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**Application of Lead Isotopes to Mineral Exploration Using Glacial
Till of the Halfmile Lake Area, Bathurst, New Brunswick**

By

Ahmed A. Hussein

A thesis submitted to

the Faculty of Graduate Studies and Research

in partial fulfillment of

the requirement for the degree of

Master of Sciences

Department of Earth Sciences, Carleton University

and

Ottawa-Carleton Geoscience Centre

Ottawa, Ontario

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**APPLICATION OF LEAD ISOTOPES TO MINERAL EXPLORATION USING
GLACIAL TILL OF THE HALFMILE LAKE AREA, BATHURST, NEW
BRUNSWICK.**

submitted by Ahmed A. Hussein, B.Sc. M.Sc.
in partial fulfillment of the requirement for
the degree of Master of Science

Thesis Supervisor

Chairman, Department of Earth Sciences

Carleton University

January, 9th, 1996

Abstract:

Pb isotope ratios from till in the Halfmile Lake area have successfully identified a glacial dispersal train down ice from the sulphide outcrop. The sediments adjacent to and down-ice from the Upper AB zone define a dispersal train that extends eastward for about 600 m. The Pb isotopic ratios of the till in the dispersal train are very low compared with till remote from mineralization. Pb abundance data also defined a primary and a secondary dispersal train trending in a south-southeasterly direction toward the Northwest Miramichi River.

Pb isotope and Pb abundance data have shown that the Pb in till from the Halfmile Lake area can be considered the product of binary mixing between Pb from the volcanogenic massive sulphide (VMS) outcrop and Pb from the surrounding country rocks. The most important finding to emerge from this study is that the Pb isotopes can be used to distinguish between Pb from a VMS deposit and Pb from other sources. This can not be done using Pb abundance data alone. The successful delineation of a Pb isotope dispersal train at Halfmile Lake shows that Pb isotopes can be used to target relatively young VMS deposits.

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CHAPTER I

INTRODUCTION

1.1. Objectives of study

New Brunswick forms the core of the Canadian Appalachians and has experienced Quaternary glaciation, isostatic depression and rebound, and submergence and emergence because of its geographic location (Rampton et al., 1984). Almost the whole of the province is overlain by Quaternary cover. Due to thick glacial overburden, most volcanogenic massive sulphides (VMS) deposits, not only in Canada but in other glaciated areas such as Scandinavia and Russia, were discovered using geophysical surveys. Other methods for mineral exploration commonly used in glaciated terrains include dispersal train detection, as well as stream and lake sediments analysis (Dilabio and Coker, 1989)

Although Pb isotopes have been used successfully to evaluate the base and precious-metal potential of gossans, ironstone, and soils (Gulson and Mizon, 1979; Gulson, 1986; Gulson et al., 1992), the application of Pb isotopes to glacial deposits and mineral exploration had not been tried until the work of Bell and Franklin (1993). They showed that Pb isotopes could be used as indicators of base metal deposits in till.

This thesis will extend the approach taken by Bell and Franklin (1993), and Pb isotopes will be used to: a) demonstrate the potential of the Pb isotope method as an effective tool for mineral exploration in the Bathurst area, b) define the target Pb isotopic signature

of the Halfmile Lake deposit, c) define the background Pb isotopic signatures in the till away from the deposit, d) define the extent and shape of the dispersal patterns of the study area, and e) compare the results based on Pb isotopes with other geochemical exploration methods that are commonly used in glaciated areas, such as the abundance of base metals in stream and glacial sediments.

1.2. Location and Accessibility

The study area (Halfmile Lake Deposit) is in Northumberland county, New Brunswick. It is located about 80 km southwest of Bathurst and about 75 km northwest of Newcastle. (Fig.1) The name Halfmile Lake originate from a small lake near the headwater of the Northwest Miramichi river, which is situated at latitude 47°19'E, and longitude 66°18'W. The Halfmile Lake deposit crops out approximately 2.5 km southwest of the lake. The area can be reached along an unpaved highway 430 south via the Heath Steele Mine, which is about 60 km southwest of Bathurst. The Halfmile Lake deposit lies 24 km west of Heath Steele Mine, along Otter Brook road, also known as Halfmile Lake Road (Fig.2)

The study area consists of a narrow band covering an area of 2.13 km² and lies within the Miramichi Highland, which is one of the six physiographic divisions of the Province of New Brunswick. The area lies between two major rivers, the Nepisiguit River to the north and the Northwest Miramichi River that runs west-southeast.

The topography of the area is characterized by hills with rounded peaks. Elevation

in the study area ranges between 410 m to 556 m above mean sea level. Generally, the area is well drained although there is a small swamp east of the deposit. The streams near the Halfmile Lake deposit drain into the Northwest Miramichi River; however, in the northern and eastern parts of the area the streams drain into the Nepisiguit River (Fig.3). Most of the study area is covered by thick forest, except in the area east of the deposit where logging activities have taken place in the past.

1.3. Previous Work

The Halfmile Lake deposit was discovered by the Middle Mining Co. in 1955 as a result of an airborne geophysical survey and soil geochemistry. The first discovery was made in the Upper AB zone, which is one of the three zones that contains significant concentrations of base-metal sulphides (Adair, 1992). Most of the literature of Bathurst Mining Camp relates mainly to a few deposits that have reached the production stage, specifically the Brunswick No.6 and No.12, Heath Steele Mine, and the Caribou deposit (Harley, 1977). Other deposits, including the Halfmile Lake, have been studied less extensively (Harley, 1977). Holyk (1957) described briefly the discovery of Halfmile Lake deposit, and the first geological sketch map was published by McAllister in 1960. McNutt (1962) and Fyffe (1971) mapped the regional geology of the Nepisiguit River-Moody Brook map area; the Halfmile Lake deposit occurs in the south central part of this sheet.

The first detailed study of Halfmile Lake deposit was carried out by Harley (1977) and this formed part of an M.Sc. thesis at the University of Western Ontario. De Roo and van

Staal (1991) outlined the structural geology of the study area based on surface mapping of the region while Adair (1992), of Noranda Exploration Company Limited, reported the results of the stratigraphy, structural, and geochemical investigations undertaken by Noranda from 1986 to 1990.

The first mapping of the Quaternary deposits of New Brunswick was initiated by Matthew in 1872, and completed by Chalmers in 1902. Chalmers' study forms the basis on which the current interpretations of glacial history are based (Grant 1989). The Quaternary geology of New Brunswick has been mapped at a scale of 1:100,000 and 1:250,000. The northern New Brunswick part of the Bathurst (21P map-sheet) area was mapped by Gauthier (1982) at a scale of 1:100,000.

Many studies have been carried out dealing with specific problems of the Quaternary geology of New Brunswick, most notable of which are the studies relating to till geochemistry initiated in 1988 by the Geological Survey of Canada and the New Brunswick Department of Natural Resources. The aims of these projects were to identify the nature and the thickness of superficial materials for mineral exploration, mine reclamation, land-use and environmental planning, and engineering and construction activities (Parkhill, 1993).

Till sampling programs, in conjunction with granular aggregate resources mapping projects, were carried out in the Nepisiguit Lake (NTS 21/07) map-area by Seaman in 1985. Mapping and till sampling were also conducted at the Halfmile Lake area (Parkhill, 1993) which is part of the California Lake (NTS 21/08) and the Nepisiguit Lake (NTS 21/07) map-areas. These studies were made in order to evaluate the geochemical response of overlying surficial sediments to known mineral occurrences. The study revealed that in both areas the

tills that overlie highly-deformed sedimentary and mafic and felsic volcanic rocks are enriched in Cu, Pb, Zn, Ba, Sb, Sc, and Th, and depleted in Br (Parkhill 1993a, 1993b).

Lamonthe during the period 1989 to 1992 undertook a detailed till sampling program in the Miramichi Highland, that was designed to: a) define the strategy and methodology of sampling and geochemical analysis for mineral exploration in drift covered areas of the Miramichi Highland, b) study the regional till geochemistry, near-surface glacial stratigraphy, and sedimentology, c) study at a local scale, the stratigraphy and geochronology of the glacial deposits in order to relate the depositional sequence to the detailed geochemical mapping of till in areas of known mineralization, and d) evaluate the ice-flow directions in the Miramichi Highland

1.4. Methods

1.4.1. Field Methods

The field work for this thesis was carried out in the summer of 1994, in conjunction with the till sampling program that formed part of the EXTECH II project, a multidisciplinary project designed to facilitate new approaches to mineral exploration in New Brunswick

Prior to the sampling program, geologists involved with the EXTECH II project undertook a detailed survey of the Halfmile lake area. On the basis of striations, they concluded that the ice direction was from west to east. A strategy for sampling was initiated

in an attempt to define and detect the dispersal train around the deposit. Up-ice samples were collected to provide background values and down-ice samples to define the glacial dispersal patterns and shape. A pre-existing cut-line (grid system) of 400 by 1000 ft running parallel to the magnetic north and east was used during the study. In order to obtain a sufficient number of samples, and increase the chances of detecting the dispersal train, the grid system was modified to 100 by 100 ft (~ 30 by 30 m) within the 600 m of the deposit. Beyond this area the grid interval was increased to 200 by 400 ft (~ 60 by 120 m). The grid is shown in Fig.4.

Based on this modified grid system, 315 sampling sites were established. However, only 247 till samples were collected because many of the proposed sampling sites were in localities that were not covered by glacial deposits. Furthermore, some samples were not collected because of the presence of swampy ground around small streams, east of the deposit (Fig.4).

At each sampling site, two till samples were collected, one for Pb isotopic analysis, and the other for till geochemistry. The average sample weight was 2 kg. The depth of the sampling pits varied between 40 cm and 80 cm, depending on the depth of the basal till below the surface. Almost all of the samples, except where the basal till is too thin or totally absent, were collected from the C-horizon. The latter is distinguished from the red oxidized B-horizon by its green colour.

Gossan samples were collected in the vicinity of sample location AH055 (Fig.4). Sulphide samples from Halfmile Lake deposit were provided for this study by Noranda Exploration.

Fig. 1. General map of the the province of New Brunswick and locality of the study area.

Fig. 2. Location of the study area (the shaded area), and VMS base-metal deposits in the Bathurst mining Camp.

Fig. 3 . The drainage system of the study area.

Fig. 4. Sampling sites

1.4.2. Laboratory Analysis

A total of 59 till samples, four sulphide samples and one gossan sample were determined for Pb isotopes. Unpublished work by Bell and co-workers has shown that the -250 mesh size fraction can be successfully used for mineral exploration. It was thus decided that the till Pb isotopic analysis be made on the -250 mesh size fraction.

The till samples were dried at a temperature of about 70 to 80°C. The samples were then sieved using plastic sieves, and the samples separated into two grain-size fractions, one > -250 mesh (> 63 µm), the other < -250 mesh (< 63 µm). During sieving, a great deal of care was taken to prevent cross-sample contamination. The sieves were cleaned between each sample using ultra-pure water and acetone. 50 mg of each sample (< -250 mesh) were used for Pb isotopic analysis. Galenas were separated from the sulphide. Pb was separated in HBr and HCl using a two column (0.5 ml and 0.2 ml) extraction procedure using AG1-X8 ion-exchange resin of 100 to 200 mesh. Details for the lead chemistry, including column procedures, are given in Appendix A.

