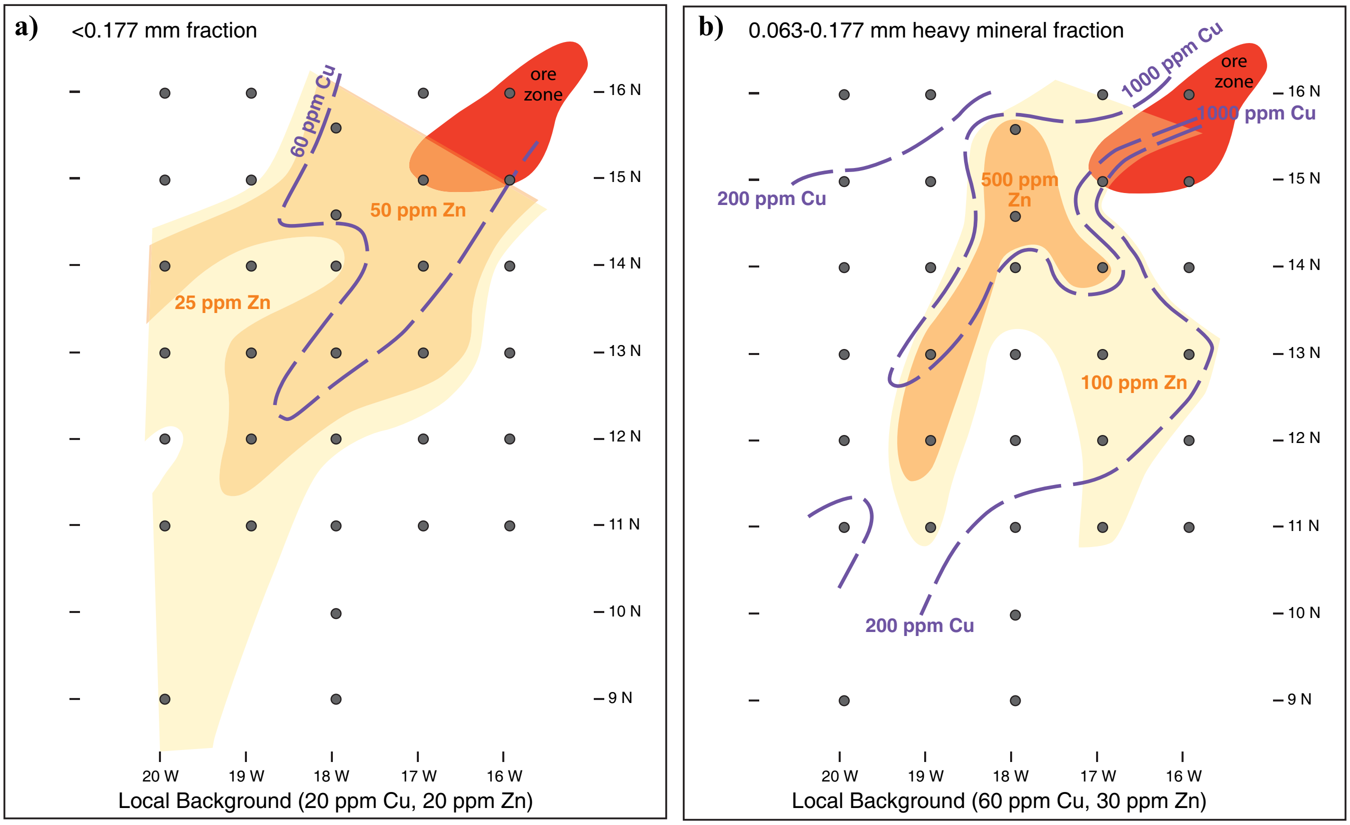

Figure 15. Copper and Zn contents of the **(a)** <0.177 mm (-80 mesh) fraction and **(b)** 0.063 to 0.177 mm (-80+230 mesh) heavy mineral fraction of till in overburden drillholes (black dots) down-ice (southwest) of the Louvem deposit (modified from Garrett, 1971).

encompassed the Kidd Creek deposit area and several gold deposits. Some of the highest Cu and Zn contents in the heavy mineral fraction (SG > 3.3) fraction of their 138 surface till samples are adjacent to the Kidd Creek open pit. Two other till samples in their regional survey display Cu and Pb contents of similar magnitude and these overlie felsic volcanic rocks (the host rocks to the deposit), indicating the potential of such a survey to locate additional VMS-type mineralization in the region.

Kam Kotia Deposit

Dreimanis (1960) was the first to collect and analyze till samples from around VMS deposits in the Timmins mining camp. He sampled till in five sections around the edges of the open pit at the Kam Kotia Cu-Zn-Au-Ag VMS deposit, 25 km northwest of Timmins (Fig. 10). Using both cold extractable heavy metal methods in the field and lab-based quantitative methods for Cu, Zn, and Pb, he documented elevated Cu and Zn contents in till at least 270 m down-ice of the deposit. Subsequently, Skinner (1973) documented glacial dispersal patterns for till geochemical data from samples collected from 92 RC holes drilled up to 5 km south of the deposit. Shilts (1976) summarized the results from Skinner's drilling program and described the dispersal pattern as "sheet-like zones of high Cu concentrations down ice" in the sand-sized heavy mineral (SG > 3.3) fraction of till (Fig. 19). Contents are close to those in the bedrock surface immediately down-ice and increase stratigraphically upward through the till

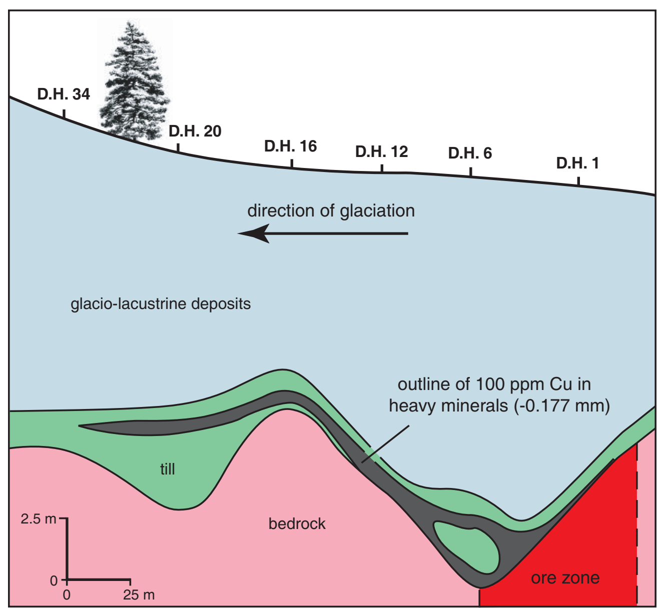

Figure 16. Cross section down-ice of the Louvem VMS deposit showing the position of Cu-rich heavy mineral fraction of till (<0.177 mm heavy mineral fraction) rising upward with increasing distance down-ice (modified from Garrett, 1971).

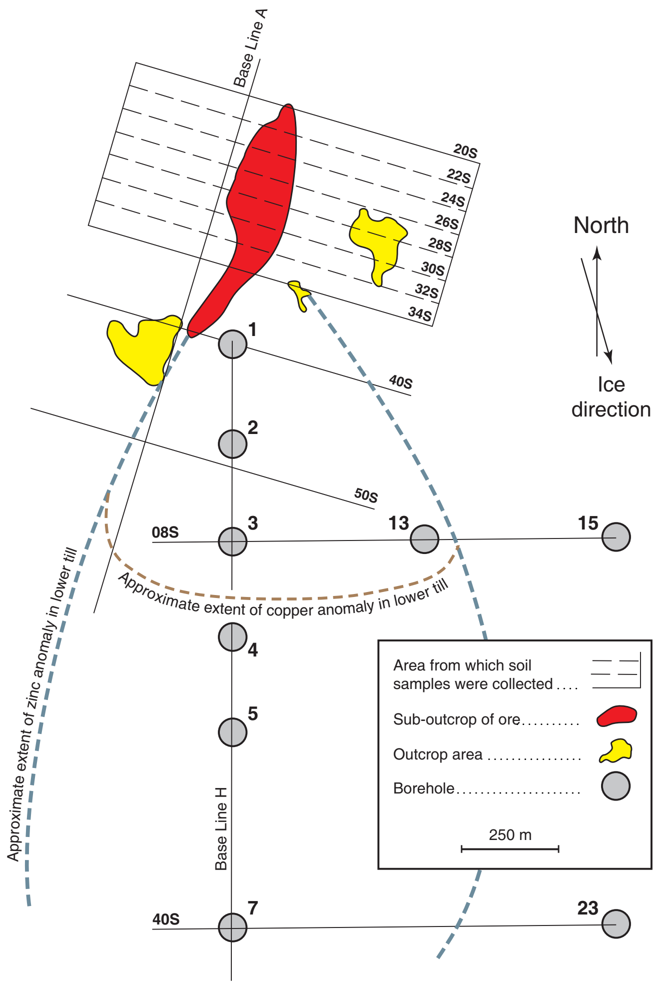

Figure 17. Glacial dispersal fan down-ice (south) of the Kidd Creek Zn-Cu-Pb-Ag VMS deposit, Timmins, in the western part of the Abitibi Greenstone Belt, identified using till collected from deep overburden drillholes (modified from Fortescue and Hornbrook, 1969).

