EXPLORATION
GEOCHEMISTRY

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TILL GEOCHEMICAL AND INDICATOR MINERAL METHODS IN MINERAL EXPLORATION

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ABSTRACT

This paper summarizes advances during the last decade in the application of glacial sediment sampling to mineral exploration. In these exploration programs, clastic sediments are tested by geochemical or mineralogical methods to detect dispersal trains of mineral deposit indicators that have been transported from source by mechanical processes. In glaciated terrain, the key sampling medium, till, is produced by abrasion, crushing and blending of unweathered rock debris and recycled sediment followed by down-ice dispersal ranging from a few metres to many kilometres. As a consequence of the mid-1980s boom in gold exploration, the majority of case studies and regional till geochemical surveys published in the past decade deal with this commodity. The most profound event in drift prospecting in the last decade, however, has been the early-1990s explosion in diamond exploration, which has dramatically increased the profile of glacial geology and glacial sediment sampling and stimulated changes in sampling and analytical methods. Approximately 20% of Canada and virtually all of Fennoscandia have been covered by regional till geochemical surveys, which aid mineral exploration and provide baseline data for environmental, agricultural, and landuse planning.

INTRODUCTION

In the latter half of this century, mineral exploration by direct inspection of rocks has been increasingly supplemented by methods for the remote detection of ore deposits by geophysical means and by the detection of mineral deposit indicators transported from their sources. Clastic sediments may be processed to recover indicator minerals and analyzed geochemically to detect minerals and the products of their decomposition. In the glaciated terrain of Canada, Fennoscandia, and mountainous areas of South America, an industry has grown around the sampling and analysis of glacial sediments, taking into account the unique characteristics of their composition and transport history. Geochemistry based on sampling of the A or B soil horizons detects elements dispersed by aqueous and gaseous processes, in addition to clastic glacial dispersal. Glacial sediment geochemistry, the subject of this review, refers to the C horizon soil or deeper material that has been affected by clastic dispersal.

This paper summarizes examples which illustrate trends in till geochemistry and indicator mineral research published in the last decade and follows on the previous reviews by Bölviken and Gleeson (1979) at Exploration'77 and by Coker and DiLabio (1989) at Exploration'87. The main sources of information have been conference proceedings: Prospecting in Areas of Glaciated Terrain, Drift Prospecting, and Drift Exploration in the Canadian Cordillera; numerous scientific articles in journals, most notably the Journal of Geochemical Exploration; publications by government agencies; and two books, *Regolith Exploration Geochemistry in Arctic and Temperate Terrains* (Kauranne *et al.*, 1992) and *Glacial Indicator Tracing* (Kujansuu and Saarnisto, 1990). Because of the large volume of material published in the past ten years, in this brief paper, we have been selective in what we have included. Our main objectives have been to highlight advances in sampling and analytical methods, to introduce diamond exploration methods, and to emphasize the significance of regional geochemical surveys to mineral exploration and environmental research. Developments in the understanding of glacial history and ice sheet dynamics applied to drift prospecting are highlighted in a companion paper by Klassen (this volume).

Glacial processes

During the Pleistocene, most recently between 10,000 and 20,000 years ago, nearly all of Canada, the northern USA, northern Europe and alpine areas of South America were glaciated. At high latitudes and altitudes, glaciers frozen to their beds incorporated some debris, but large areas of residuum were left unscathed. In contrast, extensive warm-based glaciers at lower latitudes were far more erosive, especially in high velocity zones known as ice streams, due to the action of basal sliding