The isotopic ratios of lead ($^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{207}\text{Pb}$, and $^{206}\text{Pb}/^{208}\text{Pb}$) were measured on Finnigan®-MAT 261 multicollector, solid-source mass spectrometer operated in the static mode. The isotopic analysis were run on a single Re filament using silica gel and phosphoric acid. An average 0.11% a.m.u. fractionation correction were applied to the measured ratios. The results of Pb isotopic analysis are given in Appendix B.

Five replicate analysis of one sample from pit CL-5, indicated an analytical uncertainty of ± 0.02 at the 2σ level for the $^{206}\text{Pb}/^{204}\text{Pb}$ ratios. These data are given in Table 1.

Table 1. Replicate sample for Pb isotope analyses.

Sample #	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
CL5-19-A	18.31	15.64	38.19
CL5-19-B	18.28	15.60	38.06
CL5-19-C	18.31	15.63	38.25
CL5-19-D	18.29	15.61	38.10
CL5-19-E	18.29	15.61	38.31
Average	18.296	15.618	38.182
SD: sample	0.013	0.064	0.103
SD: Population	0.010	0.017	0.092

The Pb abundances were determined using the -250 mesh ($< 63 \mu$) size fraction. Preparation of samples for the geochemical analyses was carried out by the New Brunswick Natural Resources and Energy's geochemical laboratory in Fredericton. All of the till samples that were collected were analyzed for their Pb contents by ICP-Emission Spectrometry and ICP-Mass Spectrometry at the Geological Survey of Canada, Mineral Resources Division Laboratory, Ottawa. ICP-Mass Spectrometry was used for those samples with < 100 ppm; ICP-Emission Spectrometry was used for the remainder of the samples. The analytical results of Pb concentration are given in Appendix C. Duplicate analysis of the Halfmile Lake samples suggest an uncertainty of ± 10 ppm at the abundance levels shown in Appendix C.

CHAPTER II

BEDROCK GEOLOGY

2.1 Regional Geology

The Halfmile Lake deposit is one of several volcanogenic massive-sulphide deposits that occur in the Bathurst mining camp of northern New Brunswick (McAllister, 1960; Harley 1977, 1979; Franklin et al., 1981; McCutcheon et al., 1989; Adair, 1992; McCutcheon, 1992). The Bathurst mining district is situated near the axis of the zone of initial deformation of the northern Appalachian Mobile Belt (Davies, 1972). The rocks of the Bathurst mining camp have been separated into three groups (van Staal et al., 1992). These subdivisions are: Miramichi Group, Fournier Group, and Tetagouche Group (van Staal and Fyffe, 1991; van Staal et al., 1992). The Tetagouche Group conformably to disconformably overlies the Miramichi Group and is structurally overlain by the Fournier Group (van Staal et al., 1992).

The Miramichi Group (Lower Ordovician to Cambrian?) consists of quartz metasediments intercalated with fine-grained quartz metagreywacke and phyllite. Although most of primary features for this unit have been obliterated by recrystallization and intense deformation, graded bedding and cross bedding have been preserved in some areas (Davies et al., 1983; Harley, 1977). The size fractions of these rocks are sand to silt size, sub-rounded to rounded quartz grains, with a few percent of feldspar clasts. The matrix is granoblastic

quartz with chlorite, sericite, and biotite. The age of the Miramichi Group is based on a single brachiopod found 10 km west of Tetagouche Falls (Fyffe, 1975, 1976), that indicates a Lower Ordovician age. The Miramichi Group is subdivided into two formations; the lower formation (Chain of Rock Formation) and the upper formation (Knight Brook Formation). The two formations can be differentiated by their abundance of graphitic slate. The graphitic slate is more abundant in the Knight Brook Formation than the Chain of Rock Formation (van Staal et al., 1992).

The Middle to Late Ordovician Fournier Group is subdivided into two formations. The older formation is Sormany Formation which consists of pillow basalt and minor gabbro. The compositions of the pillow basalts are between MORBs (mid-oceanic ridge basalt) and OIBs (oceanic-island basalt). This composition reflects the depositional setting of oceanic back arc (van Staal et al., 1991). The second formation is the Millstream Formation which consists of lithic and feldspathic wackes and slate with minor intercalation of limestone and basalt.

The Tetagouche Group of Late to Middle Ordovician rocks underlie the central part of the district and are intruded by gabbro and diorite of Ordovician, Silurian, and Devonian age, as well as granitic stocks and masses of Devonian age (Davies, 1972). The Tetagouche Group is a bimodal volcanic and sedimentary sequence that probably formed during the development of an ensialic back-arc rift (van Staal, 1987). The most important base-metal sulphide deposits in the Bathurst-Newcastle mining district, including the Halfmile Lake deposit, are hosted by rocks of the Tetagouche Group.

Other rocks that outcrop in the Bathurst mining camp are the less deformed Silurian

and Devonian sedimentary and volcanic rocks, and flat-lying Pennsylvanian sedimentary rocks. The Silurian-Devonian rocks occur in the northern and northwestern part of the district (see Fig 5) and consist of volcanic and sedimentary rocks of early Silurian and middle Devonian age. The deformation of these rocks is not as intense as that in the Ordovician rocks. Locally, these geological units are intruded by gabbro and diorite sills and dykes, and quartz-feldspar and porphyry dykes. These intrusions are believed to be of Upper Silurian or Devonian age (Davies, 1972).

The Pennsylvanian cover, in the eastern part of the area, consists of flat-lying red conglomerate, sandstone, and siltstone. These overlie unconformably all older rocks and were deposited after the principal ore deposits of the district were formed (Smith and Skinner, 1958).

This thesis is concerned with only the general geology of Halfmile Lake rocks, all of which form part of the Ordovician Tetagouche Group; hence, only the distribution and lithological descriptions of the Ordovician Tetagouche Group are discussed. Because the distribution of the Silurian, Devonian, and the Pennsylvanian rocks of the district are not described in the thesis. Table 2 serves as reference for those interested in the general lithology of these rocks.

**Fig.5. General geology of the northern part of New Brunswick (Bathurst area),
modified after Davies et al. (1983).**

Era	Period or Epoch	Rock Unit	Lithology
Cenozoic	Pleistocene/Recent		Gravel, sand, and glacial till and outwash
			Angular unconformity
Palaeozoic	Pennsylvanian	Clifton Formation	Mudstone, shale, conglomerate, and quartz pebbles
		Bathurst Formation	Sandstone, shale, grit, quartz-pebble conglomerate
			Angular unconformity
	Middle Devonian		Granite, gr. nodiorite, and granite porphyry
			Intrusive Contact
	Middle Devonian / Older		Diabase, gabbro, diorite, and peridotite
			Intrusive contact
	Early Devonian	Dalhousie Group	<u>Upper Unit:</u> Greywacke, shale, siltstone, argillite, basalt, and andesite <u>Middle Unit:</u> basalt, andesite, rhyolite, trachyte, limestone, and conglomerate <u>Lower Unit:</u> shale, slate, siltstone, greywacke, limestone, and basalt

Table 2. Lithology and formations of the rocks of the Bathurst mining camp (modified after Skinner, 1974)

Era	Period or Epoch	Rock Unit	Lithology
Palaeozoic	Conformable and fault contact		
	Middle and Late Silurian	Chalcurs Bay Group	<u>Volcanic Units:</u> rhyolite and trachyte flows and tuffs, basalt and andesite; conglomerate, greywacke, siltstone, shale, feldspar and quartz-feldspar porphyry <u>Limy Sedimentary Unit:</u> limy slate and greywacke, shaly limestone, siltstone, quartz greywacke; basalt and andesite <u>Conglomerate Unit:</u> volcanic conglomerate, greywacke, slate <u>Greywacke Unit:</u> greywacke, slate, limestone; basalt, rhyolite, chert
	Angular unconformity and fault contact		
	Middle to Late Ordovician	Fournier Group Telagouche Group	Pillow basalt and minor gabbro Bimodal volcanic and sedimentary rocks
	Cambrian to Late Ordovician	Miramichi Group	Sequences of wacke and slate

Table 2. Continued..... Lithology and formations of the rocks of the Bathurst mining camp.

2.2. Tetagouche Group

The supracrustal rocks of the Miramichi massif form the Tetagouche Group (Skinner, 1956). The name Tetagouche Group was first used by Young (1911), and it was applied to the dark slates, and interbedded sandstones and red slates that outcrop along the Tetagouche River and occupy a large area of the Bathurst mining camp (Smith and Skinner, 1958), including the Halfmile Lake area. The stratigraphic sequence of the Tetagouche Group is difficult to unravel because of the scarcity of outcrop, rare fossils, complex and rapid facies changes in volcanic units, polyphase folding, and lack of marker horizons (Davies et al. , 1983). However, the geological mapping of the area over the past 20 years or so, has established general stratigraphic relationships between different rock formations. The stratigraphic order of the units making up the Tetagouche Group are: a) Vallee Lourdes Formation, b) Patrick Brook Formation, c) Nepisiguit Falls Formation, d) Flat Landing Brook Formation, and e) Boucher Brook Formation. Fig. 6 is a schematic stratigraphic column of the Tetagouche Group (redrawn from van Staal et al., 1992).

Descriptions of major rock types of the Tetagouche Group have been published by Helmstaedt (1971), Skinner (1974), van Staal et al., (1992), de Roo and van Staal (1991), and Rice and van Staal (1992). The different formations that make up the Tetagouche Group, with special references to the Halfmile Lake rocks, are described briefly below.

2.2.1. Vallee Lourdes Formation

The vallee Lourdes Formation (VF) consists of calcareous phyllite, crossbedded calcarenite, and conglomerate (van Staal et al., 1992). This formation occurs as lenses at the base of the Tetagouche Group (van Staal et al., 1992; McCutcheon et al., 1993). Fossils (brachiopods and conodonts) found in this formation indicate a middle Arenigian to early Llanvirnian in age (van Staal et al., 1992).

2.2.2. Patrick Brook Formation (PB)

The lithological descriptions of this formation have been published by Rice and van Staal (1992) and van Staal et al., (1992). The PB Formation consists mainly of grey to black slate, and very fine-grained dark grey sandstone and intercalated metagreywacke. The minor intercalated metagreywacke rocks are poorly-sorted and show graded bedding. Some researchers believe that this unit is lithologically transitional between the underlying Knights and overlying Nepisiguit Falls formations (McCutcheon et al., 1993).

In the Halfmile Lake area (Fig 7), the sedimentary rocks of the Tetagouche Group consist of shaly and sandstone epiclastic sedimentary rocks. These rocks look like rocks of both the Nepisiguit Falls and Patrick Brook Formations, however, the predominance of black shales indicate that these rocks belong to the PB Formation (de Roo and van Staal, 1991). The sedimentary rocks are interlaminated with volcanic-derived detritus and felsic tuffs. In the Halfmile Lake area, the PB formation is host to at least two massive sulphide deposits, the Halfmile north and the Halfmile Lake south (Adair, 1992; de Roo and van Staal, 1991).

The host rocks of Halfmile Lake deposit consist of argillaceous sedimentary rocks, with abundant wackes and minor arenites, large bodies of porphyritic rhyolite, and minor felsic and mafic tuffs. The sulphide-bearing rocks are subdivided into a stringer zone and massive sulphide unit; these subdivisions are based on lithology and textural features that are related to sulphide deposition (Adair, 1992).