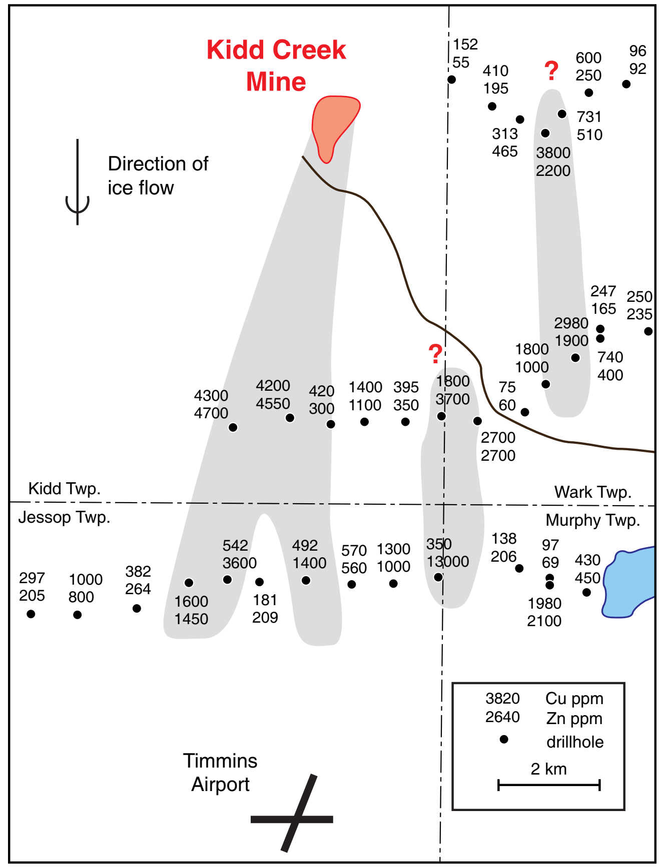

Figure 18. Distribution of base metal-rich (grey) heavy mineral fractions of till down-ice (south) of the Kidd Creek VMS deposit (modified from Nichol and Bjorklund, 1973).

sequence with increasing down-ice distance. More recently, Smith (1990, 1992) reported on the metal contents of 14 closely spaced overburden holes drilled to collect till immediately down-ice (southwest and southeast) of the Kam Kotia deposit. Raw geochemical data published by Smith (1990) reveal a broad suite of VMS pathfinder elements. For example, till samples in drillhole 53, 1 km down-ice (southwest) of the Kam Kotia open pit, contain elevated contents of Cu (359 ppm) and Zn (371 ppm), as well as Fe, Co, Cd, Sb, Se, Ga, Tl, and V in the <0.002 mm fraction.

Jameland Deposit

Skinner (1973) also reported on 21 RC holes drilled around the Jameland Cu-Zn VMS deposit, approximately 1 km southeast of the Kam Kotia deposit (Fig. 10). Shilts (1976) also summarized the results from Skinner's (1973) drilling program around this deposit (Fig. 19). Elevated Cu and Zn contents were reported in the sand-sized heavy mineral (SG > 3.3) fraction of till. This case study demonstrated that the highest contents in till are not universally restricted to immediately down-ice of the deposit. Instead they are displaced 45 to 75 m down-ice and have been sheared upwards.

MANITOUWADGE MINING CAMP

The Manitouwadge mining camp, 330 km east of Thunder Bay (Fig. 1) in northwestern Ontario, was discovered in 1932 and contains four deposits: Geco, Willroy, Big Nama Creek, and Lun-Echo. Morris (1966) first reported elevated metal contents in soil in the Lun-Echo property in the Manitouwadge area (Fig. 1). He sampled C-horizon soil developed on till, determined cold extractable heavy metal contents, and found that the strongest anomalies (300 ppm total heavy metals) overlie mineralized zones. Garrett (1969b) and Hornbrook (1975b) subsequently reported geochemical data for till collected around the Geco and Big Nama Creek Zn-Cu-Ag VMS deposits in the camp. Here, calcareous, metal-poor till derived from Paleozoic carbonate rocks 100 km to the northeast overlies the bedrock and, in places, can mask the signature of the underlying bedrock.

A regional till sampling survey was carried out across the Manitouwadge mining camp by the GSC in

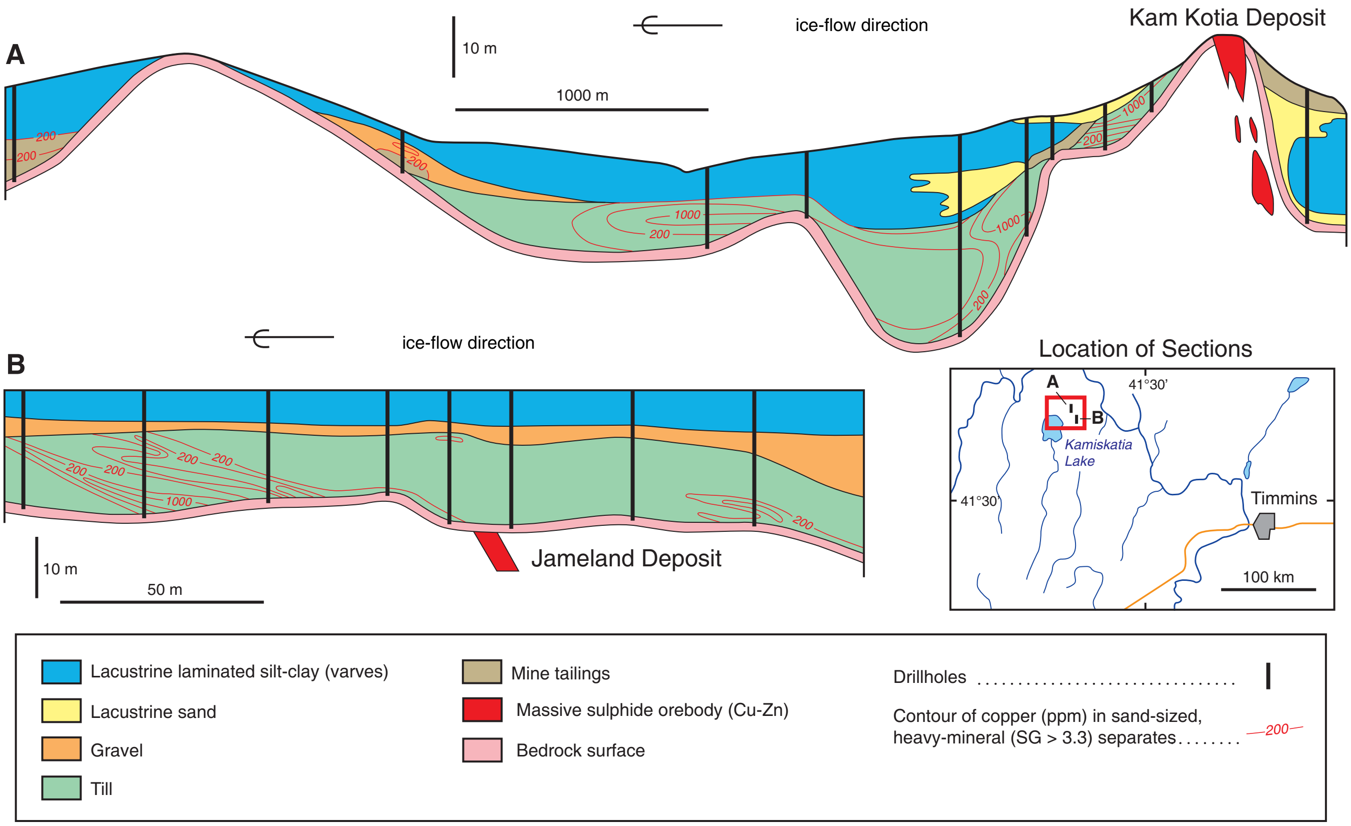

Figure 19. Cross section showing Cu (ppm) contents in the sand-sized heavy mineral fraction (SG > 3.3) of till collected from reverse circulation overburden holes drilled down-ice (south) of the Kam Kotia and Jameland VMS deposits, Timmins (modified from Shilts, 1976). Elevated Cu contents in till are detectable at least 300 m down-ice.

the 1990s, with more closely spaced till samples collected near the Geco and Willroy VMS deposits (Kettles et al., 1998). They reported that the till immediately overlying mineralization is metal-rich despite the presence of distally derived carbonate till. In particular, the <0.063 mm fraction of till near the Geco and Willroy deposits has elevated Cu, Zn, Ag, Fe, Mn, As, Ba, V, Sc, and Ti contents. In addition to reporting the regional till survey data, Kettles et al. (1998) reanalyzed and reported data for Garrett's (1969b) original till samples collected in 1960s around the Nama Creek deposit. They reported elevated Cu (up to 1215 ppm) and Zn (up to 2780 ppm) contents in till overlying mineralization and up to 30 m down-ice from it, reflecting the strong but local base metal signature in till.

Simonetti et al. (1996) tested the use of Pb isotopic analysis of selective leachates from two near-surface till samples collected down-ice of the Geco and Willroy VMS deposits. They found that Pb isotopic signatures in the <0.063 mm fraction of till are similar to those of ore galena within the nearby deposits. They concluded that the Pb in the till is of a secondary origin and was probably scavenged and redeposited in the till after destruction of original sulphide minerals during post-glacial weathering of the till.

FLIN FLON MINING CAMP

The Flin Flon greenstone belt in central Canada (Fig. 1) hosts more than 30 VMS deposits in the largest Paleoproterozoic VMS district in the world (Syme and Bailes, 1993). It is the richest greenstone belt in Canada per square kilometre (Franklin, 1995). Initial surficial geochemical studies in the Flin Flon mining camp were carried out by Byers (1956). He tested Bloom's (1955) cold extractable metals method on soil overlying and down-ice of the Coronation Cu-Zn VMS deposit and determined that metal contents in soil are highest at least 120 m southeast of deposit in the direction of ice flow. Subsequent soil studies by Scott and Byers (1964) determined that Cu and Zn are effective pathfinders for underlying Cu-Zn mineralization.