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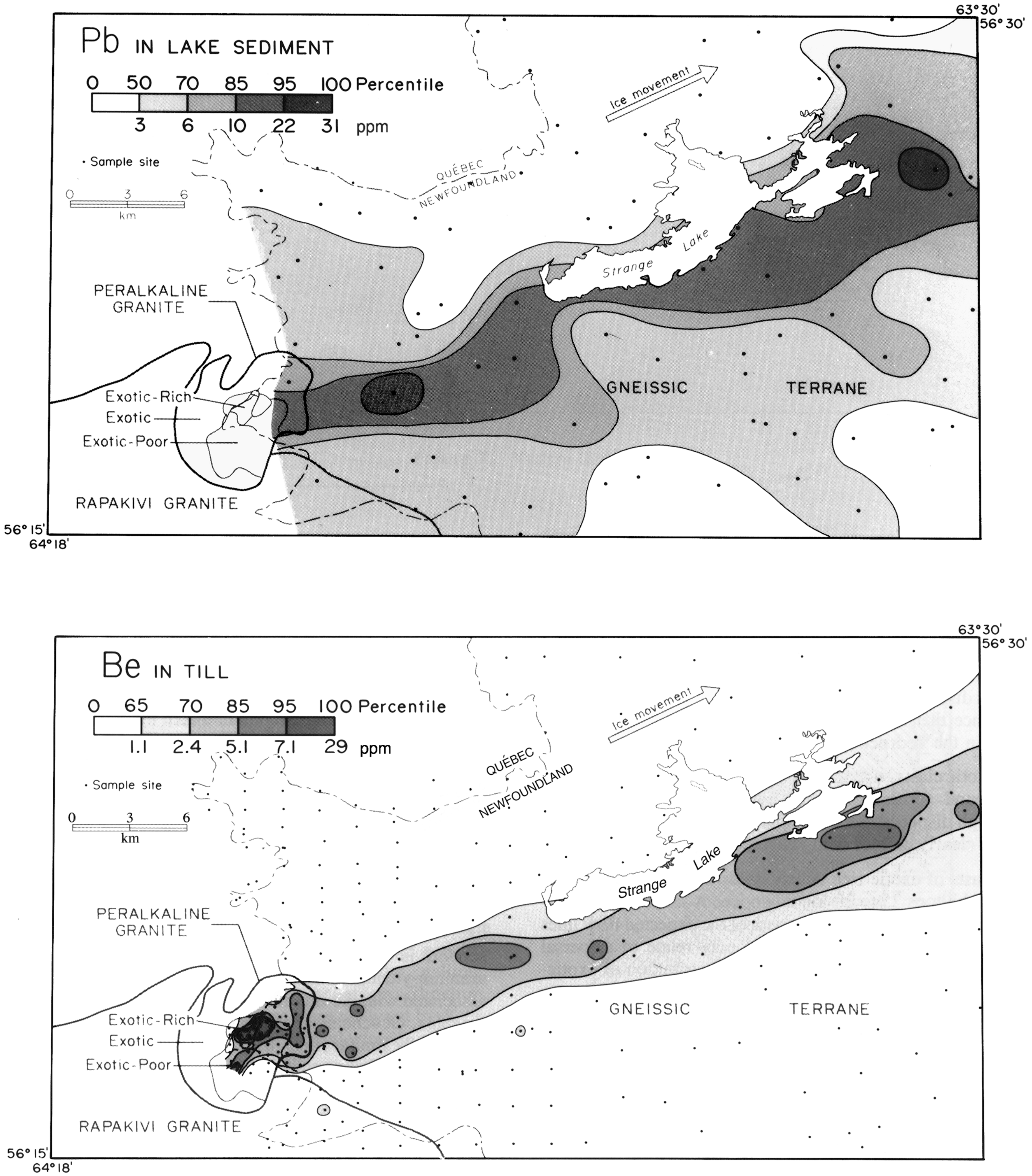

Figure 1: *Ribbon-shaped Strange Lake dispersal train shown by: (**a**) Be in <0.063 mm fraction of till, and (**b**) Pb in the <0.180 mm fraction of lake sediments, Labrador (from Batterson, 1989b).*

which abraded, striated, and plucked bedrock surfaces. Freshly crushed, first-cycle sediment was transported and blended with reworked sediments. The bulldozing and homogenizing action of the ice produced unsorted sediment which is called till, or, in non-genetic descriptions, diamict or diamicton. This mixture of rock and mineral fragments, from boulder- to clay-sized, was plastered onto the bed or released by melting from the ice at its base or surface. Till ranges from clay-rich to sand-rich, depending on the lithology of rock that was abraded and the sediments that were reworked. Till, typically 1 to 10 m thick, ranges from thin, freshly abraded rock debris deposited near source to thick, largely reworked material carried great distances. Glaciofluvial sediments, such as those in eskers and outwash, result from recycling of till by meltwater. The fine fraction washed from these sediments was transported further and deposited as silt and clay in glaciolacustrine or glaciomarine environments. In glaciated regions, modern fluvial sediments are in turn derived from reworked till and glaciofluvial sediments.

Ice flow history

Ice flow patterns are determined from striations on bedrock, striated boulder pavements between tills, the orientation of elongate clasts in till (fabric), till provenance, and glacial landforms (e.g., Liverman, 1992), although the final ice flow phase indicated by geomorphology may differ from dominant sediment transport paths (Lundqvist, 1990; Kujansuu, 1990). The past decade has seen a substantial increase in the recognition of multiple ice flow directions and in the understanding their significance to drift exploration in areas affected by continental ice sheets (e.g., Veillette, 1989; Veillette and McClenaghan, 1996; Klassen and Thompson, 1989, 1993; Stea, 1994; Klassen, this volume) and by alpine glaciation (e.g., Ryder, 1995; Levson and Giles, 1995; Plouffe and Jackson, 1995).