2.2.3. Nepisiguit Falls Formation (NF)

The Nepisiguit Falls Formation consists of medium- to coarse-grained quartz-feldspar volcanoclastic rocks interlayered with quartz-feldspar porphyritic tufflavas and/or subvolcanic sills and fine-grained sedimentary rocks (van Staal et al., 1992). Light to dark greenish grey, chloritic mudstone and iron formation including the massive sulphides occur at or near the top of this formation and together they constitute the well-known "Brunswick Horizon" (van Staal et al, 1992). The Nepisiguit Falls Formation is distinguished from the Patrick Brook Formation by the absence of dark and black shale (van Staal et al., 1992).

In the Halfmile Lake area, the sedimentary rocks of the Tetagouche Group resemble rocks of both NF and PB formations that were observed in the northern part of the Bathurst mining camp (de Roo and van Staal, 1991). The Nepisiguit Falls Formation corresponds closely with the augen schist or porphyry units of Skinner (1974) and Davies (1979).

2.2.4. Flat Landing Brook Formation (FLB)

In the Halfmile Lake area, the rocks of Patrick Brook Formation are stratigraphically overlain by rocks of the Flat Landing Brook Formation (de Roo and van Staal, 1991). This formation consists of volcanic and minor sedimentary rocks. The volcanic rocks are composed of aphyric to feldspar-phyric rhyolite flows with minor pyroclastic rocks, and basalt (van Staal et al., 1992). Mafic volcanic rocks of the Halfmile Lake area are metamorphosed into greenschists (de Roo and van Staal, 1991). The Flat Landing Brook Formation is largely equivalent to the rhyolite tuff unit of Skinner (1974).

The FLB formation occurs as sheet like-bodies with thicknesses that range from a few centimetres to several hundred meters. The units are mostly non-laminated although laminated varieties can be found. Harley (1977) noted that in the Halfmile Lake area the non-laminated rhyolite is much more abundant than the laminated varieties. Furthermore, this rhyolite unit (see Fig 7) is the most abundant rock-type at Halfmile Lake.

Locally, the FLB consists of rhyolite tuffs, with extensive diabase lenses, and minor quartz feldspar porphyry, dacitic lithic tuff, and sedimentary rocks. The mafic volcanic rocks are estimated to form about 20% of the total succession of this unit.

2.2.5. Boucher Brook Formation (BB)

The Boucher Brook Formation conformably overlies the Flat Landing Brook Formations (Fig. 6) and consists of two major components. The first component is

predominantly sedimentary rocks and consists of fine-grained wacke and siltstone that grade upward into homogeneous black shale (van Staal et al., 1992). The second is alkali basalt that constitutes the main rock type of this formation. The most common rock types of this unit are tuffs and massive lava flows. Some workers believe that their composition is basaltic, although there are minor intercalations of trachyte (Harley, 1977). The mafic volcanic rocks are divided into two distinct types: the spilitic type and the greenstone type (Smith and Skinner, 1956). The spilitic type is characterized by basaltic texture, while the greenstone is distinguished by its metamorphic texture and by the presence of sodic plagioclase and secondary mafic minerals. Smith and Skinner (1956) observed that the mafic volcanic rocks are intercalated with sedimentary rocks. Tuffaceous varieties of mafic rocks also occur as intercalations within the felsic volcanic rocks.

Fig. 6. Schematic stratigraphic column showing the internal stratigraphy of the Tetagouche Group (modified after van Staal et al., 1992)

Fig. 7. Surface geological map of Halfmile Lake (redrawn from de Roo and van Staal, 1991)

2.3. Sulphide Deposit

The Bathurst-Newcastle mining district contains about 100 known base-metal occurrences or deposits, which includes 37 deposits with defined tonnage (McCutcheon, 1992). The Halfmile Lake deposit is one of the largest, undeveloped deposits in the district, containing 26 million tonnes of iron (pyrrhotite, pyrite) and base-metals (sphalerite, galena, chalcopyrite).

The most important base-metal sulphide deposits in the Bathurst-Newcastle mining district occur in the Tetagouche Group, which is a bimodal volcanic and sedimentary sequence, that probably formed during the development of ensialic back-arc rift (van Staal, 1987). The deposits occupy a subcircular area, approximately 50 km in diameter (McCutcheon, 1992). Most of these deposits were discovered since modern exploration began in 1952, although some were found much earlier. Two of the earliest discoveries are the Austin Brook Deposit found in 1898, and the Brunswick No-6 in 1907. The Halfmile Lake deposit was discovered by Middle River Mining Co. in 1952 using airborne electromagnetic surveys and soil geochemistry (Harley, 1977; Adair, 1992).

In general, the sulphide deposits in the Bathurst-Newcastle mining district consist of concordant masses of pyrite, sphalerite, galena, chalcopyrite, and pyrrhotite, that range in size from small showings to world-class deposits. With one exception, all of these deposits are classified as Zn-Pb-Cu volcanogenic massive sulphides (Franklin et al., 1981). Massive sulphide deposits of the district occur at several stratigraphic positions within the Tetagouche Group, and many of them are closely associated with felsic volcanoclastic rocks of The Nepisiguit Falls Formation. Other sulphides occur in the lower sedimentary part of Boucher

Brook Formation and a few are within the Flat Landing Brook formation (McCutcheon et al., 1993; van Staal et al., 1992). According to de Roo and van Staal (1991), the massive sulphide deposits of the Halfmile Lake north and the Halfmile Lake south are hosted by the sedimentary rocks of Patrick Brook Formation.

Two main types of sulphide mineralization occur in the Halfmile Lake deposit, a stringer sulphide zone and a massive sulphide zone, commonly separated by an interval of unmineralized rocks which range up to 10 m thick (Harley, 1977). Both mineralized zones crop out as gossans in the Upper AB zone (the Halfmile Lake South). The stringer zone is characterized by strongly magnetic pyrrhotite and chalcopyrite; pyrite is also a common mineral. Pyrrhotite-chalcopyrite, constituting 5% to 60% of the total rock volume in the stringer zone, is locally associated with quartz veins and veinlets (Adair, 1992). In the stringer zone, the mineralization occurs in the fine-grained mudstones and siltstones, whereas the felsic volcanic rocks in this zone are only weakly mineralized (Harley, 1977; Adair, 1992).

The massive sulphide zone, that occurs structurally below the stringer zone, consists of pyrite, pyrrhotite, sphalerite, galena, and chalcopyrite (Adair, 1992). Harley (1977) has observed that within the massive sulphide zone, layers rich in sulphides are separated by layers of weakly-mineralized host rocks. The host sedimentary rocks consist of exhalite units that were thought to be of chemical origin (Adair, 1992). At the Halfmile Lake deposit, the base-metal sulphides occur in three zones, which are the North, Upper AB zone (South), and the Lower AB zone. A comparison of ore grades and their tonnage (from McCutcheon, 1992) of these three zones, and several well-known deposits of the Bathurst mining camp, is given in Table 3.

Table 3. Base-metal sulphide deposits of the Bathurst mining camp

Name	Tonnes x10 ³	Grade			
		Cu%	Pb%	Zn%	Zn/Pb
Armstrong A	3180	0.29	0.42	2.29	5.5
Austin Brook	900		1.86	2.93	1.6
Brunswick No. 12	59222	0.31	3.55	8.82	2.5
Brunswick No. 12	74977	0.30	3.60	8.87	2.5
Brunswick No. 12	13798	0.41	3.62	9.10	2.5
Brunswick No. 6	12125	0.39	2.16	5.43	2.5
Canoe L. Lake	16638	0.57	0.61	1.71	2.8
Caribou	5492	0.04	3.59	8.37	2.3
Flat Landing Br.N	816	0.02	1.71	6.94	4.1
Flat Landing Br.S	453	0.08	0.53	3.23	6.1
Halfm. L. (C/Zone)	800	0.46	3.63	10.0	2.8
Halfmile L.(North)	1088.6	0.01	0.87	4.63	5.3
Halfmile L.(L/ AB)	7900	0.45	2.43	7.45	3.1
Halfmile L.(U/ AB)	2100	0.70	2.26	6.55	2.9
Heath S. (A-Zone)	508	1.01	2.98	7.60	2.6
Heath S. (B-Zone)	15793	0.34	1.65	4.48	2.7
Heath S. (C-Zone)	6.4	0.36	0.56	4.55	8.1
Heath S. (D-Zone)	149.6	1.18	2.54	9.61	3.8
Heath S.(E-Zone)	695	0.35	2.48	5.29	2.1
Heath S. N-5	204	0.22	3.18	6.84	2.2
Key Anacon	1106		3.47	8.41	2.4
Orvan Brook	1000	0.32	2.93	6.32	2.2
Restigouche	1029	0.30	5.99	7.72	1.3
Rocky Turn	180	0.50	1.50	7.00	4.7
Stratmat Central	181	0.37	4.30	8.00	1.9
Stratmat S-1	2800	0.30	2.82	6.87	2.4
Stratmat Main	635	2.17	1.80	5.2	2.9
Wedge	1503.8		0.24	0.46	1.9

The origin of the massive sulphide deposits of the Bathurst mining district has been discussed in many papers dealing with individual deposits. The sulphide deposits, including the Halfmile Lake deposit, are considered to be the result of exhalative deposition on the Ordovician sea floor, during or near the end of felsic volcanism (Davies et al., 1983). Harley (1979) considered the relationship between the sulphide deposits and the volcanic evolution of the Tetagouche Group as a whole and hypothesised that the Tetagouche Group rocks and associated sulphide ore deposits represent a mineralized Ordovician caldera complex.

CHAPTER III

QUATERNARY GEOLOGY

1.1. Introduction

The study area and the entire area of New Brunswick province has experienced glaciation. As a consequence, various types of Quaternary deposits overlie the weathered and glaciated bedrock and cover more than 90% of the province. The glacial geology and till geochemistry have been integrated into mineral exploration in glaciated countries such as Finland and Canada (Shilts, 1984).

There is a wealth of data in the literature that shows that mineral exploration using glacial sediments has been successful in delineating mineral deposits. Systematic studies of the Quaternary geology of the study area, such as the glacial history, involving the superficial deposits and the ice-flow directions, are very important, because they help understand the glacial dispersal patterns, and hence facilitate the interpretation of the geochemical and Pb isotopic data collected from the basal till.

This chapter presents previous and present studies of the Quaternary geology of New Brunswick, and in particular the northern part of New Brunswick. Special emphasis will be given to those studies that directly relate to the study area.

deposit, and (v) compare the Pb isotope dispersal train with that delineated by the Pb abundance data.

5.2. Fundamentals of Pb Geochemistry

Lead is distributed throughout the Earth and is found as a trace element in every kind of geologic materials. Lead on Earth also exists both as the radiogenic products of U and Th, and as non-radiogenic lead. The non-radiogenic Pb is found in lead-rich minerals, such as galena, which contains little U or Th. Furthermore, Pb on Earth consists of the Pb that was present when the Earth formed (primeval) and the Pb that was derived from the radioactive decay of U and Th.

Uranium has three naturally occurring radioactive nuclides, ^{238}U , ^{235}U , and ^{234}U ; Th has one long-lived radioactive nuclide, ^{232}Th , and five short-lived radio-nuclides which are the intermediate daughters of ^{238}U and ^{235}U . Three decay series are involved in the radioactive decay of U and Th to form the stable daughter products ^{206}Pb , ^{207}Pb , and ^{208}Pb . The decay of ^{238}U and ^{235}U give rise to ^{206}Pb and ^{207}Pb respectively, while ^{208}Pb is produced by the radioactive decay of ^{232}Th . The other isotope of lead, ^{204}Pb , has no radioactive parent and is commonly used as a reference isotope.