Another early study of the applicability of soil geochemical analysis for exploration in the Flin Flon mining camp is that of Bradshaw et al. (1973). Based on results from limited A-, B-, and C-horizon soil sampling over the Keg Lake VMS deposit near Flin Flon, they concluded that the Hg content of the organic-rich soil was the best indicator of underlying base metal mineralization. However, given the paucity of details provided, it is not known if the soil was developed on till or some other glacial sediment, how thick the glacial sediment cover is, or the direction of ice flow rela-

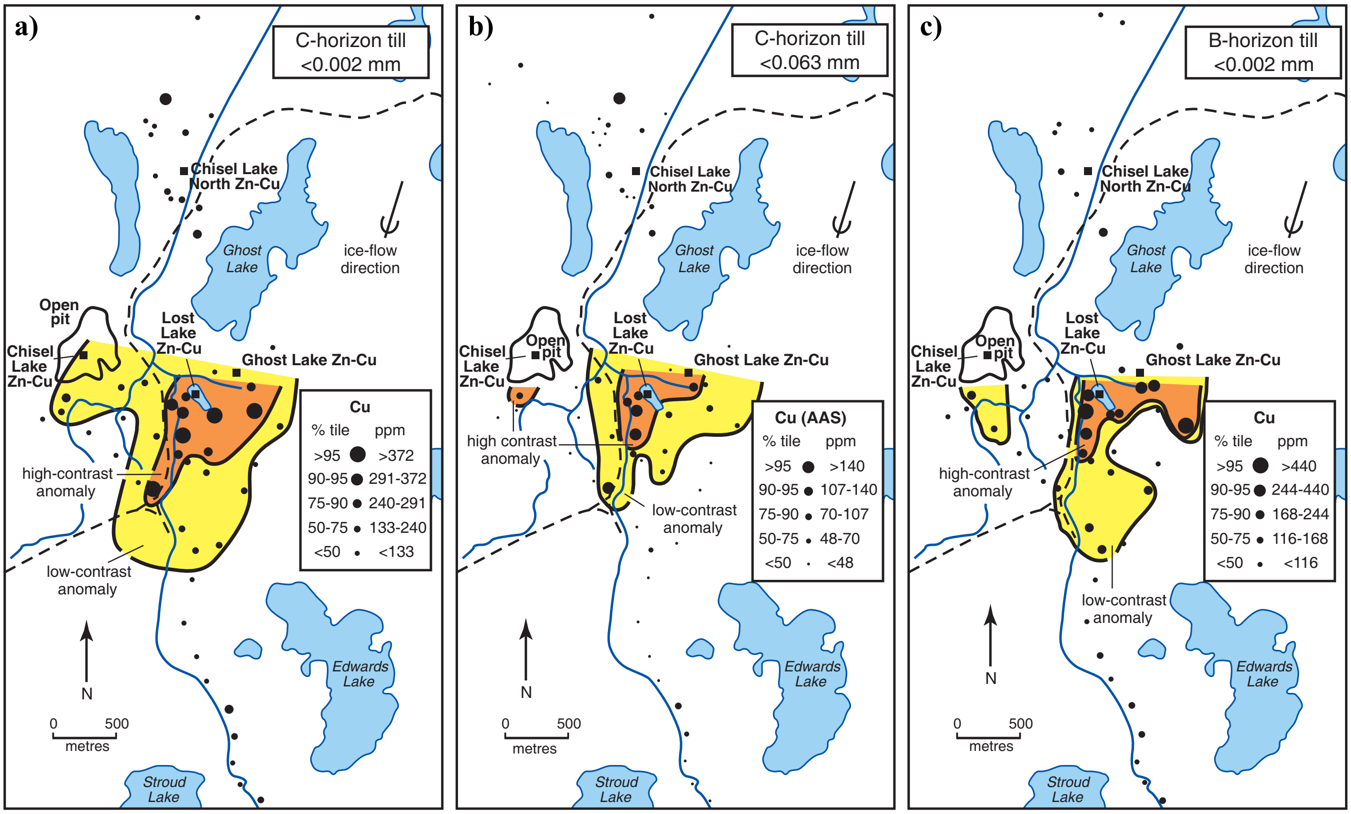

Figure 20. Distribution of Cu (ppm) in surface till around the Chisel Lake, Lost Lake, and Ghost Lake Zn-Cu VMS deposits in the Snow Lake Camp, Manitoba: **a)** <0.002 mm fraction of C-horizon developed on till; **b)** <0.063 mm fraction of C-horizon developed on till; and **c)** <0.002 mm fraction of B-horizon developed on till (modified from Kaszycki et al., 1996).

tive to sample locations. A more thorough till sampling program in this area may indeed reflect the underlying mineralization.

McMartin et al. (1996, 2012) carried out a large regional-scale till sampling program across a 375,000 km^2 area, which includes the major mining camps of Flin Flon and Snow Lake (Fig. 1), to provide a better understanding of the Quaternary history and glacial dispersal patterns of the region as well as provide till geochemical data in underexplored areas to help assess its mineral potential and assist explorationists. They analyzed the <0.002 mm fraction of till for a broad suite of elements and reported elevated contents of one or more of Zn, Cu, Cd, and Hg in till near VMS deposits in the Flin Flon and Snow Lake areas. In addition to anomalous metal contents in areas of known VMS mineralization, they also identified metal-rich till in areas with no known VMS deposits that warrant further investigation.

Till sampling in support of VMS exploration in the Flin Flon region must take into consideration the fallout from the Flin Flon base metal smelter, which has contaminated the upper 0.5 m of soil and oxidized till. Detailed soil profile and till studies at varying distance from the smelter have shown that at sites >3 km from the smelter, till collected at depths of >0.5 m reflects natural compositions derived from erosion of underlying bedrock, and not smelter emissions (Henderson et al.,1998; McMartin et al., 1999) and is thus a suitable exploration medium.

SNOW LAKE MINING CAMP

In the Snow Lake mining camp (Fig. 1) 70 km east of Flin Flon, detailed till sampling was carried out in the early 1990s to document glacial dispersal patterns associated with VMS deposits and evaluate the efficacy of various surficial media, including humus, and B- and C-horizon soils developed on till, as well as analytical techniques best suited to VMS exploration in this glaciated region. Around the Chisel Lake, Lost, and Ghost Cu-Zn VMS deposits, Kaszycki et al. (1996) documented well defined south-southwest-trending dispersal fans defined by Cu and Zn in two fractions of C-horizon soil developed on till. The authors concluded that the contrast between background and anomalous Cu and Zn contents is greatest for the <0.002 mm fraction of till, compared to the <0.063 mm fraction. Furthermore, glacial dispersal of these metals is detectable up to 1 km down-ice from the deposit (Fig. 20). Areas of anomalous metal contents in the B horizon developed on till are smaller in areal extent and the anomalies are smaller, indicating that the B horizon contains less metals than the C horizon in this area.

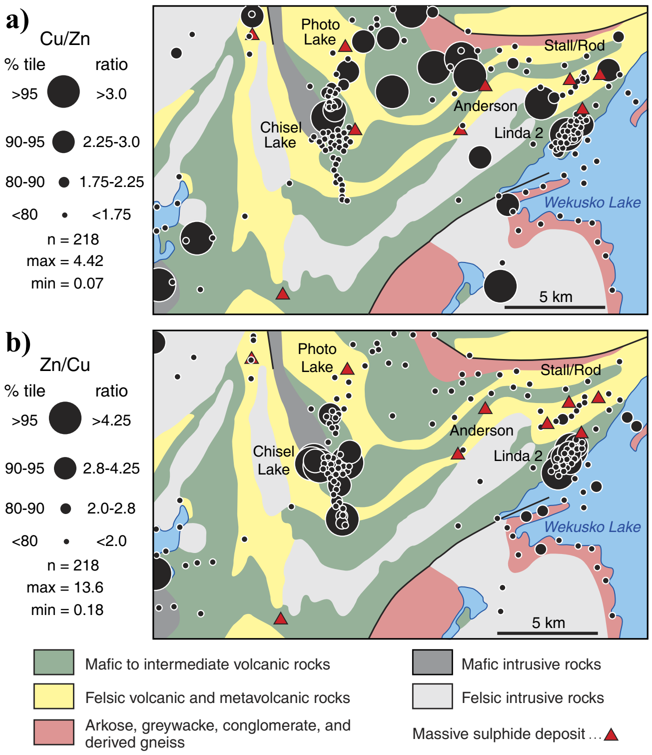

Figure 21. Regional variations in the relative proportions of Cu and Zn in the <0.063 mm fraction of till in the vicinity of past producing deposits in the Chisel Lake area of the Snow Lake greenstone belt, Manitoba: **a)** Cu-Zn ratios; **b)** Zn/Cu ratios (modified from Kaszycki et al., 1996).

Kaszycki et al. (1996) also identified a Cu, Hg, Pb, As, Au, and Sb multi-element anomaly in till north of Chisel Lake, an area where the Photo Lake Cu-Zn-Au VMS deposit was later developed. In addition to documenting the multi-element signatures of till down-ice of the VMS deposits, they compared Cu/Zn ratios in till to those of underlying source rocks. They found that high Cu/Zn ratios in till closely match those in underlying felsic rocks that host Cu-rich VMS deposits and that high Zn/Cu ratios in till closely reflect underlying mafic rocks with Zn-rich deposits (Fig. 21).

Bell and Franklin (1993) reported the first published Pb isotopic analyses of till around VMS deposits in samples collected down-ice of the Chisel Lake, Lost, and Ghost deposits. They found that the Pb isotopic composition of the <0.002 mm fraction of till clearly reflects the presence of the up-ice VMS deposits. Bell and Murton (1995) subsequently carried out additional Pb isotopic analyses of till samples from the Chisel Lake area and, again, demonstrated that VMS-derived Pb can be differentiated from Pb derived from country rocks in till down-ice of the deposits. Simonetti et al. (1996) subsequently tested the use of Pb isotopic ratios on selective leachates from four near-surface till samples collected close to the Chisel Lake deposit. The results for these till samples, similar to those for their Manitouwadge test site, indicate that Pb isotopic signatures in the <0.063 mm fraction of till are similar to those from galena within the nearby deposit.