Dispersal trains

Glacial debris eroded from a discrete bedrock source is deposited down-ice in a dispersal train (DiLabio, 1990a; Parent *et al.*, 1996). The thin plume, typically 3 m thick (Averill, 1990), rises down-ice, becoming gradually more dilute. A single ice flow typically produces a ribbon-shaped dispersal train as wide as the bedrock source (Figure 1), whereas a change in ice flow direction reworks the ribbon into a fan shape (Figure 2). Reversal of flow direction produces a stellate or amoeboid dispersal pattern (Stea *et al.*, 1989; Klassen and Thompson, 1989; Shilts, 1993). Dispersal trains are much larger than their bedrock sources, making them easier to find. Till geochemistry, indicator minerals or boulder tracing may be used to detect some part of the dispersal train, which can then be traced back to its head and ultimately its bedrock source. Sampling at spacing of tens of kilometres will define continental-scale trains that are hundreds of kilometres long and consist of distinctive or abundant debris, such as the plume of distinctive erratics and carbonate rocks dispersed south and southwest of Hudson Bay (Shilts, 1996). At the regional scale, a 10 km sample spacing may detect a mineral belt or kimberlite cluster. Local scale sampling, such as 1 km spacing, may detect a mineralized environment or the tail of a train, and small scale spacing at tenths of kilometres may be used to find narrow trains or to test deposit-scale geophysical or geological targets.

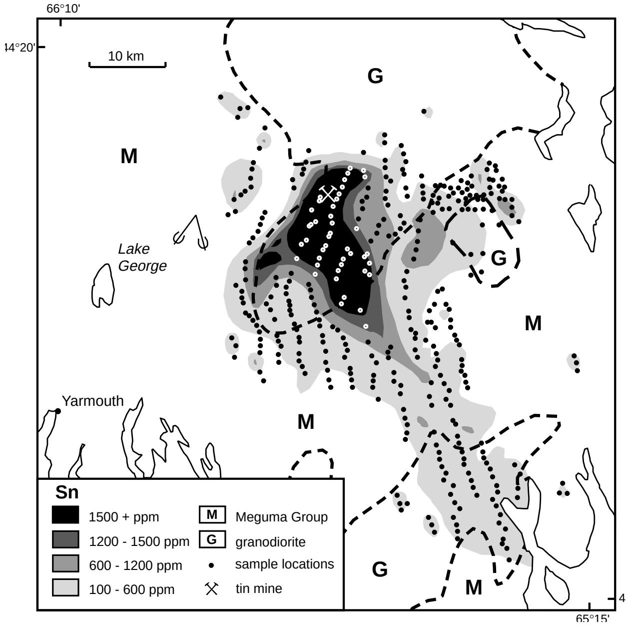

Figure 2: *East Kemptville dispersal train: tin in the sand-size heavy minerals from till. The train has been shaped by southwest and southeast ice flow (modified from Rogers et al., 1990 and Stea et al., 1989).*

Weathering

Postglacial weathering of till has removed labile minerals such as sulphides and carbonates in the oxidation zone above the water or permafrost table, commonly to a depth of a few metres (Shilts and Kettles, 1990; Shilts, 1993, 1996; Thorleifson and Kristjansson, 1993; Kaszycki *et al.*, 1996). Weathering produces a colour change from weathered, brown till at surface to grey, unweathered till at depth. Oxidized till will contain, at best, a few surviving sulphide grains, pseudomorphs after sulphides, or grains coated with Fe and Mn oxides and hydroxides. Weathering has dissolved carbonate to several tens of centimetres depth in carbonate-rich till to several metres in slightly calcareous sediments (Kettles and Shilts, 1989, 1994).

Geochemical partitioning

Minerals grains are physically partitioned into certain size fractions, or terminal modes, by glacial abrasion and crushing. The chemistry of individual size fractions therefore reflects the minerals that dominate each size fraction (Shilts, 1993, 1996). For example, base metals, Au, and PGE have a strong tendency to be concentrated in the fine (<0.06 mm) till fraction (Nevalainen, 1989; Salminen *et al.*, 1989; DiLabio, 1995). Elements which tend to occur in coarser sand-size fractions include Cr in chromite, W in scheelite, and Sn in cassiterite (Shilts and Kettles, 1990; Shilts, 1993, 1995).

In the fine fraction, geochemical variations may reflect glacial processes, provenance, textural differences or weathering (Shilts, 1993). The proportion of clay in the <0.06 mm (silt+clay) fraction may influence metal contents to the degree that elemental concentrations reflect textural changes (Shilts, 1993, 1995; Tarvainen, 1995; Lintinen, 1995).