Uranium and Th have long half-lives compared to their short-lived intermediate daughters. Under conditions of secular equilibrium the rate of growth of the stable radiogenic daughters at the end of the decay series is equal to the rate of decay of the parent that starts the series. When this condition is met, the three decay series can be treated as though the

considered by Rampton et al. (1984) to be old, and probably represents the last glaciation in parts of the Northern Miramichi Highland which took place in pre-Wisconsinan time.

Based on the flow patterns and the ice-contact systems, Gauthier (1982) divided the glacial events of northern New Brunswick into one primary glacial period (Late Wisconsinan) and three phases of deglaciation. According to the orientation of striae, fluted bedrock, and the dispersal of erratics, the main glacial period is marked by an easterly ice-flow direction. The first phase of deglaciation began when the Escuminac Ice Centre, that was situated in the Gulf of St. Lawrence and Northern Prince Edward Island, caused an ice-flow reversal in the eastern part of New Brunswick, and as a result the ice-flow direction shifted to the east-northeast toward the Bay of Chaleurs. Fig 8 shows the local Appalachian ice centres and Late Wisconsinan ice-flow patterns in northern New Brunswick. Several north-northeast flow indicators, have been found, such as well-developed fluted morphology, striae, eskers, and frontal morainic ridges. This flow pattern is defined as the Nepisiguit flow pattern (Gauthier, 1982).

According to Gauthier (1982), the start of phase two of deglaciation coincided with the opening of the Northwest Miramichi River and the re-establishment of its current drainage system. This phase represents reactivation of ice in the Miramichi Highland that caused glacial re-advancement into the Nepisiguit River valley. Based on the chronology of striations, the earlier north-northeast flow pattern was overridden by a late eastern flow pattern from the Miramichi Highland ice. Finally, during phase three of deglaciation, two glacial lakes (Lake Nictau and Glacial Lake Upsalquitch) developed and the ice retreated in westerly direction. For an in-depth review of the Quaternary Geology of New Brunswick, the reader is referred

to the work of Rampton et al. (1984).

3.3. Quaternary Deposits

Most of the glacial deposits in northern New Brunswick region were laid down during the last glaciation in the Late Wisconsinan. The surficial deposits that were mapped by Rampton et al., (1984) in the region include basal till, ablation till, glaciofluvial and organic deposits, alluvial and colluvial deposits, and soils (Fig. 9), as well as weathered bedrock.

During the 1994 field season Chris Lochner, another M.Sc. student at Carleton University, collected till samples from 12 pits for Pb isotopic studies, and these pits showed a single basal till in the study area. The basal till in the lower elevations was generally found to be greater than one metre thick. However, on the top of the hills, the basal till is generally less than one metre thick or even absent.

Till samples collected both from the grid system and the pits have confirmed that a sandy/clayey basal till covers most of the study area. The till is greenish to yellowish brown in colour, depending on its degree of oxidization. The non-oxidized basal till is green in colour, while the oxidized till is red to yellowish brown in colour. Figure 8 is a simplified surficial geological map of the study area, modified after Parkhill and Dioron, (1995).

Fig. 8. Local Appalachian ice centres and Late Wisconsin ice-flow patterns in northern New Brunswick (redrawn from Rampton et al. 1984; Parkhill, 1994)

Fig. 9. Simplified surficial geology map of the study area (redrawn from Parkhill and Doiron, 1995).

3.4. Ice Flow Indicators in the Study Area

Different ice-flow indicators mapped in the study area include glacial striations, grooves, till fabrics, pebble and boulder trains, and glacially sheared bedrock (Parkhill, 1994). During the 1994 field season, efforts were made to determine the ice-flow direction. Several striations on intensely polished bedrock were found east of the study area along a newly-opened logging road. The direction of these striations was found to be between 80° to 110° . This finding of an eastward flow direction is in agreement with the previous studies involving mapping of striations, pebble lithology tracing, and boulder erratics. Furthermore, two boulders with striations oriented 93° and 81° were found in place in the bottom of pits CL-11 and CL-12 respectively, located 300 m down-ice from the sulphide outcrop of the Upper AB Zone. The dispersal of erratics is another element that can be used to determine the ice-flow directions in the study area. Granitic boulder erratics that originated from the Silurian, Mount Elizabeth Intrusive Complex were found in close proximity to the Halfmile Lake area (Parkhill, 1993a). These erratics belong to a large, glacial dispersal train that extends for a distance of about 25 to 30 km across the California (NTS 21 O/8) map area, down ice from its source (Parkhill, 1994b). Once again, these granitic erratics indicate that the ice flowed in an easterly-northeasterly direction.

Parkhill (1993) also conducted a detailed till geochemical study in the Nepisiquit Lake (LTS 21 O/7) and California (NTS 21 O/8) map areas. The main objectives of this study were to define the glacial dispersal patterns as well as the background of till geochemical values. Geochemical studies revealed that the basal till and the till geochemical anomalies were locally derived, and transported for no more than 2 km in an east-northeast direction.

CHAPTER IV

Pb ABUNDANCE DATA

4.1. Introduction

The geochemical techniques for exploring for mineral deposits in glaciated terrains were developed in Finland. The development and history of mineral exploration in drift covered areas were discussed by L.K. Kauranne (1976), who pointed out that the displacement of boulders (erratics) by ice was known as early as 1740. The basic idea of geochemical exploration in glaciated terrains is simple. Patterns can develop down ice from geochemically distinct bedrocks and ore bodies. Such patterns are referred to as glacial dispersal trains (Shilts, 1976).

Shilts (1976) describes a glacial dispersal train as being made up a head and a tail. He referred to the *head* as an area of very high metal concentration in the drift at or near the source, which decays exponentially down-ice to a ribbon-shaped *tail* of dispersal, where the metal contents are slightly above the background values due to dilution by metal-poor debris eroded from the glacial floor of the dispersal area. Understanding the shape and the extent of the geochemical dispersal pattern in the study area is very important. In an attempt to define the scale of any dispersal at the Halfmile Lake deposit, Pb abundances for 247 samples were obtained by ICP-Mass spectrometry and ICP-Emission spectrometry at the Geological Survey of Canada. These data were first used to discriminate between background and anomalous values. A series of computer programs were then used to develop the Pb

abundance contour maps. Finally, the data were used to evaluate the size and the shape of the dispersal train.

4.2. Pb Contour Map

In order to define the shape and the extent of a geochemical dispersal train, a Pb content contour map was generated using "SURFER", which is a grid-based (XYZ) contouring and three-dimensional plotting graphic package. This program offers six gridding methods for contouring and surface plotting. These are: Kriging, Minimum Curvature, Radial Basis Function, Shepard's method, Inverse Distance, and the Triangulation method.

Because SURFER creates the contour maps from the gridded data, the original data points may not be honored exactly in the grid files. However, some of the gridding methods are better than others in preserving the integrity of the data, and trial attempts were necessary before the best contouring method could be chosen. During the experimentation of contouring of the data, the Kriging, Minimum Curvature, and Radial Basis Function all produced acceptable contour maps with a smooth appearance. However, the Inverse Distance, Shepard's Method, and Triangulation methods produced less acceptable contour maps. The Inverse Distance, and Shepard's methods, both tended to generate "Bull's Eye" contour pattern. With the Triangulation method, there are too few data points to generate acceptable maps. The best recommended gridding method is Kriging, because, it is more flexible and is useful for gridding almost any type of data set. The Kriging method attempts to express the trends suggested in the data set, and one of the advantage of this method is that

the high values might be connected along ridges, rather than isolated "Bull's Eye" type contours. For more information regarding this method and its mathematical and/or statistical concepts, the reader is referred to text books of statistics and data analysis in geology, such as Davis (1986).

4.3. Anomalies and Threshold

Local scale dispersal trains in the study area can be defined by using the Pb abundance data from the tills. A total of 247 samples were analyzed at the Geological Survey of Canada for Pb abundances, and the localities have already been shown in Fig.4. Ten of the analyzed samples are located up-ice from the deposit. The results of the Pb analyses are presented in Appendix. C.

The maximum Pb concentrations of 1700 ppm were found at sites AH094 which is close to the deposit, and AH130 which is located at about 1000 ft (330 m) east, down-ice from the deposit. The minimum Pb values are found in samples that are both up ice and down ice from the deposit. The Pb abundance of up-ice samples (AH021, AH035, AH052, AH053, AH500, AH501, AH502, AH503, AH504, and AH505) average 65 ppm (50 to 89 ppm). This value could be regarded as the upper limit of the background values of the till in the study area. However, to better understand and interpret the results, anomalous and background values of Pb in the till have to be defined statistically and/or graphically. Threshold values can be used in geochemical exploration when the geological setting is the same for all samples and their distribution over the area is fairly homogeneous, which is

generally true for surveys conducted over fairly small areas (Plouffe, 1989).

Topography and bedrock lithologies are two variables that could affect the geochemical background for a particular element. The background value depends on the composition of the bedrock, while topography plays a secondary role in which it can influence the transport distance of debris by glacier ice (Clark, 1987; Shilts, 1975; Strobel and Faure, 1987). In this study, the samples were collected over a small area with relatively little variation in topography, and the underlying bedrock forms part of the Tetagouche Group. Assuming that the bedrock type had no effect on the background value of Pb, then the threshold values could be used.

Intimately related to threshold values are those that are designated "background" and "anomalous" values. Threshold is the "line" dividing the two, and the simple definition is the outer limit of the background variations. There are several statistical methods that can be used to estimate the threshold in a study area. Two well-known procedures for rapid characterization of the distribution of chemical elements are frequency distributions and spatial interpolations (Qiuming et al., 1994).

The threshold of the study area was estimated using an interpolation procedure by creating contour maps which represent the spatial distribution of Pb. Fig. 10 shows Pb abundance contour maps employing single contours to divide the data set into two parts. Each map portrays two areas, the first is the dark area enclosed within the contour value under consideration, and the second area represents values below the same Pb contents. The shape of the areas that are enclosed by the contour values gradually change as the Pb contents decrease and the total enclosed areas decrease as the value of the contour increases. From

these contours, the threshold that separates the anomalies from the background areas can be selected by means of log (Pb concentration)-log (enclosed contour area) relationship plot. Fig. 11 is the enclosed area of each of the contours vs Pb abundance. As can be seen, the threshold value coincides to the break where there is a sudden change in rate of decrease of the area enclosed by the 100 ppm contour. A figure close to this was found using data from the California map area by Parkhill (1994) and Mersereau (1989a). Parkhill calculated the threshold of lead (mean + two times standard deviation) of the California map area as 98 ppm, while Mersereau (1989a) quoted a value of 50 ppm.

4.4. Lead dispersal patterns

A Pb abundance map is shown in Fig. 12. This map indicates the actual uninterpolated distribution of Pb concentration values of the till. The Pb abundance data have been divided into three groups. The group between 0 and 100 ppm includes all background values. Based on this map an east-northeast dispersal train can be defined. The observed easterly and north-easterly trend of the dispersal train can be attributed to glacial dispersion. This supports the general ice-flow direction in the study area based on glacial striae and pebble lithologies.