LYNN LAKE MINING CAMP

Neilsen and Conley (1991) sampled till around the Lar Cu-Zn VMS deposit, 55 km southwest of Lynn Lake, northern Manitoba (Fig. 1), to document the geochemical signature of this VMS deposit and determine if the deposit extended farther west. Their research builds on the earlier work in the region of Kaszycki et al. (1988). Copper, Pb, and Zn contents of the <0.002 mm fraction of till demarcate a short dispersal train extending up to 400 m down-ice (southwest) from the deposit (Fig. 22); metal contents of the <0.063 mm fraction outline a smaller dispersal train with a length of only 100 m. They also documented the vertical distribution of base metals in till profiles at selected sites and concluded that metal contents are highest in unweathered till (C-horizon) below approximately 1 m depth, compared to similar material from more shallow depths or in B-horizon soil developed on till. More recently, re-analysis of archived till samples from the Lynne Lake-Leaf Rapids area by the Manitoba Geological Survey identified multi-element geochemical patterns likely related to yet unidentified VMS mineralization (McMartin et al., in press).

CANADIAN CORDILLERA

The topographically rugged and geologically complex terrain of the Cordillera in western Canada offers different challenges for VMS exploration than the Canadian Shield. First is the greater potential for hydromorphic dispersion of metals downslope from anomalous metal-rich till or bedrock (Paulen, 2001; Lett and Jackaman, 2002). This movement can alter clastic glacial dispersal patterns, either through dilution or enrichment of the geochemical signature in till, and widen or lengthen dispersal trains (e.g. Paulen, 2001). Second, down-slope movement of material can form colluvium. Where colluvium is derived from till, differentiating between both sediment types can be challenging. Levson (2001a,b) has outlined the criteria for differentiating till from colluvium.

Adams Lake Area

Deposit-scale till, soil, and vegetation sampling carried out around VMS occurrences and deposits 80 km north of Kamloops in the Adams Lake area of south-central British Columbia (Fig. 1) has been reported by Lett et al. (1998), Lett (2001), and Paulen (2001). The Samatosum and Rea Ag-Pb-Zn-Cu VMS deposits are located in the Adams Lake area of south-central British Columbia. These relatively small (each <1 Mt) deposits occur in highly deformed and metamorphosed mafic volcanic and argillaceous sedimentary rocks of the Eagle Bay Assemblage (Bailey et al., 2000). Till and B-horizon soil developed on till around and down-

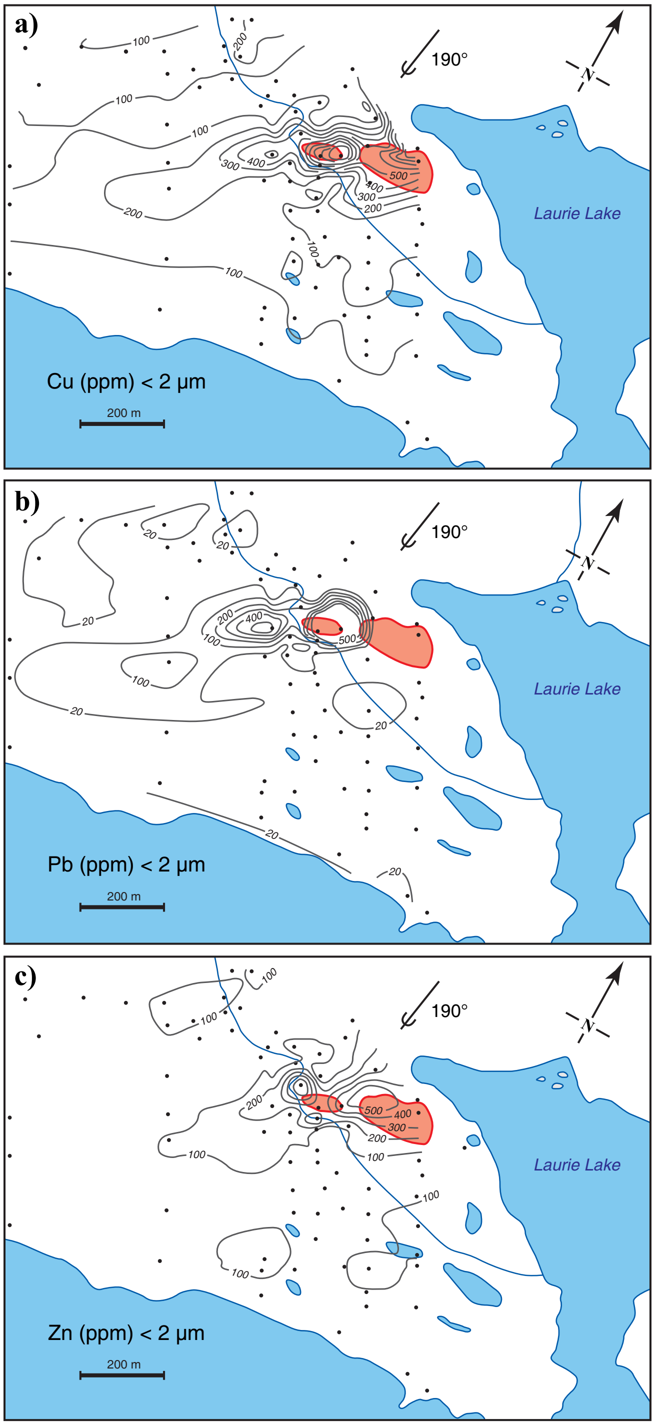

Figure 22. Distribution of **(a)** Cu, **(b)** Zn, and **(c)** Pb in the <0.002 mm fraction of till around the Lar Cu-Zn VMS deposit, Lynn Lake, Manitoba (modified from Nielsen and Conley, 1991).

ice of the deposits have elevated Pb, Ag, As, Hg (Fig. 23), Sb, Au, and Zn contents in the <0.063 mm fraction of surface till (Lett, 2001; Paulen, 2001). Maximum metal contents of till occur 1.8 km down-ice (southeast); however, the surface till anomalies can be traced up to 10 km down-ice (Bobrowksy et al., 1997). Elsewhere in the Adams Lake region, Lett et al. (1998) and Lett (2001) reported elevated Bi, Pb, Hg, and Se contents in the <0.063 mm fraction of till proximal to mineralized rocks on the Harper Creek property. Till around the Broken Ridge Cu-Pb-Zn-Ag VMS occurrence contains anomalous base metal contents near the deposit, and Cu is detected only up to 2 km down-ice of mineralization (Lett, 2001).

Lett and Jackaman (2002) subsequently compiled data and observations from the numerous published reports of surficial (stream sediments, soils, till) geochemical data around VMS deposits and occurrences in the Adams Lake region. From the compiled data, they presented a series of three-dimensional exploration models to assist in the design and interpretation of till geochemical surveys for VMS exploration that takes into account the nature and thickness of glacial deposits, as well as topography and surface drainage. Their models build on the general conceptual models first proposed by Bradshaw (1975) for mineral exploration in the Canadian Cordillera. The model of Lett and Jackaman (2002) is heuristic and identifies key pathfinder elements in till and derivative B-horizon soils, and predicts the shape and trend of geochemical anomalies. The authors noted that base metal contents are higher in till (C horizon) than in B-horizon soil developed on till because the former is less weathered, and thus more directly reflects the composition of the bedrock source.

Ward et al. (2011) carried out regional-scale till sampling in the Interior Plateau, 50 km northwest of Prince George, British Columbia (Fig. 1). Though they did not specifically sample around known base metal mineralization, they appreciated the potential of the local rocks to host VMS deposits and the extensive suite of pathfinder elements that can be routinely determined. They documented elevated Zn, Cd, Bi, and Tl contents in the <0.002 mm fraction of till, which may indicate the presence of Pb-poor VMS style mineralization in the eastern part of their study area.

Myra Falls

The Myra Falls Cu-Zn-Pb-Au-Ag-Cd VMS deposits (Lynx, Myra, Price, HW) on Vancouver Island (Fig. 1) were discovered in the early to mid-1960s based on follow-up drilling of outcropping mineralization. The deposits occur in a host sequence of basaltic andesite, rhyolitic volcaniclastic and black mudstone (Barrett and Sherlock, 1996). Hicock (1986, 1995) collected till samples down-ice and down-valley of the VMS deposits and analyzed the <0.002 mm fraction of till. He reported elevated Cu, Pb, and Zn contents that are highest 1 km down-ice from the deposits, but can be traced up to 20 km down-ice and down-valley.

Finlayson Lake Camp

The first VMS deposit discovered in the Finlayson Lake area (FLA) (Fig. 1) was the Fyre Lake deposit in