During weathering, elements may preferentially accumulate in the clay fraction (0.002 mm) because minerals in the clay fraction have large surface area, high exchange capacity and can accommodate wide ranges of ionic radii (Shilts, 1995). Orientation studies are carried out to determine the size fraction of ore minerals in the host rocks, the size fractions to which they are glacially comminuted (terminal grade size) and the size fraction where elements have accumulated during weathering (Nevalainen, 1989; DiLabio, 1995).

FIELD METHODS

Sampling media

Till is used for geochemical and indicator mineral surveys due to its simple transport history, although glaciofluvial sand may be sampled in indicator mineral surveys to obtain a regional overview. Till is found at or near surface in areas of bedrock outcrop away from eskers, and in most streamlined terrain. In areas affected by alpine glaciation, till in moraines may be sampled to test specific portions of up-ice terrain (e.g., Stephens *et al.*, 1990). Frost boils are excellent sampling opportunities for till in permafrost terrain (e.g., Batterson, 1989a; Klassen, 1995; Ward *et al.*, 1996). Glaciofluvial sand is obtained from eskers, braided subaerial outwash, proximal subaqueous outwash, kames, and moraines, or beaches formed on these deposits (Lilliesköld, 1990). The principal criterion for sampling glaciofluvial sediments, in most cases, should be the presence of medium to very coarse sand and some gravel, to obtain sediment usable for indicator minerals and to avoid eolian and littoral deposits. Mineralized boulder trains are mapped and sampled in conjunction with sediment sampling (e.g., Steele, 1988).

Sample size

As little as 200 g (0.1 litre) of till, the sample size returned by portable drills, may suffice for geochemical analysis. Where sampling methods permit, however, at least 1 kg (~0.5 litre) of till should be collected for geochemical analysis of the <0.06 mm fraction, and possibly the <0.002 mm fraction, and for archiving. For heavy mineral geochemistry and indicator mineral analysis, at least 10–20 kg (~5-10 litres) of sediment, or more where the till is silty or clayey, are required (Clifton *et al.*, 1969; Averill, 1990).

Site layout

Regional geochemical surveys, designed to aid mineral exploration by determining background trends in regional geochemistry, and determining sediment provenance, use sample spacing of 1–50 km to obtain an overview of an area. In mineral exploration, elongate dispersal trains are most likely to be intersected by a series of transects perpendicular to ice flow, with sample spacing along lines (10 m to 1 km) much shorter than the space between lines (100 m to 100 km). Spacing will depend on the area tested, the size of the deposit or cluster sought, the style of glacial dispersal in the area, sampling medium, and analytical methods. Less sensitive methods, such as the fine fraction geochemistry rather than heavy mineral geochemistry or indicator minerals, may be compensated for by closer sample spacing (Averill, 1990).

Sampling methods

Sampling procedures used in glaciated terrain have been summarized by Hirvas and Nenonen (1990), Kauranne *et al.* (1992), McClenaghan (1992, 1994) and Plouffe (1995a). In areas of thin glacial sediments or where till outcrops at surface, samples can be collected from hand-dug holes, backhoe excavator trenches, natural sections along river or lake shorelines or road cuts. Where glacial sediment thickness exceeds 5 m, drilling is required to access till below the surface cover of other sediments, to characterize the till stratigraphy and to determine lateral and vertical variations in till geochemistry. Availability and cost are major factors in the choice of drilling method (Coker and DiLabio, 1989; Coker, 1991). Reverse circulation drills recover a slurry of cuttings up to 1 cm in size down to and into bedrock (Averill, 1990). The more expensive rotasonic drilling method produces 8 cm diameter continuous core of glacial sediments and bedrock, enabling much more detailed geological observations and sampling (Averill *et al.*, 1986; Averill, 1990). Auger and percussion drills recover small sediment and rock samples. Diamond drills will core hard, fine-grained till with the aid of drilling fluids, but sand intervals are lost. Portable drills are useful for recovery of small, disturbed geochemical samples where boulders do not intervene (Kauranne *et al.*, 1992; Hartikainen and Nurmi, 1993). Brass fittings, diamond drill bits, and tungsten-carbide drill bits can contaminate heavy mineral fractions, and drilling grease can contaminate geochemical samples with Zn, Pb and Mo (Averill *et al.*, 1986). All till and glaciofluvial sediments in a drilled sequence should be sampled because dispersal trains may be intersected at any depth (McClenaghan, 1994), and because corroboration by vertically adjacent samples is a key to confirming an anomaly (Averill, 1990).