Another Pb content contour map of the till in the study area is shown in Fig. 13. This map shows interpolated values of Pb contents and shows two distinct dispersal trains. The first trends east-northeast from the deposit, while the second dispersal train trends south-southeast. From Fig. 13 it can be seen that the areas immediately adjacent to the sulphide outcrop have high Pb values. This is followed down-ice by a zone of moderate to high Pb

contents that continues to increase for several hundred of metres down ice until again high contents of Pb (≥ 600 ppm) are reached. Beyond this point, the Pb values begin to decrease.

The primary dispersal train extends to line L10400E (650 m from the deposit), and the Pb values decrease until the background values are reached. However, at about 400 m from the deposit, the original easterly direction of the dispersal train begins to change direction to the north-northeast, and the Pb values remain greater than the background level (≥ 100 ppm) for the remainder of the grid. Because the extent of the north-northeast dispersal train continues beyond the study area, it is very difficult to define its true dimension. High values of Pb are found in the area immediately adjacent to the sulphide outcrop, and a narrow dispersal train of high Pb abundance develops from the deposit trending south-southeast, and continuing for the remainder of the grid.

A three-dimensional plot of interpolated Pb abundance data from the till (Fig. 14) again shows the existence of two dispersal trains, a primary dispersal train and a narrow secondary dispersal train trending south-southeast. For the primary dispersal train, the *Head* and the *Tail* can be visualized.

Knowing that the topography can control the magnitude and the shape of the dispersal train, integration of the topography with Pb concentration data may disclose information that is not perceivable using only the Pb content of the till. In order to understand the relationship between the topography and the dispersal train, the topographic map of the study area was digitized and the three-dimensional view of the area was prepared. This is shown in Fig. 15. The Pb abundance contour map (Fig. 13) was then overlain on the 3-D topographic map of the area. This is shown in Fig. 16.

The Pb content of the till and the topography can help explain the dispersal train around the sulphide outcrop, and the narrow train that develops from the deposit towards the south-southeast. It is clear that the narrow dispersal train is not related to primary glacial activity and may be related to secondary processes such as post-glacial weathering. The narrow dispersal train defines a narrow track that coincides with a topographic depression (valley) which is the surface-run-off pathway from the Upper AB Zone toward the Northwest Miramichi River. Therefore, the process responsible for the enrichment of Pb along this pathway is probably hydromorphic dispersion.

Fig. 16 also helps to explain why the primary dispersal train deviates from its original easterly trend to a northeasterly trend. The area in which the deviation begins, appears to corresponds to a change of slope. In other words, the dispersal terrain in this part of the study area closely follows the shape the of the topography

Fig. 10. Binary pattern for separate contours showing enclosed areas between different contours.

Fig. 11. Threshold estimation diagram using areas occupied by different contour lines and their concentrations. Solid lines represent the best fit to the data points.

Fig. 12. Pb abundance map.

Fig.13. Lead content contour map, showing the primary glacial dispersal train, and dispersal perhaps related to hydromorphic processes.

Fig. 15. 3-D plot of topography of the study area.

Fig. 16. Lead contour map, overlain with topography, showing primary and secondary dispersal trains.

CHAPTER V

LEAD ISOTOPES

5.1. Introduction

In mineral exploration programs, a wide range of exploration methods are used to locate high-priority areas for mineral deposits. Such methods include geophysical surveys, and geochemical exploration, including dispersal train detection, heavy-metal analyses, and stream and lake sediment analyses commonly used in glaciated terrains.

A new method that has been developed for mineral exploration is the application of Pb isotopes to VMS exploration in glaciated terrains (Bell and Franklin, 1993). Until recently, the major applications of Pb isotopes have been to assist and understand the genesis and age of ore deposits (Gulson, 1986). Although Pb isotopes have also been used to evaluate the age and precious-metal potential of gossans, ironstone, and soils (Gulson and Mizon, 1979; Gulson, 1986; Gulson et al., 1992), no attempt had been made to use glacial material until the work of Bell and Franklin (1993) and Bell and Murton (1994).

The two recent papers by Bell and Franklin (1993) and Bell and Murton (1994) have laid down the foundations of a new method for VMS mineral exploration using the Pb isotope signatures of till. It is the purpose of this chapter to (i) critically evaluate the use of Pb isotopes as glacial indicators, (ii) define the extent and the shape of the Pb dispersal train at Halfmile Lake area, (iii) discriminate the background and anomalous Pb isotopic value derived from the sulphide outcrop, (iv) establish the target Pb isotopic signature of the Halfmile Lake

deposit, and (v) compare the Pb isotope dispersal train with that delineated by the Pb abundance data.

5.2. Fundamentals of Pb Geochemistry

Lead is distributed throughout the Earth and is found as a trace element in every kind of geologic materials. Lead on Earth also exists both as the radiogenic products of U and Th, and as non-radiogenic lead. The non-radiogenic Pb is found in lead-rich minerals, such as galena, which contains little U or Th. Furthermore, Pb on Earth consists of the Pb that was present when the Earth formed (primeval) and the Pb that was derived from the radioactive decay of U and Th.

Uranium has three naturally occurring radioactive nuclides, ^{238}U , ^{235}U , and ^{234}U ; Th has one long-lived radioactive nuclide, ^{232}Th , and five short-lived radio-nuclides which are the intermediate daughters of ^{238}U and ^{235}U . Three decay series are involved in the radioactive decay of U and Th to form the stable daughter products ^{206}Pb , ^{207}Pb , and ^{208}Pb . The decay of ^{238}U and ^{235}U give rise to ^{206}Pb and ^{207}Pb respectively, while ^{208}Pb is produced by the radioactive decay of ^{232}Th . The other isotope of lead, ^{204}Pb , has no radioactive parent and is commonly used as a reference isotope.

Uranium and Th have long half-lives compared to their short-lived intermediate daughters. Under conditions of secular equilibrium the rate of growth of the stable radiogenic daughters at the end of the decay series is equal to the rate of decay of the parent that starts the series. When this condition is met, the three decay series can be treated as though the

initial parent decays directly to the stable daughters. The decay of ^{238}U , ^{235}U , and ^{232}Th , in a closed system, then can be summarized as follows:

Since the Earth formed 4550 Ma (4.55 Ga) years ago, the abundance of radiogenic isotopes of ^{206}Pb , ^{207}Pb , and ^{208}Pb have increased due to the radioactive decay of U and Th. The growth of the various lead isotopes in U- and Th-bearing minerals and/or rocks with time in a closed system in which a secular equilibrium has been attained, can be illustrated by the following equations:

$$(^{206}\text{Pb}/^{204}\text{Pb})_t = (^{206}\text{Pb}/^{204}\text{Pb})_i + (^{238}\text{U}/^{204}\text{Pb})_i (e^{\lambda_1 t} - 1) \quad (4)$$

$$(^{207}\text{Pb}/^{204}\text{Pb})_t = (^{207}\text{Pb}/^{204}\text{Pb})_i + (^{235}\text{U}/^{204}\text{Pb})_i (e^{\lambda_2 t} - 1) \quad (5)$$

$$(^{208}\text{Pb}/^{204}\text{Pb})_t = (^{208}\text{Pb}/^{204}\text{Pb})_i + (^{232}\text{Th}/^{204}\text{Pb})_i (e^{\lambda_3 t} - 1) \quad (6)$$

where, $(^{206}\text{Pb}/^{204}\text{Pb})_t$, $(^{207}\text{Pb}/^{204}\text{Pb})_t$ and $(^{208}\text{Pb}/^{204}\text{Pb})_t$ are the Pb isotopic ratios of the rock and or the minerals at the present time and $(^{206}\text{Pb}/^{204}\text{Pb})_i$, $(^{207}\text{Pb}/^{204}\text{Pb})_i$, and $(^{208}\text{Pb}/^{204}\text{Pb})_i$ represent the initial Pb isotopic ratios that were present in the rock and/or minerals at a particular time (t). The constants λ_1 , λ_2 , λ_3 , are the decay constants of ^{238}U , ^{235}U , and ^{232}Th respectively, and t is the time elapsed since the closure of the system.

If Pb is separated from U and Th to form an orebody at a particular geologic time (t), its isotopic composition will remain unchanged throughout its history. Therefore, the Pb isotopic composition of common Pb can be defined by the following equation.

$$(^{206}\text{Pb}/^{204}\text{Pb})_t = (^{206}\text{Pb}/^{204}\text{Pb})_i + (^{238}\text{U}/^{204}\text{Pb})_i (e^{\lambda_1 T} - e^{\lambda_1 t}) \quad (7)$$

where T represents the age of the Earth and t represents the time at which the Pb evolution have ceased. Similar equations for the other two lead isotopes can be written in a similar way.

Because of the separation of the Pb from the U- and Th-bearing source to form a Pb-rich orebody (such as the volcanogenic massive sulphides) or even one single crystal of galena, the ore/galena will have a Pb isotopic composition that reflects the time it was separated from its U-bearing source (Gulson, 1983). Because such minerals are essentially free of U and Th, their Pb isotopic ratios will remain unchanged. By comparison, minerals and the country rocks that contain U and Th will have variable Pb isotopic ratios that show a continuous change with time due to the radioactive decay of U and Th.

The evolution of Pb isotopes can be best explained by considering a hypothetical well-behaved closed system, in which its components (minerals and associated rocks) have formed contemporaneously at a particular geologic time in (t_0). It is assumed that the system started with the same initial lead isotopic ratios, but variable Pb/U and/or Pb/Th ratios. An example of such a system could be volcanogenic massive sulphides and their associated volcanic rocks. At the time of the formation of the system, all of the components (e.g. galena, sphalerite, pyrite, chalcopryite, and whole rock) have similar Pb isotopic ratios. For those minerals that have the highest Pb/U and/or Pb/Th ratios, such as galena, the Pb isotope ratios will remain unchanged throughout their history. However, the associated volcanic rocks have the lowest Pb/U ratios compared to the sulphide minerals, and hence, their radiogenic Pb will increase with time due to the radioactive decay of U and Th to form Pb. Other minerals such as sphalerite, pyrite, and chalcopryite, have intermediate amounts of U and Th in their system, and therefore, their radiogenic Pb will increase in amounts proportional to their original U/Pb and Th/Pb contents.

A graphical depiction of the U-Pb systematics is presented in Fig. 17. In this diagram

$^{206}\text{Pb}/^{204}\text{Pb}$ is plotted against $^{238}\text{U}/^{204}\text{Pb}$. As can be seen from the graph, at t_0 the system had a uniform $^{206}\text{Pb}/^{204}\text{Pb}$ ratio, but different $^{238}\text{U}/^{204}\text{Pb}$ ratios. A Pb-rich mineral, such as galena, does not generate any radiogenic Pb, because of its low U/Pb ratio. On the other hand, the whole rock sample generates the largest amount of radiogenic lead, because it has the highest U/Pb ratio. Other minerals (sphalerite, pyrite, and chalcopyrite) have intermediate U/Pb ratios and hence, their $^{206}\text{Pb}/^{204}\text{Pb}$ ratios fall between those of the galena and the whole rock. From the plot all components fall along a straight line at time which is known as an isochron. The slope of the isochron defines the age of the system.

The evolution of Pb isotopes can also be presented using a plot of $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, known as the Pb isotope correlation diagram (Fig. 18). The advantages of using this plot are basically two. In the first case, the Pb data are presented solely as ratios, in which the radiogenic ^{206}Pb and ^{207}Pb are compared to the non-radiogenic and invariant ^{204}Pb isotope. This approach is usually used for dating U-free minerals (Gulson, 1986). Secondly, there is no need to know the U/Pb ratios of the sample.