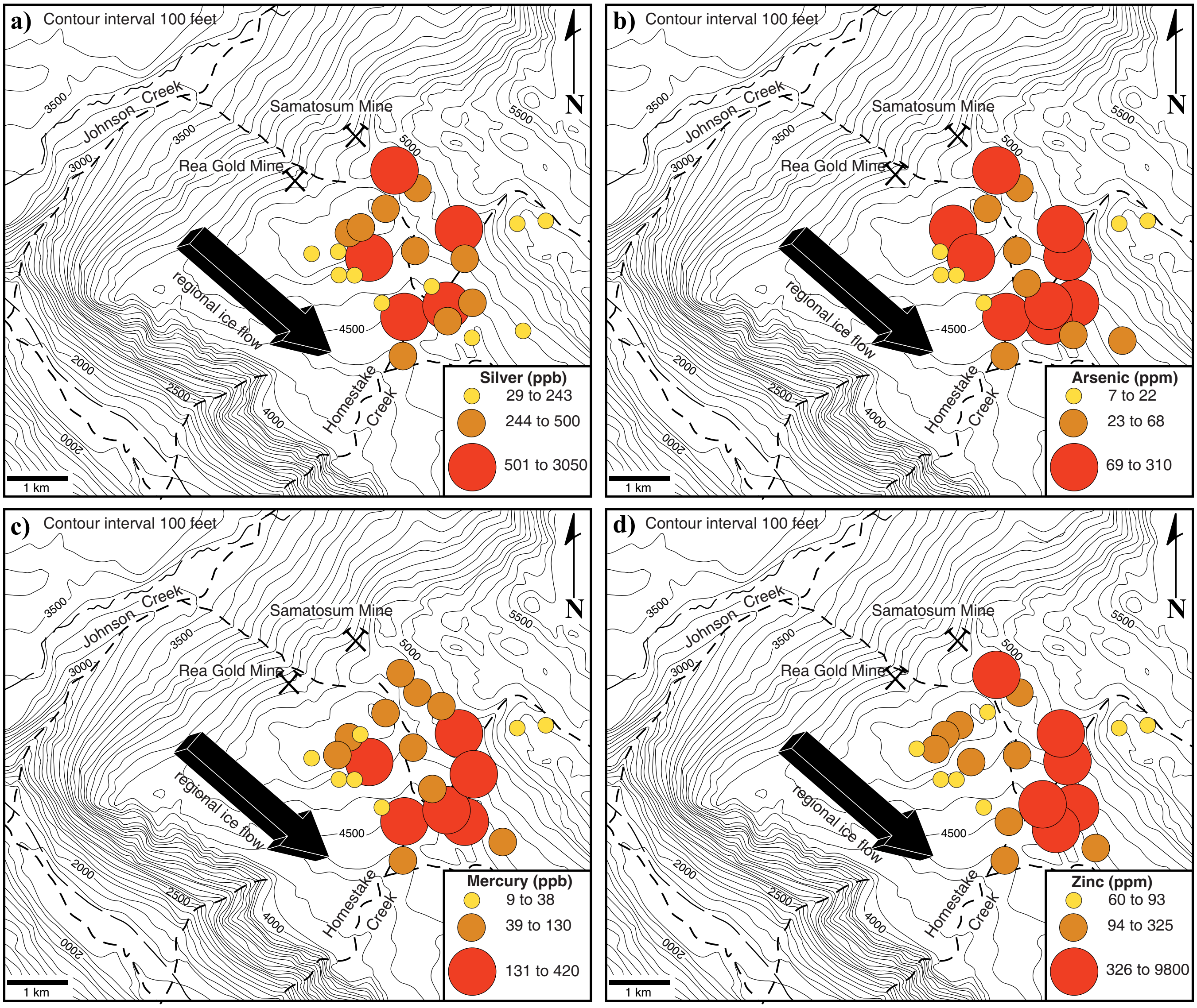

Figure 23. Distribution of **(a)** Ag, **(b)** As, **(c)** Hg, and **(d)** Zn in the <0.063 mm fraction of till down-ice (southeast) of the Rea Gold and Samatosum VMS deposits (modified from Paulen, 2001).

1960 during follow-up investigations to locate the source of massive sulphide float boulders (Peter et al., 2007). Exploration in the FLA was sporadic throughout the 1970s and 1980s, and it was not until 1993 to 1995 that renewed exploration (based on application of the VMS genetic model) led to the discovery of the Wolverine and Kudz Ze Kayah deposits (Peter et al., 2007), creating the largest staking rush in Yukon's history. The camp hosts several mid-sized Zn-Pb-Cu-Ag-Au VMS deposits. Stream sediments are the optimal sample medium in this mountainous region where relief and drainage density are high. However, in lower relief terrain in this area where drainage density is low, till is the optimal sampling medium for VMS exploration (Bond and Plouffe, 2002). Regional and closely spaced till samples collected around the largest of the VMS deposits in the camp, the Kudz Ze Kayah and Wolverine deposits and the Argus property, indicate that till geochemistry is an effective exploration tool in the region. Till contains high Zn, Pb, Ag, and Au contents in the <0.063 mm fraction at least 500 m down-ice (northwest) of the Kudz Ze Kayah deposit. Other nearby anomalies in till indicate the potential for further discoveries.

CANADIAN ARCTIC

The Canadian Arctic is challenging for base metal exploration because the region is remote. To date, no VMS deposits in the Arctic have been mined. Another challenge is the permanently frozen ground, with the exception of the uppermost 0.5 to 2.0 m that thaws during the summer months.

Kaminak Lake

Ridler and Shilts (1974a,b) and Shilts (1974a, 1977) provide guidelines for base metal deposit exploration in permafrost terrain, based on their regional surveys and case studies in the Kaminak greenstone belt (Fig. 1). Through their regional sampling over the greenstone belt, they introduced the concept of mudboils to mineral explorationists and demonstrated how to take advantage of the summer permafrost thaw cycle to easily collect fresh till at shallow depths from mudboils (Shilts, 1977, 1978). Closely spaced sampling of till near the Spi Lake VMS prospect (Miller and Tella, 1995) in the western part of the belt led to the discovery of sphalerite- and galena-rich boulders and a 4 km long till dispersal train that indicates the mineralized bedrock source lies beneath Spi Lake (Ridler, 1974; Shilts 1974a,b). To assist mineral exploration in the region, Shilts and Wyatt (1989) reanalyzed the till samples collected between 1970 and 1975 for a broader suite of elements.

Hackett River Deposit

In the 1970s, Miller (1979) sampled soil and other surficial media (organic material, lake sediments) and waters (snow-melt runoff, seepage pits, lakes) in the permafrost terrain around the Bathurst Norsemines base metal occurrence (Fig. 1). Today this Zn-Pb-Cu-Ag deposit is known as the Hackett River "Main Zone". There are also three other significant deposits (East Cleaver, Boot Lake, Jo Zone) and showings along a 6.6 km long strike length of the Hackett River Greenstone Belt (HRGB) (PEG Mining Consultants, 2010). The Main Zone is one of the most Ag-rich VMS deposits in the world (Grant, 2009). Miller (1979) sampled what he referred to as "soil layer 2" from between 0.3-0.6 m depth, which in most cases is developed on till. Samples were collected from around what is now known as the Main Zone between Banana and Camp lakes (Fig. 24). Lead in the <0.177 mm fraction of soil is dispersed at least 600 m down-ice (west) of the deposit, and Ag and Fe in soil show similar patterns to Pb. Miller suggested the low Cu and Zn contents of till down-ice of the A Zone were due to post-glacial weathering of till and mobilization of these elements out of this area.

Yava Deposit

Cameron and Durham (1975) sampled soil in stony mudboils in the permafrost terrain around the Agricola Lake massive sulphide occurrence, which is now known as the Yava Zn-Pb-Cu-Ag VMS deposit. The deposit is located 50 km south of the Hackett River deposits within the HRGB (Fig. 1). Because the samples are described as being collected from stony mudboils, they are assumed to be till and thus are included in this review. Surface soil samples collected proximal to the deposit have high Pb, Ag, Hg, and Au contents in the <0.177 mm fraction, which reflect glacial dispersal from the deposit towards the northwest (Fig. 25).

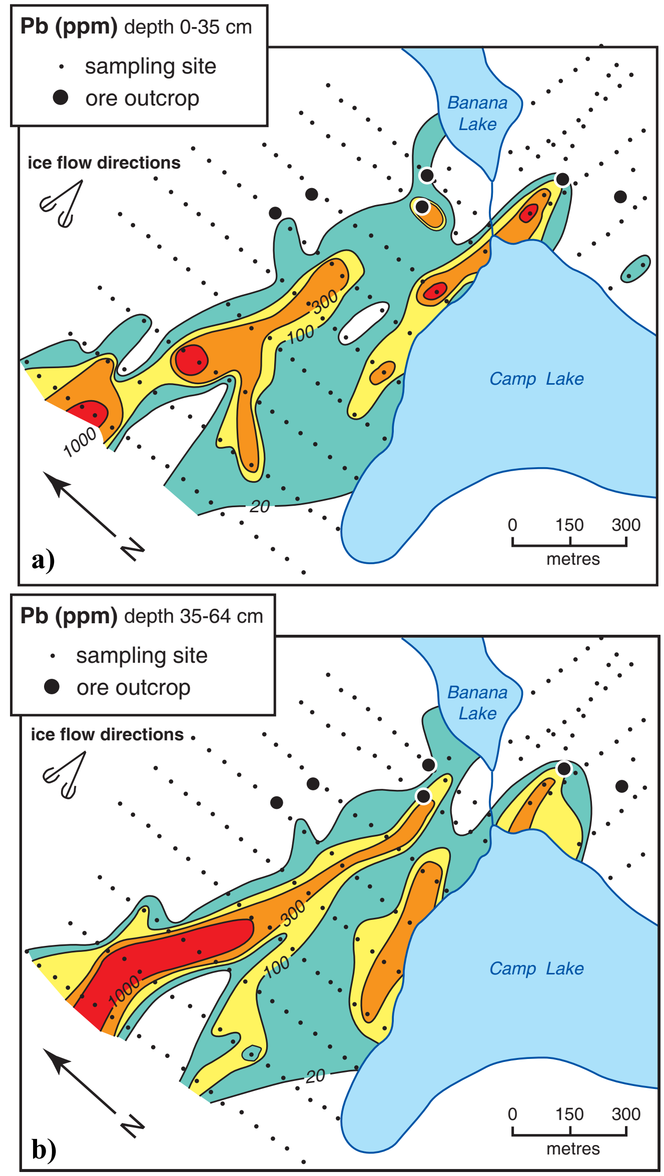

Figure 24. Distribution of Pb in the till in **(a)** soil layer 1 (0-35 cm) and **(b)** soil layer 2 (0.3-0.6 m depth) around the A Zone of the Hackett River VMS deposit (modified from Miller, 1979).

Copper and As have been hydromorphically dispersed down-drainage.