LABORATORY METHODS

Sample preparation

Indicator mineral samples are usually 10–20 kg (~5-10 litres) in size, of which small 500 g (~0.25 litre) subsamples may be set aside for geochemistry and archiving (Figure 3). The remaining material is disaggregated, typically by agitation in a dispersant and the gravel fraction (>2 mm) is removed for lithological analysis (pebble counts). The <2 mm fraction is then pre-concentrated using density methods (e.g., jig, table, spiral, dense media separator, or pan). Density pre-concentration may be combined with the use of an inexpensive heavy liquid such as tetrabromoethane, prior to final concentration. Screening to recover the medium to very coarse sand-sized fraction may be used instead of density preconcentration at this stage, if recovery of gold and sulphide grains is not a priority. Final density concentration is completed using heavy liquids such as methylene iodide diluted with acetone or a magstream separator using a threshold of about 3.2 specific gravity to ensure more complete recovery of Cr-diopside (e.g., McClenaghan *et al.*, 1996). The ferromagnetic fraction is removed using a hand magnet or roll separator, weighed and archived. The non-ferromagnetic heavy mineral concentrate is then examined for indicator minerals and sometimes analyzed geochemically (Figure 3). Scheelite and zircon may be counted under short-wave ultraviolet light. Kimberlite indicator minerals are picked from samples during a visual scan, in most cases, of the 0.25–0.5 mm and 0.5-2.0 mm fractions. Depending on regional mineralogy, paramagnetic sorting may be required, especially for the 0.25–0.50 mm fraction, in order to reduce the number of grains to be scanned. Picking of a concentrate may take 0.1 to 1 hour, and a few to several dozen grains may be picked. Gold grains may be intercepted for morphological analysis at two stages of processing; the grains may be panned, counted, and classified with the aid of optical or scanning electron microscopy after density pre-concentration (Figure 3) or concentrates may be examined after nondestructive geochemical analysis using the Au results as a guide (Figure 3).

The 500 g geochemical subsamples are dried below 40°C, to prevent the loss of volatile elements such as Hg, and sieved using stainless steel screens to recover specific size fractions for geochemical analysis (Figure 3). Averill (1990) noted the tendency for gold grains to pass through sieves preferentially, implying that thorough screening of a split, rather than the rapid recovery of a small portion, is advisable. Centrifuging is used to recover the clay-sized fraction (<0.002 mm) for geochemical analysis (Lindsay and Shilts, 1995).

Geochemical analysis

The choice of size fraction and analytical methods depends on the commodity sought, its mineral form and the weathering history of the source and glacial sediments. In the last decade, many studies have used the <0.06 mm till fraction for gold exploration (e.g., Pronk and Burton, 1988; Toverud, 1989; Äyräs, 1991; Lestinen *et al.*, 1991; Koljonen, 1992; Hartikainen and Nurmi, 1993; Sibbick and Kerr, 1995; Cook *et al.*, 1995). Other studies have recommended analysis of both the heavy mineral and fine till fractions (Makela *et al.*, 1988; Campbell and Schreiner, 1989; Chapman *et al.*, 1990; McClenaghan, 1992, 1994; Bloom and Steele, 1989) in order to detect both fine- or coarse-grained gold and because the heavy mineral fraction may provide better contrast between background and anomalous samples (Brereton *et al.*, 1988; Bernier and Webber, 1989; Gleeson *et al.*, 1989). Although expensive to recover, several geochemical surveys analyzed the <0.002 mm fraction of till (e.g., Steele, 1988; Kettles, 1992; Kaszycki *et al.*, 1996) because of its greater capacity to retain elements released during weathering and to avoid textural bias on geochemistry. Other fractions less commonly analyzed geochemically, include heavy minerals (e.g., Glumoff and Nikkarinen, 1991; McClenaghan, 1992, 1994; Thorleifson and Kristjansson, 1993) and the <2 mm whole till (e.g., Bloom and Steele, 1989; Tarvainen, 1995).

Geochemical methods commonly used to analyze glacial sediments are summarized by Hall (1991), Koljonen (1992), Kauranne *et al.* (1992), and Lett (1995). Most exploration programs and regional geochemical surveys use partial digestions such as aqua regia (Koljonen