The Pb isotope correlation diagram (Fig. 17) reflects the changes that have occurred in the U/Pb systems. As it can be seen from the graph, all samples started at same initial Pb isotopic composition represented by a point that has a coordinate $(^{206}\text{Pb}/^{204}\text{Pb})_0$ and $(^{207}\text{Pb}/^{204}\text{Pb})_0$. Samples that have the least U/Pb ratios such as galena and lead-rich VMS deposits do not generate any growth curve, whereas those with high values of $^{238}\text{U}/^{204}\text{Pb}$ (μ) generate growth curves. Any Pb of the same age will have isotope ratios that form an array of $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ ratios which fall along a straight line known as secondary isochron. The age of the formation of this system can be calculated from the slope of the

secondary isochron, which is represented by the following equation:

$$R = m = \frac{1}{137.88} \frac{[e^{t, \lambda_2} - e^{t, \lambda_1}]}{[e^{t, \lambda_1} - e^{t, \lambda_1}]} \quad (9)$$

Where, m , is the slope of the isochron, t_r is the time at which all Pb had the same isotopic composition and t is the time at which Pb is separated from the system (i.e. time of formation of the ore deposits and/or the galena) If t equal to zero, then the slope is given by:

$$m = \frac{1}{137.88} \frac{[e^{t, \lambda_2} - 1]}{[e^{t, \lambda_1} - 1]} \quad (10)$$

5.3. Common-Pb Dating and Ore Deposits

Nier (1938) and Nier et al. (1941) were the first to note the variations of Pb isotopes of galena from different ore deposits. Galena can be considered U-free mineral. In addition, they recognized a general correlation between the Pb isotope composition and the assumed geologic age of the deposition. The isotopic compositions of these deposits, are generally higher for samples from younger ore deposits (Faure, 1986, Gulson, 1986). Nier et al. (1941)

proposed that any variations of Pb isotopic compositions are produced within the source from which the Pb ores were concentrated. Because of the radioactive decay of U and Th in the source, the radiogenic Pb content increased with time. Thus, Pb that was concentrated to form an ore body represents a mixture of radiogenic Pb and the primeval Pb.

Interpretations of Pb isotopes of galenas from different ore deposits, opened the way for a quantitative treatment of the isotopic composition. The so-called "common-Pb" method has served as the basis for a number of models, including a way by which the age of the Earth was calculated (Faure, 1986). The mathematical basis for the variation of lead isotopes with time were presented in the previous section (5.2)

Unlike the absolute ages determined for minerals containing radioactive element (U-Pb, Sm-Nd, and Rb-Sr), ages calculated for galenas depend on the model used (Russell and Farquhar, 1960). Several different "models" have been proposed. For a more detailed discussion of common-Pb dating model ages the reader is referred to works of Kanasewich (1986), Doe (1970), and Stacey and Kramers (1975). The two frequently used common-Pb models are the single-stage and two stage-models.

The single stage-model assumes that a) all the samples have started with the same lead isotopic composition (primeval Pb), but with different U/Pb and Th/U ratios, b) no U, Th, and Pb, have been added or lost since their formation, and c) the variations of Pb isotopes in the system is caused only by the radioactive decay of U and Th.

Lead isotopic data from submarine exhalite deposits of different ages showed that all samples fall close to single Pb evolution curve, with a unique U/Pb and Th/Pb ratios (Stanton and Russell, 1959). Based on this, Stanton and Russell (1959) suggested that the

VMS ore deposits were derived from a relatively homogeneous source which has maintained nearly constant U/Pb and Th/Pb ratios since the formation of the Earth 4.55 Ga ago. Fig. 19 is a plot $^{207}\text{Pb}/^{204}\text{Pb}$ against $^{206}\text{Pb}/^{204}\text{Pb}$ from galenas obtained from several different deposits of differing ages. The data from the ore deposits define a unique growth curve. This was originally interpreted as a single-stage growth curve. This curve implies that the Pb ores were generated from a reservoir that had a uniform U/Pb ratio. When Pb is removed from the single-stage reservoir, the isotopic composition of the source is frozen and a model age it can be calculated by using equation 7 and 8

$$(^{206}\text{Pb}/^{204}\text{Pb})_t = (^{206}\text{Pb}/^{204}\text{Pb})_i + (^{238}\text{U}/^{204}\text{Pb})_i (e^{\lambda_2 T} - e^{\lambda_1 t}) \quad (7)$$

$$(^{207}\text{Pb}/^{204}\text{Pb})_t = (^{207}\text{Pb}/^{204}\text{Pb})_i + \frac{\mu}{137.88} (e^{\lambda_2 T} - e^{\lambda_1 t}) \quad (8)$$

where, $(^{206}\text{Pb}/^{204}\text{Pb})_t$ and $(^{207}\text{Pb}/^{204}\text{Pb})_t$ are the lead isotopic values of ore deposits, and $(^{206}\text{Pb}/^{204}\text{Pb})_i$ and $(^{207}\text{Pb}/^{204}\text{Pb})_i$ are the initial Pb isotope ratios of primeval Pb in the Earth. These initial Pb isotope ratios are considered to be the same as those in U-free phases (troilite) from meteorites. μ is the present day $^{238}\text{U}/^{204}\text{Pb}$ ratio of the source region and $1/137.88$ is the present day $^{235}\text{U}/^{238}\text{U}$ ratio ($1/^{238}\text{U}/^{235}\text{U}$). The constants λ_1 , λ_2 are decay constants of ^{238}U and ^{235}U , respectively (which are 1.55125×10^{-10} and 9.8485×10^{-10}). T is the

age of the Earth (4.55 Ga), and (t) is the time of formation when lead was effectively removed from the U and Th in the source material. The age of the Pb that had a single stage history can thus be calculated from the formulas given in equations 7 and 8.

Because of the disagreement between the single-stage dates of many ore deposits and their known geological age, many isotope geochemists revised the growth curve and proposed other models. Stacey and Kramers (1975) developed a two-stage model. Their model assumes that Pb evolution started 4.57 billion years ago, and continued to evolve till a latter time (3.70 Ga), at which time a major differentiation of the initial homogeneous Earth took place that changed the U/Pb ratios of the source. Since differentiation (3.7 Ga) the reservoir for the lead-rich ores (VMS) deposits evolved with a unique U/Pb and Th/Pb ratios.

The two-stage model is graphically presented in Fig 20. The plot shows the variation of Pb isotopes as a function of time, and the single curve indicate that the massive sulphide deposits were derived from a single source that developed 3.7 Ga ago with a unique $^{238}\text{U}/^{204}\text{Pb}$ ratio of 9.74. This source with a constant U/Pb and Th/Pb ratios was originally believed to represent a mixture of both upper mantle and the continental crust. However, Gariépy and Dupré (1991) interpreted that the growth curve to represent the mean Pb isotope compositions of a large volume of continental crust. The Stacey-Kramers growth curve is used by most isotope geochemists as a reference line on Pb-Pb isotope ratio diagrams.

Fig. 17. Evolution of Pb indicating the increase of radiogenic ^{206}Pb caused by radioactive decay of ^{238}U (from Gulson, 1984).

Fig. 18. Evolution of Pb isotopes in a system which started with the same initial Pb isotopic ratios, but different U/Pb ratios (from Bell and Murton, 1995)

Fig. 19. Diagram illustrating the single-stage model for common-Pb dating.

Fig. 20. Diagram illustrating the Stacey-Kramers (1975) model.

5.4. Pb Isotopic Signature of the Halfmile Lake Deposit

In order to establish the target Pb isotopic composition and find the degree of isotopic homogeneity of the Halfmile Lake deposit, four galena samples, as well as one gossan sample from the study area were analyzed. Table 4 lists the isotopic signatures of the sulphide and gossans from the Halfmile Lake deposit

Table 4. Lead isotopic signature of the Halfmile Lake deposit.

sample	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
Halfmile Sul1	18.24	15.70	38.28
Halfmile Sul2	18.23	15.67	38.18
Halfmile Sul3	18.23	15.68	38.20
Halfmile Sul4	18.28	15.74	38.40
HML. Gossan	18.32	15.68	38.30

The table clearly shows that the four of Pb isotopic ratios of the sulphide samples are similar, and that the Pb isotopic signature of the Halfmile Lake deposit is homogeneous. Furthermore, Pb isotopic ratios from the gossan sample also show close affinity to the sulphide samples, suggesting that the gossan was indeed derived from the weathering of the sulphide outcrop.

The isotopic signature of Pb from the Halfmile Lake deposit was found by averaging

the Pb isotopic values of the four sulphide samples. The average Pb isotopic values of Halfmile Lake deposit, i.e. $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ are 18.24, 15.69, and 38.26 respectively. Even if the Pb ratios for the gossan are included in the calculation the value changes very little.

The $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios and $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ of the Halfmile Lake deposit are plotted in Fig.21a and Fig.21b respectively; shown for reference is part of the Stacey-Kramer's growth curve. Also shown for comparison are data from other sulphide deposits of Bathurst mining camp (from McCutcheon et al., 1993). The samples from different deposits show some scatter and fall slightly above the Stacey-Kramers curve.

Fig. 21a. Lead isotopic signature of Halfmile Lake ore, Halfmile Lake gossan and other sulphide deposits from the Bathurst camp; SK = Stacey-Kramers.

Fig. 21b. Lead isotopic signature of Halfmile Lake ore, the Halfmile Lake gossan, and other sulphide deposits of the Bathurst mining district; SK = Stacey-Kramers.

5.5. Lead Isotope composition Of The Till

5.5.1. Principles

The basic concepts of applying lead isotopes to glacial sediments are quite similar to other methods used for mineral exploration in glaciated terrains. Lead isotopes, like other glacial indicators, must meet the following requirements: a) the materials were eroded and transported down-ice from their sources; b) the source material should be distinct from the surrounding materials; and c) the source of the indicator should be a point source which permits the measurements of transport distance and the direction (Bell and Murton, 1995).

Till sediments are formed as the result of glacial erosion and transport of pre-existing rocks. The Pb isotopic composition of the till is therefore a function both of the isotopic signature and the amounts of Pb contributed from each of these sources. In areas that have a distinct Pb isotopic source, such as the Halfmile Lake area, the isotopic signature of the deposit should differ from those of the surrounding country rocks. Any material that has been transported down-ice from the deposit should reflect the low Pb isotopic ratios of the deposit.

Plots of $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$ for all of the till samples, the Halfmile Lake sulphides and other deposits from Bathurst are shown in Fig. 22a and 22b respectively. The most important features that emerge from both figures are:

- a) all the data fall slightly above the Stacey-Kramer's curve.
- b) the data define a crude linear array on a plot of $^{207}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$.
- c) all of the data points fall along a crude linear array on a plot $^{208}\text{Pb}/^{204}\text{Pb}$ vs $^{206}\text{Pb}/^{204}\text{Pb}$.
- d) in both figures, the sulphide samples are those with the lowest Pb isotopic ratios.