This study is noteworthy because it is one of the first to report the usefulness of sampling from mudboils for base metal exploration and it provides analyses of what, at the time, was a broad suite (12) of trace elements. Cameron (1977) reported up to 9700 ppb Hg, 13,000 ppm Pb, 1500 ppm Cu and Zn, and 2200 ppb Au in soil near the deposit. Further analysis of some samples using aqua regia digestion reported up to 237 ppm Ag. Size-partitioning studies of metal-rich soil showed that the <0.002 mm (clay) and the 0.6 to 1.2 mm (coarse to very coarse sand) fractions have the highest metal contents. Based on the spatial distribution patterns for the 12 elements, Cameron (1977) concluded that the geochemical signature around the VMS

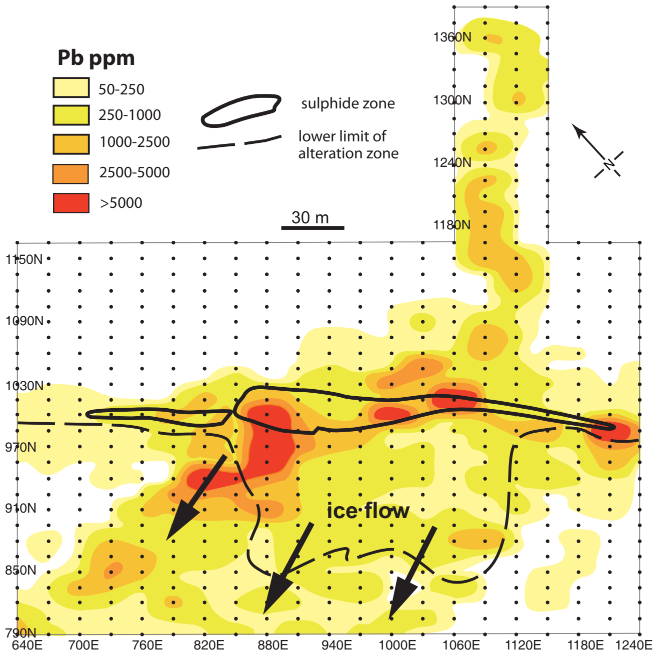

Figure 25. Distribution of Pb in soil sampled from mudboils around the Yava VMS deposit (modified from Cameron, 1977).

deposit is the net result of glacial dispersal, solifluction, and hydromorphic dispersion (Fig. 26), all of which are important processes that require consideration when exploring in permafrost terrain.

Izok Lake Deposit

The Izok Lake Zn-Cu-Pb-Ag VMS deposit, 360 km north of Yellowknife (Fig. 1), is one of the largest undeveloped Zn-Cu resources in North America (Morrison, 2004). The deposit was discovered by following up mineralized boulders first found along the west shore of Izok Lake in the 1970s. As part of an indicator mineral study of this deposit, Hicken et al. (2012) collected closely spaced till samples from mudboils around the deposit; which were found to contain accessory gahnite (Zn spinel). They documented elevated Zn (339 ppm), Cu (308 ppm), Pb (458 ppm), Ag (168 ppm), Cd (1.28 ppm), and Bi (4.08 ppm) and to a lesser extent Sb, Hg, Se, In, and Tl contents in the <0.063 mm fraction of till overlying the deposit and down-ice (northwest) from it. Mudboils closest to the deposit (<400 m down-ice) are oxidized and have an orange-brown colour, in contrast to the typical grey colour of metal-poor till, indicating the breakdown of (formerly) abundant sulphide minerals (Fig. 27). Till geochemical surveys show glacial dispersal up to 6 km down-ice (northwest) from the deposit (Fig. 28).

DISCUSSION

Dispersal Patterns

The maximum transport distance (i.e. long-axis length) of base metal-rich (e.g. Cu, Pb, Zn) dispersal trains

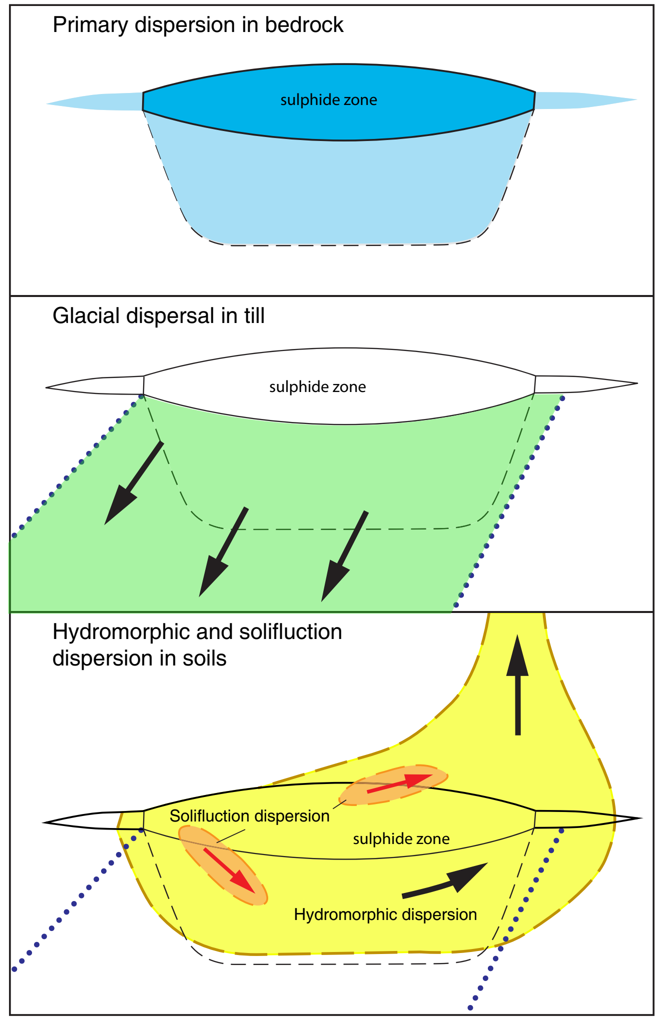

Figure 26. Schematic model of dispersal and dispersion processes affecting the soil geochemical signature of the Yava VMS deposit (modified from Cameron, 1977).

Figure 27. Photograph looking east from the west shore of Izok Lake at (foreground) oxidized, orangey brown mudboils 500 m down-ice (west) of the Izok Lake VMS deposit. The orangey brown colour of these metal-rich mudboils is in contrast to metal-poor grey mudboils that are typical of the region. (Background) Drill rig on an island in Izok Lake.

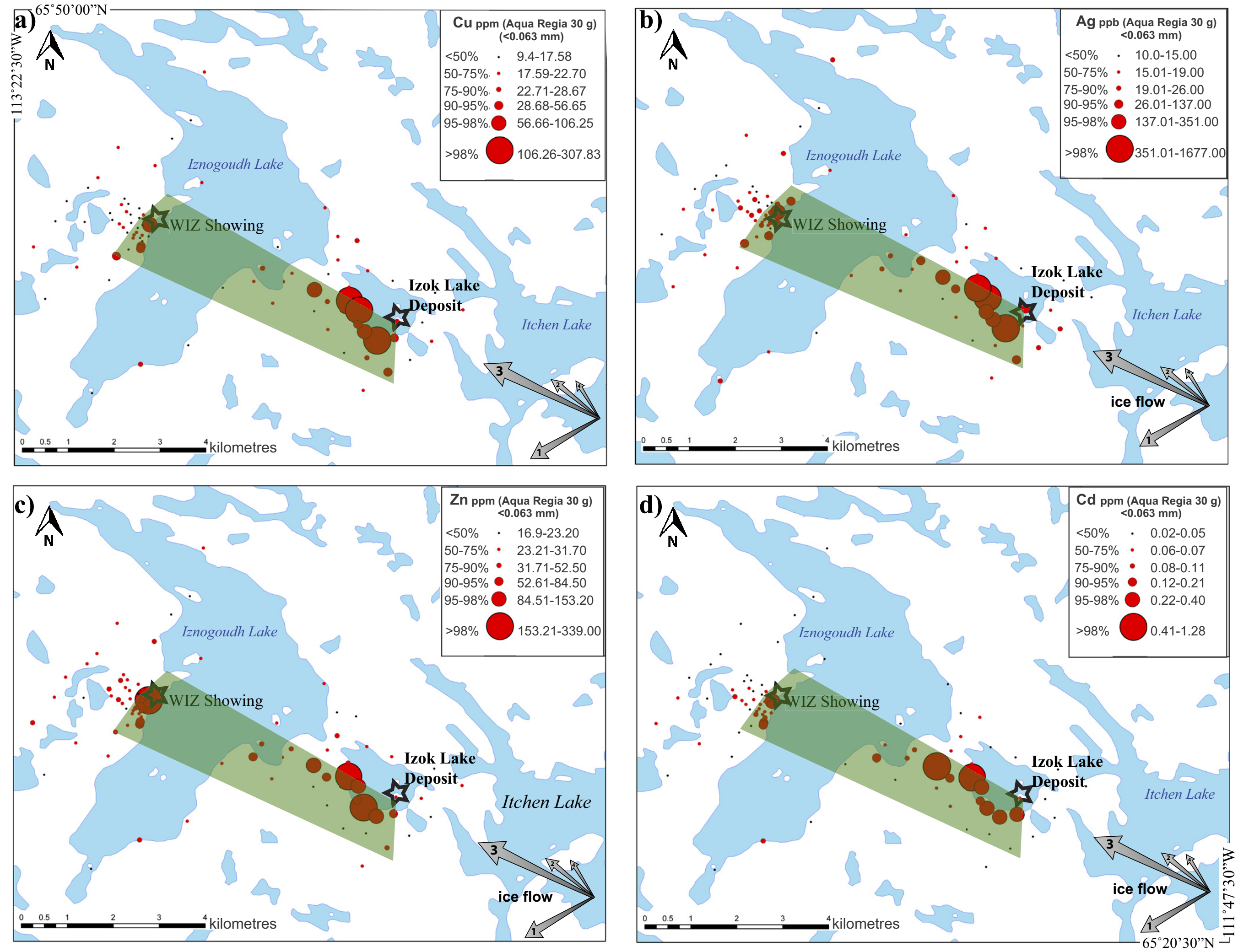

Figure 28. Distribution of **(a)** Cu, **(b)** Ag, **(c)** Zn, and **(d)** Cd in the <0.063 mm fraction of till around the Izok Lake VMS deposit, Nunavut (modified from Hicken et al., 2012) with the glacial dispersal outlined in green shading. Black stars indicates location of mineralization. Ice-flow directions and their relative ages (1=oldest) are indicated in the bottom right corner.

documented down-ice of Canadian VMS deposits varies from a few 100 metres (e.g. BOG, Halfmile Lake, Hackett River Main) to a few kilometres (e.g. Horne, Restigouche, Samatosum, Izok Lake, Buchans). Factors that can influence the tenor of the base metal enrichment suite in till and the maximum distance it is transported include the size, morphology, and erodibility (hardness) of the sulphide body; depth below the bedrock surface; surface topography (DiLabio, 1990; Shilts, 1996); the presence or absence of pre-glacial metal-rich gossan (readily eroded and dispersed down-ice); the geochemical contrast between the deposit and the surrounding host rocks; and the complexity of ice flow.