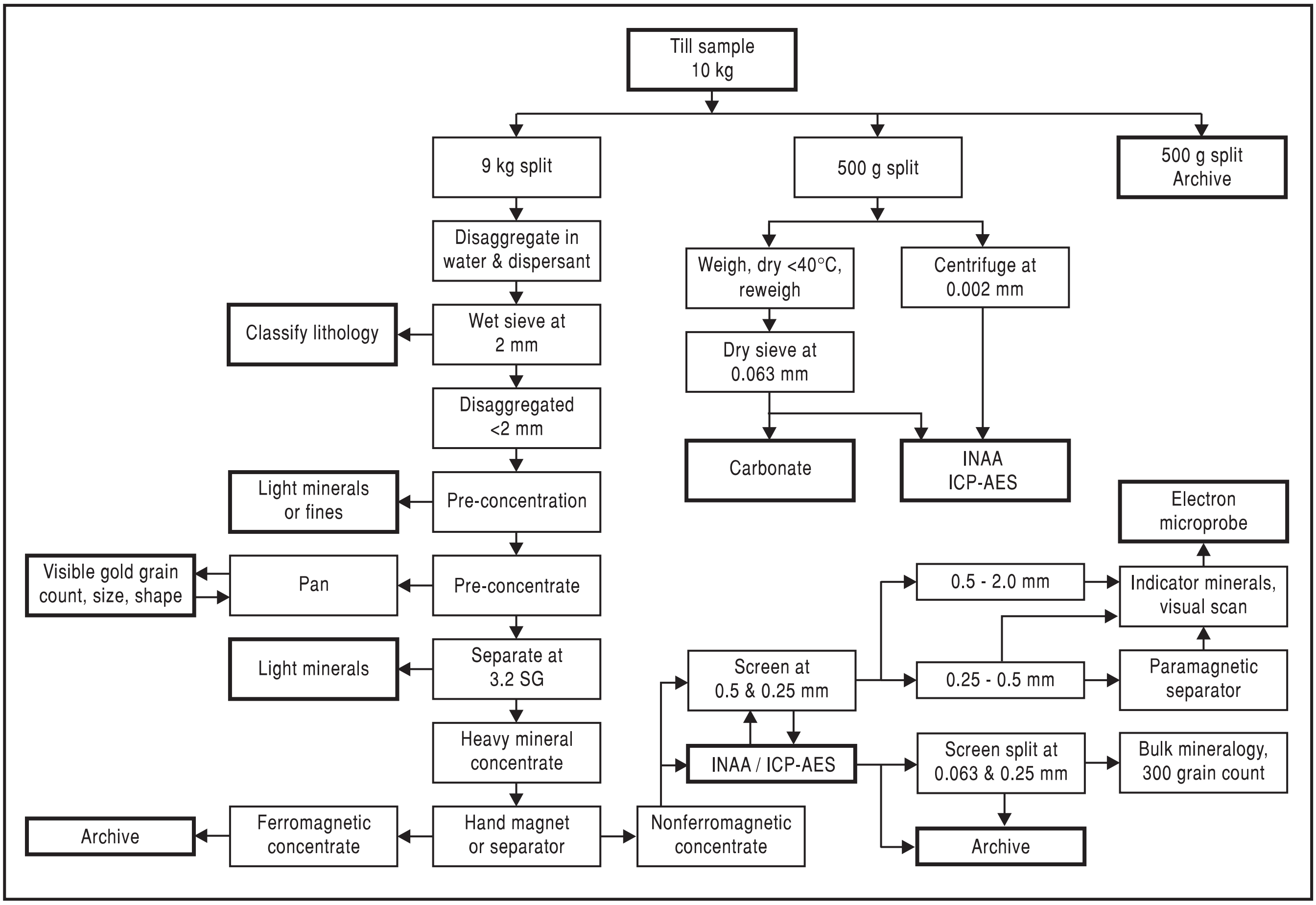

Figure 3: *Generalized glacial sediment sample processing flow chart for geochemical and indicator mineral applications.*

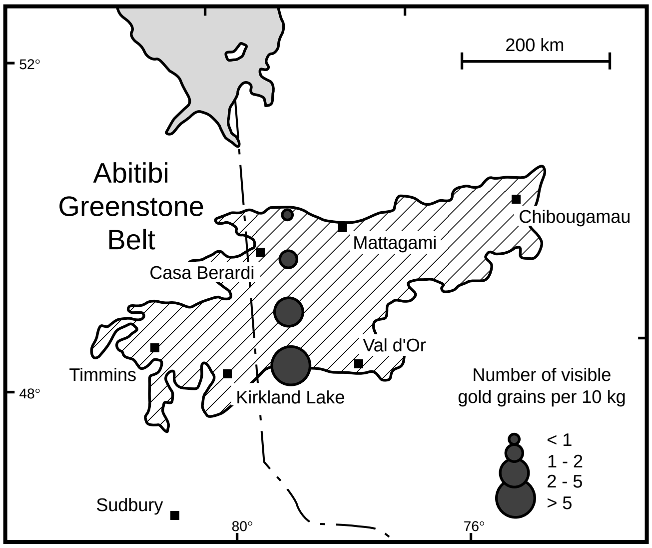

Figure 4: *Southward-increasing background concentrations of native gold grains in till across the Abitibi Greenstone Belt (modified from Averill and Huneault, 1991).*