Presenting the Pb isotopic values simply as ratios may sometimes create some

confusion to readers not familiar with Pb isotope systematics. Therefore, the Pb isotopic values are presented in a manner similar to that used for stable isotopes using a δ (delta) notation. This notation was first used for Pb by Bell and Murton (1995) in their study of the glacial sediments at Chisel Lake and Buchans. The δ notation uses the average Pb isotopic value of the ore as a reference ratio, and the Pb isotope ratios in the till are calculated in terms of relative deviation from those of the ore. The $\delta^{206}\text{Pb}$ value of the till are given in the following equation, and it is expressed in ‰.

$$\delta^{206}\text{Pb} = \frac{(^{206}\text{Pb}/^{204}\text{Pb})_s - (^{206}\text{Pb}/^{204}\text{Pb})_{\text{VMS}}}{(^{206}\text{Pb}/^{204}\text{Pb})_{\text{VMS}}} \cdot 10^3 \quad (11)$$

In this equation, $\delta^{206}\text{Pb}$ is the relative Pb isotopic deviation of till samples from the ore value, $(^{206}\text{Pb}/^{204}\text{Pb})_s$ is the isotopic ratio of the till sample, and $(^{206}\text{Pb}/^{204}\text{Pb})_{\text{VMS}}$ is the average Pb isotopic value of the ore deposit. The delta notation is much easier to comprehend than the raw Pb isotope ratio values. If the $\delta^{206}\text{Pb}$ value of the glacial till is zero, then the sediment is isotopically identical to the VMS value. On the other hand, if the $\delta^{206}\text{Pb}$ value is greater than zero, then it has higher isotopic value than the ore, and thus more radiogenic than Pb is contained within the deposit.

Fig. 22a. Pb isotopic ratios for till, Halfmile Lake sulphides, Halfmile Lake gossan, and other Bathurst sulphide samples.

Fig. 22b. Pb isotope ratios for till, Halfmile lake sulphides, Halfmile gossan and other Bathurst sulphide samples.

5.5.2. Pb Isotopes-Background Samples

Pb isotopic values of the till in the study area were measured on till samples collected from small pits throughout the study area. Of the samples collected, fifty eight were chosen for analytical work. In order to increase the sample distribution, three extra till samples were obtained from the top of three deep pits used by C. Lochner during his study of the vertical Pb variations in the Halfmile Lake area. The localities of these pits are shown in Fig.23. The results of the Pb isotopic analysis of the till is presented in Appendix B, and the sample localities are shown in Fig.23.

Defining the background Pb isotopic value of the till is very difficult. Up-ice samples and samples located further down ice were used to give an overall picture of the background values. Of fifty eight samples analyzed five (AH500, AH501, AH502, AH503, and AH504) located about 300 m west of the deposit as well as two extra up-ice samples (AH52, and AH53) close to the sulphide outcrop (90 and 50 m, respectively), were chosen to define the background Pb isotopic value. In addition, seven samples at distances > 1000 m from the deposit were also analyzed in order to better understand the extent of the glacial dispersal train (Fig.23).

The $^{206}\text{Pb}/^{204}\text{Pb}$ ratios of up-ice samples gave some of the highest values with an average $^{206}\text{Pb}/^{204}\text{Pb}$ of about 18.54 which is equivalent to a $\delta^{206}\text{Pb}$ value of 18.68‰. Sample AH55 which is located directly above the deposit gave $^{206}\text{Pb}/^{204}\text{Pb}$ ratios that are even higher than those from the up-ice samples. The highest $^{206}\text{Pb}/^{204}\text{Pb}$ ratio of 18.67 ($\delta^{206}\text{Pb} = 26\text{‰}$) found is from sample AH39 which is located only 60 m north of the ore deposit. Similarly, the samples located further down-ice (>1000 m) from the deposit yielded $\delta^{206}\text{Pb}$ values

greater than 13 ‰.

By considering the overall $\delta^{206}\text{Pb}$ distribution of both the up-ice and down-ice samples an arbitrary background value can be assumed. A background of $\delta^{206}\text{Pb}$ of 13‰ was chosen, because it is the lowest value of both the up-ice and down-ice samples.

5.5.3. Pb Isotopic Dispersal Train

The areal distribution of the $\delta^{206}\text{Pb}$ values of the till samples is plotted on Fig. 24. The most important feature to emerge from these data is that the low $\delta^{206}\text{Pb}$ values define an easterly-trending dispersal train. The data have been arbitrarily divided into four groups based on $\delta^{206}\text{Pb}$ values. From the map, the area west and up-ice from the deposit is characterized by high $\delta^{206}\text{Pb}$ values falling in the range 26 to 3 ‰. The area immediately to the east of the deposit shows high values that extend for about 1000 ft (~ 330 m). The area immediately adjacent and east of the sulphide outcrop shows low $\delta^{206}\text{Pb}$ values between 4 and 12 ‰. This dispersal train extends to line L10400E, almost 600 m away from the deposit. The other remaining two data groups represent the extreme $\delta^{206}\text{Pb}$ values. One sample gave a negative $\delta^{206}\text{Pb}$ value, but given the analytical uncertainty of ± 1 ‰, this overlaps with the ore signature, while the other yielded a $\delta^{206}\text{Pb}$ value > 17 ‰.

A $\delta^{206}\text{Pb}$ contour map of the till is shown in Fig. 25. From the map it can be seen that those samples close to and down-ice from the deposit have $\delta^{206}\text{Pb}$ values much less than the $\delta^{206}\text{Pb}$ value of 13 ‰. The general trend of the dispersal train is eastward, however, the original easterly direction of the dispersal train begins to trend north/northeast and continues

to persist for the remainder of the grid. Because the extent of the interpolated north-northeast dispersal train continues beyond the study area, it is difficult to define its true extent. The Pb isotope data show, quite clearly, that there is an input of Pb from the ore into the glacial till and that the ore signature can be detected 600 m down-ice from the deposit.

Knowing that the topography can control the shape of the Pb abundance dispersal train, integration of the topography with Pb isotope data may disclose information that is not perceivable using only the Pb isotopic data. Therefore, in order to understand the relationship between the topography and the dispersal train, the topographic map shown in Fig. 14 was overlain with the $\delta^{206}\text{Pb}$ contour map (Fig. 25). This figure is shown in Fig. 26. From Fig. 26 it can be seen that the dispersal train is partly controlled by the topography, and coincides with a change in slope. The observed dispersal train leading down ice from the deposit is consistent with the ice-flow direction toward the east-northeast.

Both the Pb isotope data and Pb abundance data have shown primary dispersal trains trending in an east-northeasterly direction. This primary dispersal can be attributed to glacial dispersal, and is consistent with the previous geochemical, pebble lithology, and till fabric studies. However, there is one important difference between the Pb isotope results and Pb abundance data as far as the dispersal trains are concerned. The narrow dispersal train running south-southeast based on the Pb interpolated abundance data is not seen in the dispersal train defined by Pb isotope data. This may be due to secondary processes, such as hydromorphic dispersion and weathering processes.

Fig. 23. Till sample localities for samples analyzed for Pb isotope ratios.

Fig. 24. Pb isotopic map showing the shape and the extent of the glacial dispersal train.

Fig. 25. Pb isotopic contour map showing the dispersal pattern of Pb from the ore.

Fig. 26. 3-D diagram showing position of the Pb isotope dispersal train

Pb isotopic mixing

Mixing can be recognized in tills by plotting Pb isotope compositions against the Pb abundance data (Bell and Murton., 1995). If only two members are involved, such a plot will generate an hyperbola whose shape is a function of the Pb isotope composition and Pb abundance data of the two end-members. Therefore, in order to evaluate mixing of Pb from different sources in the till in the study area, Pb isotope ratios were plotted against Pb content.

The $^{206}\text{Pb}/^{204}\text{Pb}$ vs Pb content in ppm, and $^{208}\text{Pb}/^{204}\text{Pb}$ vs Pb concentration in ppm are plotted in Fig. 27 a and 27 b. Both figures indicate that till samples that have high Pb abundance have the lowest Pb isotopic ratios, and those samples with low Pb concentration have high Pb isotopic ratios. In addition, the data from Halfmile Lake show an hyperbolic relationship similar to those documented by Bell and Murton (1995) from deposits at Chisel Lake and Buchans. The curves are best interpreted as simple binary-mixing between two end-members, the first end-member characterized by a low Pb isotopic ratio and high Pb concentration (the ore) while the second end-member is characterized by a high Pb isotopic ratio and low Pb concentration (the country rocks). From both figures, the conclusion can be made that the till in the study area is derived from mixing between Pb from the VMS deposit and the country rocks. The mixing hyperbola of Fig. 27a and 27b can be transformed into a straight line by plotting Pb isotopic ratios against the reciprocals of Pb content. This transformation is useful (Faure, 1986), because it is then possible to fit a straight line to the data points. Fig. 28 a and 28 b show such plot for the samples from Halfmile Lake. The approximation of the data to linear arrays reflects the hyperbolic arrays shown in Fig. 27 a and 27 b.

Fig. 27. a and b. Both diagrams reflect mixing between two components with different Pb isotope compositions and Pb abundances.

Fig. 28. a and b. Transformation of mixing hyperbola into a straight line by plotting the reciprocal of Pb concentrations.

CHAPTER VI

CONCLUSIONS

The Pb isotopes and the Pb abundances of the glacial till in the study area have successfully identified a glacial dispersal train from the Upper AB zone sulphide outcrop. In addition, both have delineated the extent and the shape of the dispersal pattern. The most significant findings to emerge from this study are:

- i) the Pb isotopic ratios from the till define a primary east-northeast dispersal train that extends for about 600 m down-ice from the deposit.
- ii) the Pb abundance data also define a primary east-northeast dispersal train. In addition, a secondary, ribbon-like dispersal train trending south-southeasterly direction toward Northwest Miramichi River has also been defined using the interpolated Pb abundance data.
- iii) the Pb isotopic ratios and Pb abundance data indicate binary mixing in which the two end-members can be thought of as Pb from the ore and Pb from the country rocks.
- iv) the dispersal train shown only by the interpolated Pb abundance data is considered secondary and probably caused by hydromorphic dispersion or weathering
- v) Pb isotope analysis of the sulphide samples from the Halfmile Lake deposit show Pb isotopic ratios similar to other deposits from the Bathurst camp suggesting some degree of isotopic homogeneity for all of the sulphide deposits in the area.

One of the main advantages of using Pb isotopes in mineral exploration is that the Pb

isotopic compositions can distinguish Pb from a VMS deposit, and Pb from the country rocks. This can not be done using only the Pb abundance data. Pb isotopes thus provide a means of "fingerprinting" Pb from different sources. In till exploration, any Pb isotope signatures that are significantly lower than values obtained from other samples suggests a possible target area because they were likely derived from VMS sources. Another advantage of using Pb isotopes in mineral exploration is that only very small sample sizes are required (~ 50 mg). Finally, this study has shown that Pb isotopes can be used as a glacial indicator not only in Precambrian terrains but also in much younger areas

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2 OF 2

PM-1 3½"x4" PHOTOGRAPHIC MICROCOPY TARGET
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PRECISIONSM RESOLUTION TARGETS

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Appendix A

Analytical Procedure of Pb isotopes

Analytical procedures of Pb isotopes

- a) Approximately 50 mg of each sample were transferred to small clean, teflon beakers. To this was added 2 ml of superpure 2.5 M of HCl. The solution was covered with parafilm, and allowed to stand for at least two hours at a room temperature. Occasional swirling helped with the leaching process.
- b) The sample was then carefully transferred into precleaned centrifuge tubes and covered tightly with parafilm, then centrifuged for 10 minutes.
- c) The clean liquid was then poured into small clean plastic beakers, and evaporated using a hot plate at a temperature of about 110 °C. After evaporation, the beakers plus the sample were removed from the hot plate and allowed to cool. 3 ml of 1 M of HBr was added and the supernatant liquid then centrifuged.
- d) Pb was separated in HBr and HCl using a two column procedure. The columns were filled with 0.5 ml and 0.2 ml of anion ion-exchange columns filled with AG1-X8 resin of 100 to 200 mesh. The Pb is eluted from the columns using 1N HBr and 3N HCl.