These base metal-rich dispersal trains from VMS deposits are significantly shorter than indicator mineral trains documented for deposits such as kimberlite, for which trains are commonly >50 km (e.g. McClenaghan and Kjarsgaard, 2007). Trains are longer because kimberlite indicator minerals (KIM) are physically robust and survive glacial transport over long distances. Gahnite is one of the more physically robust (hardness = 8) VMS deposit indicator minerals, (Spry and Scott, 1986; Heimann et al., 2005) and thus can be detected much further down-ice from deposits such as Izok Lake (McClenaghan et al. 2012) than geochemical indicators in the <0.063 mm fraction of till.

Glacial dispersal trains in till down-ice of VMS deposits: 1) are areally larger than the deposits themselves, providing a larger exploration target area; 2) are relatively short (hundreds to thousands of metres) compared to dispersal trains defined by oxide and silicate indicator minerals (e.g. kimberlite indicator mineral dispersal trains), thus requiring more closely spaced till sampling; and 3) contain pathfinder elements of VMS deposits that reflect the mineralogy of the deposit (i.e. Cu/Zn ratios, Au-rich, Ag-rich), which provide sound indications of the mineralogy of the massive sulphide mass (or part thereof) that was eroded and dispersed.

Effects of Post-Glacial Weathering on Till Geochemical Signal

Shilts (1973, 1974a,b, 1975) recognized that base metal contents were higher in the <0.002 mm fraction than in the <0.063 mm fraction of the same till samples from areas around VMS deposits. He attributed the higher contents in the <0.002 mm fraction to weathering of sulphides in the till. He suggested that metals released during weathering of sulphide minerals are hosted in amorphous oxides or hydroxides or are bound to surfaces of phyllosilicate minerals. This seems plausible where the till is weathered and the material being sampled is B-horizon soil developed on till (e.g. early soil surveys in BMC, Yava deposit).

Nielsen and Conley (1991) investigated the clay mineralogy of selected metal-rich till samples around the Lar VMS deposit to document the mineral hosts of high Cu, Pb, and Zn contents in the <0.002 mm fraction. Since no sulphide minerals were detected, they concluded that the hosts of the metals were either amorphous oxide or hydroxide minerals or that the elements were bound to surfaces of silicate minerals (although no phyllosilicates minerals were found to be present). The authors detected jarosite in the clay fraction and concluded that the base metals bound to the surface of the jarosite accounted for the higher base metal contents in the <0.002 mm fraction for this site.

For unweathered till, a more plausible explanation for the high metal contents in the clay-sized fraction is that the ore minerals themselves are clay-sized, and/or the primary clay-sized minerals in the VMS deposits, such as chlorite, also host Cu, Pb, and Zn (Frondel and Einaudi, 1969; Rule and Radke, 1988).

Sample Media (till not soil)

The earliest surficial geochemical investigations around VMS deposits in Canada were made using "soil" rather than till samples. Soil sampling is still used by some exploration companies instead of till sampling in the rugged terrain of the Canadian Cordillera (e.g. Kerr and Levson, 1995; Levson and Giles, 1995). Soil formation destroys labile minerals, such as sulphides, and, therefore, the geochemical signatures in soils formed on till are the result of a combination of clastic glacial dispersal and elements dispersed by aqueous and other processes. As a result, base metal contents are typically lower in weathered till (B horizon) than in fresh till (C horizon), and dispersal patterns may be more difficult to interpret and follow-up to find the bedrock source (e.g. Hoffman and Woods, 1991; Kaszycki et al., 1996; Lett and Jackaman, 2002 Hall et al., 2003). In glaciated terrain, soil can be developed on a variety of substrates that have different depositional histories, including till, glaciofluvial sand, or glaciolacustrine silt and clay. Soil sampling could potentially include any of these different glacial sediment types, making interpretation of geochemical patterns difficult.

To obtain an unimpeded signal of first-order glacial dispersal, unoxidized till is the target medium. Till sampling strategies to obtain the optimal till sample for mineral exploration in the glaciated terrain of Canada have been summarized by Plouffe (1995), Levson (2001 a,b), McMartin and McClenaghan (2001), McMartin and Campbell (2009), Spirito et al. (2011), and most recently, McClenaghan et al. (in press).

In areas of permafrost, the ability to sample till at depth is typically restricted by the thickness of the active layer. This layer commonly thaws to a depth of up to 1 m during the maximum summer thaw period (McMartin and Campbell, 2009). In these areas, fresh till can be sampled from active mudboils (Shilts, 1973, 1977; Cameron, 1977; McMartin and McClenaghan, 2001; Hicken et al., 2012). In areas free of permafrost that are covered by thin till or where till occurs at surface, samples can be collected from holes dug using a hand-held shovel or backhoe excavator, or from sections along rivers, lakes, or roadcuts. Samples should be collected between 0.5 and 1.0 m depth and below the B-horizon, as the surface part of the till can contain material from a broader area than till at depth. In local- and property-scale surveys, till sampling close to the bedrock surface is most effective because the composition of the till closely resembles that of the underlying bedrock. Where glacial sediments are thicker than ~5 m, drilling is required to reach locally derived till and effectively characterize the till stratigraphy, as well as to determine lateral and vertical variations in till geochemical compositions (Coker and DiLabio, 1989). Drilling methods for collecting till samples are described in detail by McMartin and McClenaghan (2001) and Paulen (2009). When sampling for VMS exploration by drilling, it is important to take into consideration that drilling grease can contaminate the till matrix with Zn and Pb (Averill, 1990).

Size Fractions

Because the main VMS ore minerals chalcopyrite (hardness = 3.5), sphalerite (hardness = 3.5-4.0), and galena (hardness = 2.5) are soft, they are readily comminuted during glacial transport to the finest fraction of till (silt + clay) over short distances (Kauranne, 1959; Salminen, 1980; Nevalainen, 1989; Hicock, 1995). Thus, the geochemical compositions of the silt + clay (<0.063 mm) or the clay (<0.002 mm) fraction of till are ideal for detecting glacial dispersal from VMS deposits. The advantage of geochemically analyzing the <0.002 mm fraction of till is the high contrast between background and anomalously high metal contents (e.g. Shilts 1974a, 1975). The disadvantages of using the <0.002 mm fraction include 1) the costly and time-consuming clay separation process required to isolate the <0.002 mm fraction and the large volume of material (~1 kg) needed to recover sufficient clay-sized material for analysis (Lindsay and Shilts, 1995; Klassen, 2003); 2) the low (<2%) clay content of typical Canadian tills; and 3) the fine fraction's susceptibility to false anomalies produced by hydromorphic dispersion of metals not necessarily related to base metal mineralization in bedrock (Pronk, 1987). The scavenging capacity of the <0.002 mm fraction is variable and depends on pH, clay mineralogy, and hydromorphic conditions. Analysis of only the clay fraction, particularly in areas where surface till samples have been collected, provides information about weathering and hydromorphic dispersion effects (Gunton and Nichol, 1974; Pronk, 1987).

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

Geochemical analyses of a coarser size fraction of till, such as the -80 mesh fraction (<0.177 mm), is not recommended because this fraction consists mainly of fine sand. The fine sand component contains abundant quartz and feldspar (Fig. 29) (Dreimanis and Vagners, 1972; Klassen, 2003) that will dilute metal contents and thus decrease the geochemical indications of a nearby VMS deposit.

Less commonly, a split of the heavy mineral fraction (SG >2.9 or >3.3) of till is geochemically analyzed for base metals as this has been shown to enhance the contrast between background and anomalous values (e.g. Garrett, 1971; Skinner, 1972a,b; Smith, 1990; McClenaghan et al., 1998). Initially, till heavy mineral concentrates were pulverized and geochemically analyzed because the commercial service did not exist to systematically visually examine and identify indicator minerals for VMS and other base metal deposits. A suite of VMS indicator minerals is now recognized and the minerals can be identified and counted in the sand-sized (0.25-2.0 mm) heavy mineral fraction of till (e.g. Averill, 2001; Hicken et al., in press). Today, if geochemical analysis of the heavy mineral fraction is warranted, it is carried out on a split of the <0.25 mm heavy mineral fraction in order to preserve the coarser fraction (>0.25 mm) for visual examination and identification of VMS indicator minerals. Till geochemical surveys for VMS exploration should include initial orientation studies to determine the optimal size fraction of till for geochemical analysis.