and Malisa, 1991), although some regional surveys in Fennoscandia have used both total and partial digestions to investigate variable element solubility as it relates to rock type and degree of weathering (Koljonen, 1992; Tarvainen, 1995; Lahtinen *et al.*, 1993). Regional surveys use instrumental neutron activation analysis (INAA) and inductively coupled plasma emission spectrometry (ICP-ES) for 30+ elements to provide extensive and complimentary analytical data for the fine till fraction. Certain elements, however, require specialized techniques. Mercury is commonly determined using cold vapour–atomic absorption spectrometry (CV-AAS), platinum group elements (PGE) and Au are determined by fire assay followed by GF-AAS, ICP-AES or DCP-AES, and major oxides are determined by XRF or ICP-ES. Heavy mineral concentrates are analyzed best by non-destructive INAA and, in the case of unoxidized sediments, a small representative split may be analyzed for base metals by aqua regia/ICP-AES. The use of destructive methods for heavy mineral concentrates, such as fire assay, is strongly discouraged, to permit storage of concentrates for future mineralogical analysis. A project geologist must be able to vouch for the reliability of data without reliance on trust of the laboratory. Ten to fifteen percent of each analytical batch should comprise in-house and certified geological reference materials, as well as field and post-preparation duplicates to monitor analytical accuracy and precision.

Geochemical analysis of as little as 0.5 g of sediment can be used to identify gold pathfinder elements, such as As, Sb, S, Cu, Bi, and Co, which are usually more evenly distributed and more abundant than gold itself (e.g., Brereton *et al.*, 1988; Saarnisto *et al.*, 1991; Hartikainen and Nurmi, 1993; Sibbick and Kerr, 1995). Unusually high or low levels of major elements in till also may act as pathfinders because they can indicate metasomatic alteration in bedrock, e.g., gold mineralization (Hartikainen and Damsten, 1991). For analysis of Au, a large aliquot (~30 g) of the fine fraction or a heavy mineral concentrate is required.

Indicator mineral analysis

Indicator minerals include gold, sulphides, scheelite, cassiterite, zircon, minerals from kimberlite, and minerals derived from metamorphosed sulphide deposits. These grains are recovered from heavy mineral concentrates and visually examined to obtain information on glacial transport directions and distances and chemically analyzed to confirm their identification and provide insight into their bedrock source (e.g., Perttunen and Vartiainen, 1992; Peuraniemi, 1990; Peltonen *et al.*, 1992; Hornibrook *et al.*, 1993). The most common indicator minerals used in drift exploration, gold and kimberlite indicator minerals, are discussed below.

Gold grains

In Canada, gold grains are routinely recovered from till samples and examined to determine their abundance, size and shape, to detect dispersal trains from gold deposits and to predict the size, grade and character of the bedrock mineralization (Averill, 1990). The degree of rounding, polishing and bending of the gold grains in till can provide information about glacial transport distance. DiLabio (1990b) proposed a graphically descriptive classification scheme (pristine-modified-reshaped) for describing shapes and surface textures of gold grains that builds on Averill's (1988) descriptions of gold grain shape related to glacial transport distance. Henderson and Roy (1995) demonstrated that gold grain shape is not always a reliable reflection of glacial processes and transport and cautioned against a simplistic use of this approach. Gold grain shape, abundance and fineness (Au/Ag ratio) in glacial sediments may be compared to what is found in mineralized rock (Nikkarinen, 1991; Grant *et al.*, 1991; Huhta, 1993). Exploration programs (Brereton *et al.*, 1988; Chapman *et al.*, 1990) and regional till surveys in Canada (e.g., McClenaghan, 1992, 1994; Thorleifson and Kristjansson, 1993; Bajc, 1991, 1996; Plouffe, 1995b) routinely report gold grain abundance in the <2.0 mm heavy mineral fraction of 10 kg till samples. In contrast, few studies in other countries (Huhta, 1988, 1993) have systematically examined gold grains in till. Averill and Huneault (1991) have determined background values of gold grains in till for parts of Canada. In the Abitibi Greenstone Belt, for example, background values increase from north to south along the general direction of ice flow, from <1 grain per 10 kg of till at the north edge to >5 gold grains per 10 kg at the south edge (Figure 4).