Appendix B

Pb isotope results

Easting	Northing	Sample No	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
8600	8900	AH4	18.56	15.67	38.49
9000	8800	AH17	18.52	15.67	38.45
8600	8600	AH39	18.67	15.71	38.79
9400	8600	AH47	18.34	15.66	38.25
9700	8600	AH50	18.43	15.66	38.37
8100	8500	AH52	18.55	15.67	38.47
8200	8500	AH53	18.47	15.66	38.39
8400	8500	AH55	18.58	15.68	38.51
9000	8500	AH61	18.63	15.71	38.69
10000	8500	AH71	18.39	15.69	38.37
8500	8500	AH77	18.18	15.64	38.10
9600	8400	AH87	18.52	15.69	38.51
10200	8400	AH93	18.44	15.69	38.42
8700	8000	AH100	18.38	15.68	38.35
9000	8300	AH103	18.61	15.67	38.65
9400	8300	AH107	18.39	15.70	38.43
9800	8300	AH111	18.38	15.68	38.36
8200	8200	AH118	18.33	15.68	38.29
8400	8200	AH120	18.58	15.72	38.63
8600	8200	AH122	18.52	15.67	38.47
8900	8200	AH125	18.47	15.69	38.37
9300	8200	AH129	18.33	15.73	38.32
9600	8200	AH132	18.45	15.68	38.42
9900	8200	AH135	18.37	15.67	38.31
10200	8200	AH138	18.38	15.66	38.31
8800	8100	AH146	18.51	15.68	38.47

Easting	Northing	Sample No	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
9200	8100	AH150	18.30	15.65	38.30
9000	8000	AH169	18.36	15.66	38.30
9600	8000	AH175	18.31	15.67	38.27
10000	8000	AH179	18.33	15.67	38.29
9200	7900	AH190	18.27	15.67	38.23
9300	7900	AH191	18.36	15.70	38.37
9400	7900	AH192	18.31	15.67	38.25
9800	7900	AH196	18.36	15.69	38.34
10200	7900	AH200	18.44	15.71	38.60
8800	7800	AH203	18.59	15.71	38.71
9000	7800	AH205	18.51	15.68	38.50
9600	7800	AH211	18.54	15.69	38.56
9100	7700	AH212	18.43	15.66	38.33
9200	7700	AH222	18.53	15.67	38.47
9400	7700	AH224	18.33	15.68	38.33
10200	7700	AH232	18.43	15.68	38.42
9600	7600	AH238	18.48	15.68	38.48
9900	7600	AH241	18.53	15.69	38.53
9400	7500	AH246	18.54	15.67	38.51
10200	7500	AH254	18.56	15.67	38.51
9600	7400	AH255	18.53	15.66	38.49
7500	9000	AH500	18.52	15.68	38.48
7300	9000	AH501	18.56	15.67	38.49
7200	8900	AH502	18.58	15.67	38.51
7200	8700	AH503	18.44	15.68	38.39
7600	8700	AH504	18.60	15.68	38.55

Eastings	Northing	Sample No	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$
11600	7800	AH514	18.44	15.70	38.49
11600	7200	AH527	18.48	15.69	38.52
12200	7200	AH528	18.52	15.70	38.55
11600	6900	AH535	18.48	15.69	38.47
12200	6500	AH545	18.59	15.69	38.60
13600	6100	AH552	18.60	15.67	38.54

Appendix C

Pb abundance data

EASTING	NORTHING	SAMPLE No:	Pb (ppm)
8500	8900	AH3	50
8600	8900	AH4	74
8800	8900	AH6	53
8400	8800	AH11	60
8500	8800	AH12	45
9000	8800	AH17	63
9100	8800	AH18	61
8200	8700	AH21	52
8500	8700	AH24	41
9100	8700	AH30	110
9200	8700	AH31	73
9300	8700	AH32	73
9400	8700	AH33	63
9500	8700	AH34	55
8200	8600	AH35	89
8600	8600	AH39	22
8800	8600	AH41	49
9300	8600	AH46	96
9400	8600	AH47	160
9500	8600	AH48	130
9600	8600	AH49	70
9700	8600	AH50	60
9800	8600	AH51	69
8100	8500	AH52	61.5
8200	8500	AH53	86
8400	8500	AH55	85
9000	8500	AH61	37
9400	8500	AH65	190
9500	8500	AH66	68
9600	8500	AH67	76
9800	8500	AH69	65
9900	8500	AH70	270
10000	8500	AH71	175
8100	8400	AH72	32
8400	8400	AH75	88.5
8500	8400	AH76	600
8600	8400	AH77	150
8700	8400	AH78	140

EASTING	NORTHING	SAMPLE No.	Pb (ppm)
9000	8400	AH81	76
9300	8400	AH84	50
9400	8400	AH85	53
9500	8400	AH86	71
9600	8400	AH87	51
9900	8400	AH90	390
10000	8400	AH91	205
10100	8400	AH92	115
10200	8400	AH93	100
8100	8300	AH94	1700
8200	8300	AH95	540
8300	8300	AH96	470
8400	8300	AH97	830
8500	8300	AH98	58
8600	8300	AH99	120
8700	8300	AH100	140
8800	8300	AH101	110
8900	8300	AH102	54
9000	8300	AH103	47
9100	8300	AH104	56
9200	8300	AH105	77
9300	8300	AH106	140
9400	8300	AH107	110
9500	8300	AH108	56
9600	8300	AH109	54
9800	8300	AH111	100
9900	8300	AH112	190
10000	8300	AH113	145
10100	8300	AH114	160
10200	8300	AH115	72
10300	8300	AH116	140
10400	8300	AH117	130
8200	8200	AH118	98
8300	8200	AH119	100
8400	8200	AH120	38
8600	8200	AH122	85
8700	8200	AH123	98
8800	8200	AH124	140

EASTING	NORTHING	SAMPLE No:	Pb (ppm)
8900	8200	AH125	98
9000	8200	AH126	52
9200	8200	AH128	66
9300	8200	AH129	235
9400	8200	AH130	1700
9600	8200	AH132	96
9700	8200	AH133	120
9800	8200	AH134	140
9900	8200	AH135	110
10000	8200	AH136	190
10100	8200	AH137	150
10200	8200	AH138	120
10300	8200	AH139	110
10400	8200	AH140	98
8300	8100	AH141	65
8400	8100	AH142	40
8800	8100	AH146	72
8900	8100	AH147	66
9000	8100	AH148	87
9100	8100	AH149	150
9200	8100	AH150	120
9300	8100	AH151	220
9400	8100	AH152	98
9500	8100	AH153	242
9600	8100	AH154	150
9700	8100	AH155	260
9800	8100	AH156	360
9900	8100	AH157	110
10000	8100	AH158	140
10100	8100	AH159	85
10200	8100	AH160	89
10300	8100	AH161	92
10400	8100	AH162	140
8400	8000	AH163	140
8500	8000	AH164	31
8600	8000	AH165	37
8700	8000	AH166	49
8800	8000	AH167	67.5

EASTING	NORTHING	SAMPLE No:	Pb (ppm)
8900	8000	AH168	53
9000	8000	AH169	200
9100	8000	AH170	600
9200	8000	AH171	1200
9300	8000	AH172	590
9400	8000	AH173	350
9500	8000	AH174	150
9600	8000	AH175	270
9700	8000	AH176	220
9800	8000	AH177	130
9900	8000	AH178	230
10000	8000	AH179	210
10100	8000	AH180	160
10200	8000	AH181	120
10300	8000	AH182	110
8500	7900	AH183	23
8600	7900	AH184	64
9000	7900	AH188	62
9100	7900	AH189	95
9200	7900	AH190	360
9300	7900	AH191	180
9400	7900	AH192	350
9500	7900	AH193	120
9600	7900	AH194	260
9700	7900	AH195	360
9800	7900	AH196	200
9900	7900	AH197	380
10000	7900	AH198	200
10200	7900	AH200	110
10300	7900	AH201	125
8800	7800	AH203	46
8900	7800	AH204	56
9000	7800	AH205	71
9100	7800	AH206	63
9200	7800	AH207	110
9300	7800	AH208	330
9400	7800	AH209	93
9500	7800	AH210	180

EASTING	NORTHING	SAMPLE No:	Pb (ppm)
9600	7800	AH211	150
9700	7800	AH212	160
9800	7800	AH213	140
9900	7800	AH214	160
10000	7800	AH215	360
10100	7800	AH216	220
10200	7800	AH217	150
10300	7800	AH218	93
9000	7700	AH220	39
9100	7700	AH221	22
9200	7700	AH222	62
9300	7700	AH223	61
9400	7700	AH224	110
9500	7700	AH225	87
9600	7700	AH226	93
9700	7700	AH227	61
9800	7700	AH228	100
9900	7700	AH229	65
10000	7700	AH230	23
10100	7700	AH231	110
10200	7700	AH232	100
9100	7600	AH233	36
9200	7600	AH234	48
9300	7600	AH235	50
9400	7600	AH236	52
9500	7600	AH237	38
9600	7600	AH238	74
9700	7600	AH239	110
9800	7600	AH240	66
9900	7600	AH241	74
10100	7600	AH243	66
10100	7600	AH243	66
10200	7600	AH244	100
10200	7600	AH244	100
9300	7500	AH245	8
9400	7500	AH246	58
9500	7500	AH247	48
9600	7500	AH248	59

EASTING	NORTHING	SAMPLE No:	Pb (ppm)
9700	7500	AH249	57
9800	7500	AH250	120
9900	7500	AH251	100
10000	7500	AH252	42
10200	7500	AH254	56
10200	7500	AH254	56
9500	7400	AH255	50
9500	7400	AH255	50
9600	7400	AH256	57
9700	7400	AH257	59
9800	7400	AH258	86
9900	7400	AH259	53
10000	7400	AH260	62
9900	7300	AH261	60
10000	7300	AH262	68
10100	7300	AH263	69
7500	9000	AH500	65
7300	9000	AH501	53
7200	8900	AH502	56.5
7200	8700	AH503	89
7600	8700	AH504	50
7600	8400	AH505	54
10400	8000	AH506	190
10800	8000	AH507	120
11200	8000	AH508	55
11600	8000	AH509	65
12000	8000	AH510	59
10400	7800	AH511	250
11200	7800	AH513	74
11600	7800	AH514	110
12000	7800	AH515	55
10400	7600	AH516	59
11200	7600	AH518	33
11600	7600	AH519	56
11800	7600	AH520	49
11600	7400	AH524	27
12000	7300	AH525	44
11200	7200	AH526	38

EASTING	NORTHING	SAMPLE No:	Pb (ppm)
11600	7200	AH527	32
12400	7200	AH528	44
11600	7000	AH529	30
12000	7000	AH530	31
12400	7000	AH531	31
12800	7000	AH532	18
13200	6900	AH533	33
12000	6500	AH543	29
12800	6600	AH544	31
12400	6500	AH545	23
13200	6500	AH546	25
13600	6500	AH547	24
12800	6300	AH548	29
13200	6300	AH549	25
13600	6300	AH550	23
13200	6100	AH551	50
13600	6100	AH552	20

END

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