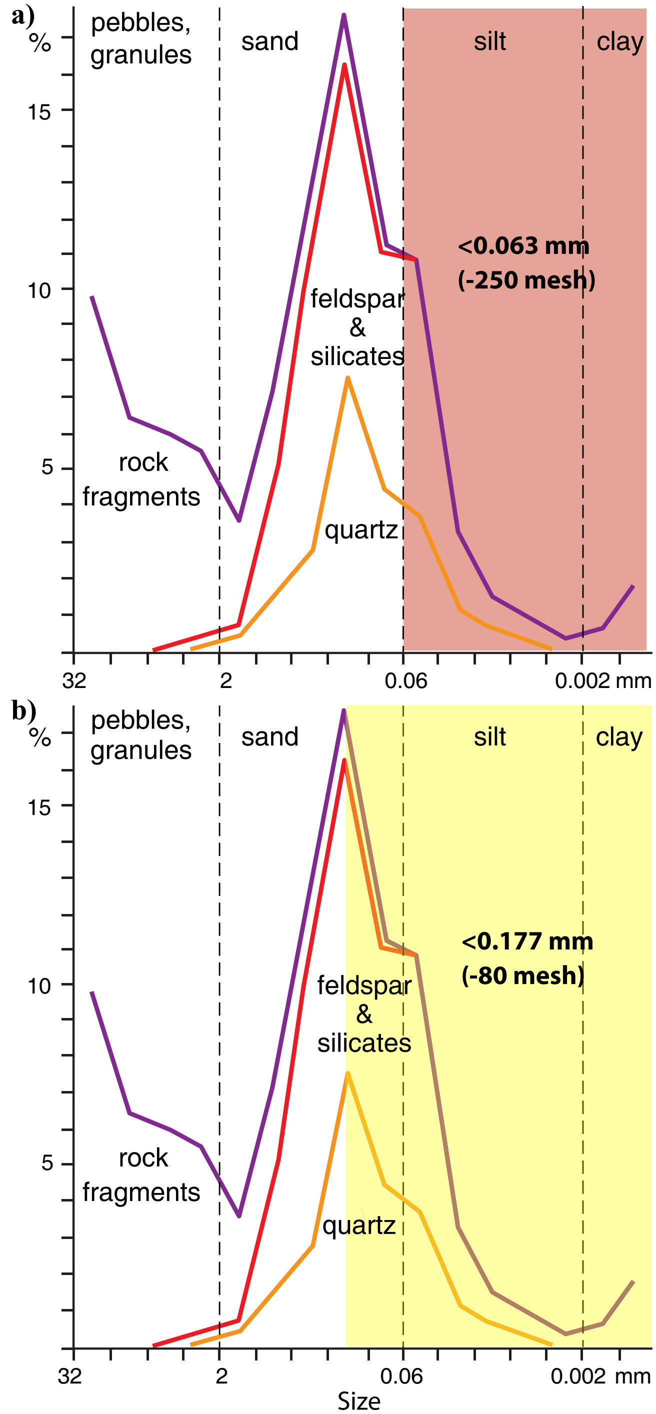

Figure 29. Frequency distribution of rock fragments and minerals in a till sample collected 50 km west-southwest of Timmins, ON overlying volcanic bedrock and down-ice from an extensive area of coarse-grained igneous and metamorphic bedrock. Colour shaded areas indicate that less quartz and feldspar would be included in the **(a)** <0.063 mm (-250 mesh) fraction (highlighted in pink) versus **(b)** <0.177 mm (-80 mesh) fraction (highlighted in yellow) (modified from Dreimanis and Vagners, 1972).

Analytical Methods

Till and soil geochemical studies conducted in the 1950s through 1980s typically only determined Cu, Pb, and Zn contents, as these are the main economic metals in VMS deposits and analyses for these elements could be readily carried out in a cost effective manner. At this time, analysis of additional elements was time consuming and expensive. Piercey (2010) observed that one of the key advances in VMS exploration was the development of inductively coupled plasma-mass spectrometry (ICP-MS) in 1980s and 1990s, as it allows for determination of a broad suite of trace elements, facilitating the application of lithogeochemistry to VMS exploration. The development of ICP-MS techniques has had a similar impact on the application of till geochemistry to VMS exploration. Commencing in the 1980s, till geochemical surveys used of a broader suite of elements, which could now be determined cost effectively. In more recent studies (1990s onward), extensive suites of pathfinder elements in till have been determined, including Zn, Cu, Pb, Ag, and Au, as well as Co, Sn, Se, Mn, Cd, In, Bi, Te, Ga, Ge, As, Sb, and Hg. It is now possible to recognize the multi-element signatures of VMS deposits in till down-ice from the deposit and even determine if the eroded VMS mineralization is enriched in salable (Au, Ag, In) or deleterious trace elements (Se).

In VMS deposits, pathfinder elements can occur as discrete sulphide minerals or as stoichiometric or non-stoichiometric lattice substitutions (and as inclusions) within sulphide, sulphosalt, and native minerals. For example, Cd, In, Hg, Ag, Sn, Ge, and Ga can be important trace elements in sphalerite (Cook et al., 2009; Pfaff et al., 2011). Tin is a major constituent of cassiterite; a mineral which is present in some VMS deposits (e.g. Boyle, 1997; Goodfellow and McCutcheon, 2003; Relvas et al., 2006). Gold in VMS deposits can be present as native gold, electrum, tellurides, or as “invisible” or refractory gold in pyrite and arsenopyrite (McClenaghan et al., 2004, 2009; Mercier-Langevin et al., 2011a). Native gold may contain Hg as well as Ag (e.g. Morrison et al., 1991; Cabri, 1992). Silver may be present in galena (e.g. Sharp and Buseck, 1993; Renock and Becker, 2011), in sulphosalts (e.g. Grant, 2009), or in other sulphide minerals (e.g. Harris et al., 1984a). Selenium in VMS mineralization is present within sulphide and sulphosalt minerals (e.g. Huston et al., 1995; Layton-Matthews et al., 2008). Antimony and Bi in VMS deposits occur in sulphosalt minerals (e.g. Harris et al., 1984b). Arsenic occurs within arsenopyrite or arsenian pyrite (e.g. McClenaghan et al., 2009; Mercier-Langevin et al., 2011a).

Most current exploration programs that utilize geochemical analysis of regional tills employ a strong partial digestion, such as aqua regia, to determine the contents of the major ore elements Cu, Pb, and Zn, as well as other pathfinder elements Hg, Ag, V, Sb, As, Bi, Cd, and Tl. Total digestion techniques, such as borate fusion or 4-acid digestion followed by ICP-MS measurement, or instrumental neutron activation analysis (INAA), are used to determine the contents of other pathfinder elements, such as In, Sn, Se, and Au. Use of both partial and total digestions allows for exploration for a broad range of deposit types, such as magmatic Ni-Cu-PGE, orogenic Au, porphyry Cu, iron oxide-copper-gold (IOCG), gold, kimberlite (e.g. Lahtinen et al., 1993; McClenaghan et al., 2011; McMartin et al., 2011), not just VMS deposits.

Pb Isotopes

The four Pb isotopic studies of till reported here (Bell and Franklin, 1993; Bell and Murton, 1995; Simonetti et al., 1996; Hussein et al., 2003) clearly show that the Pb isotopic signatures in the <0.063 mm fraction of till reflect the Pb isotopic signature of the nearby VMS mineralization. At the time these papers were published, Pb isotopic analyses of the fine fraction of till were conducted by thermal ionization mass spectrometry; the application was predicted to be a “new” approach to mineral exploration for massive sulphide deposits (VMS) in glaciated terrain. Since then, there has been much progress in the application of ICP-MS for Pb isotopic analysis (e.g. Meffre et al., 2008), and this may yet be what brings rapid and affordable analyses to the explorationist. The technique is best applied to Pb-rich till samples that display a VMS signature (Cu-Pb-Zn) in areas prospective for VMS mineralization.

Future Analytical Methods

In the 2000s, analytical techniques such as laser ablation (LA) ICP-MS have become widely available that provide bulk compositional or isotopic data for individual sulphide grains (or spots within them) from till. These methods can be used to determine Pb isotopes in a single galena or sphalerite grain (e.g. Paulen et al., 2011) or Cu isotopes in chalcopyrite grains (e.g. Mathur et al., 2009) from till. The advantages of LA ICP-MS over conventional isotopic techniques that use the bulk till matrix are that it does not require the costly and time-consuming leaching of the till matrix prior to isotopic analysis, does not require a minimum element content of a till sample, and does not require the source of the element to be clearly known (e.g. Pb in a galena grain).

Portable x-ray fluorescence spectrometry (pXRF) is increasingly being used for soil geochemical surveys; the method also shows great promise for determining metal contents of till in the field, which can actively guide till sampling, allowing for follow-up of anomalies in the same field season. Metal contents determined by pXRF also can be used to prioritize till samples for lab-based geochemical analyses (Peter et al., 2010; Hall and McClenaghan, 2013; McClenaghan, 2013; Sarala, in press).

CONCLUSIONS AND IMPLICATIONS FOR EXPLORATION

Over 50 years ago, Dreimanis (1958, 1960) predicted that till geochemistry and boulder-tracing methods, when combined with geophysical and other prospecting methods, would lead to new discoveries of ore deposits. Since his pioneering work around VMS deposits in the BMC and AGB, the use of till geochemistry has indeed contributed to the discovery of VMS deposits, some of which have been described here (BOG, Photo Lake). These case studies provide important information about till geochemical methods for VMS exploration. The methods, which most commonly employing the <0.063 mm fraction, are now well developed and widely used. Analysis of the HMC can also be useful. The development of ICP-MS analytical instruments allows the determination of an extensive suite of VMS pathfinder elements, which includes Cu, Pb, Zn, Ag, Au, Tl, Sn, Se, Hg, In, Cd, Bi, As, Sb, and Ge. In order to detect the true clastic glacial dispersal signal down-ice of a deposit, collection and analysis of unoxidized to weakly oxidized till is optimal. Soil sampling is not recommended, as soil geochemical signals are weaker and this sampling medium includes soil developed on till, as well as glaciofluvial sand, glaciolacustrine silt or clay, and/or alluvium and reflects not only clastic dispersal, but also hydromorphic dispersion. Glacial erosion and incorporation of preglacial gossans developed on VMS deposits may result in stronger geochemical signals in till down-ice, as gossans are softer than underlying host rocks, and thus easier to erode. Although this paper only describes examples from the glaciated terrain of Canada, till geochemistry is also used for VMS exploration in the glaciated terrain of Fennoscandia, Russia, the USA (e.g. Woodruff et al., 2004), and even Tasmania (e.g. Reid and Meares, 1981).

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