Kimberlite indicator minerals

Several minerals are useful indicators of kimberlite, and to a certain extent, in evaluation of the diamond potential of kimberlite. These minerals survive glacial transport, are far more abundant in kimberlite than diamond is, and are visually and chemically distinct. Cr-pyrope, eclogitic garnet, Cr-diopside, Mg-ilmenite, Cr-spinel, and olivine are the most commonly used kimberlite indicator minerals, although in rare cases, diamond is abundant enough to be its own indicator. Kimberlite indicator minerals are recovered from the medium to very coarse sand-sized fraction of glacial sediments, and analyzed by electron microprobe to determine concentrations of major oxides (e.g., Fipke *et al.*, 1989, 1995; Ward *et al.*, 1996; Garrett and Thorleifson, 1996; McClenaghan *et al.*, 1996). Kimberlites typically contain large concentrations of garnets from peridotitic rocks and a few from eclogitic rocks. Peridotitic garnets are subdivided on the basis of Ca content into wehrlitic (high Ca), lherzolitic and harzburgitic (low Ca) affinities. Most garnet inclusions in diamonds have low-Ca harzburgitic composition (see Figure 13, Fipke *et al.*, 1995) and thus these garnets are sought in diamond exploration (Fipke *et al.*, 1989, 1995). Other chemical criteria include Na_2O levels in eclogitic garnet (Figure 17, Fipke *et al.*, 1995) and MgO and Cr_2O_3 concentrations in ilmenites to determine probability of diamond preservation (McCallum and Vos, 1993). Cr-spinel with >60% Cr_2O_3 and >12% MgO (Figure 14, Fipke *et al.*, 1995) are judged to have a diamond inclusion composition (Fipke *et al.*, 1989), and diopsides with >0.5% Cr_2O_3 are classified as Cr-diopside (Deer *et al.*, 1982; Fipke *et al.*, 1989).

TILL GEOCHEMISTRY

Regional geochemical surveys

In the last decade, the bulk of published literature on till geochemistry relates to regional till geochemical surveys conducted in Fennoscandia and Canada. The development of inexpensive and rapid multi-element geochemical analysis has broadened the application of geochemical surveys to a wide range of commodities and to other disciplines such as environmental or agricultural research (DiLabio, 1989; Fortescue, 1991; Koljonen, 1992). Finland has been well covered by till surveys at varying scales (e.g., Nevalainen, 1989; Vallius, 1992, 1993; Salminen, 1995; Gustavsson *et al.*, 1994; Salminen and Tarvainen, 1995; Tarvainen, 1995), which have resulted in the comprehensive Till Geochemical Atlas of Finland (Koljonen, 1992). In contrast to Fennoscandia, only 20% of Canada has been covered by till geochemical surveys with an emphasis on evaluating the mineral potential of favorable geological terranes, such as the precious and base metal potential of Archean greenstone belts (e.g., McClenaghan, 1992, 1994; Thorleifson and Kristjansson, 1993; Kaszycki *et al.*, 1996; Bajc, 1991, 1996), the Cordillera (Cook *et al.*, 1995; Plouffe and Jackson, 1995) and the Appalachians (Pronk and Burton, 1988; Stea *et al.*, 1989; Turner and Stea, 1990; McClenaghan and DiLabio, 1993, 1996; Klassen and Thompson, 1993; Klassen and Murton, 1996), and the diamond potential of Archean cratons (Ward *et al.*, 1996; Garrett and Thorleifson, 1996; McClenaghan *et al.*, 1996). In these areas, Quaternary mapping and studies of ice flow history were carried out in conjunction with geochemical surveys to provide a framework for the interpretation of geochemical data. Some programs have been conducted as regional multimedia surveys (e.g., Kaszycki *et al.*, 1996; Cook *et al.*, 1995; Bajc *et al.*, 1996; Salminen and Tarvainen, 1995). For the Nordkalott Project, till, stream sediments, stream organic matter and stream moss were collected north of 66° in Finland, Sweden and Norway (Bölviken *et al.*, 1986; Bölviken *et al.*, 1990; Steenfelt, 1993). Subsequently, an ultra low density multimedia survey of Fennoscandia was conducted to evaluate media for global geochemical mapping and the usefulness of extremely low (1 site per 23 000 km^2) sampling densities, including till (Edén and Björklund, 1995), overbank (flood plain) sediments, humus and river water. Multimedia geochemical surveys of Finland have been published as a series of geochemical atlases for till (Koljonen, 1992), groundwater (Lahermo *et al.*, 1990) and stream water and sediments (Lahermo *et al.*, 1996). Multimedia geochemical patterns for Zn in Finland are shown in Figure 5 to highlight the variety of geochemical information now available and to emphasize the variable geochemical distribution in each medium (Salminen and Tarvainen, 1995).

During the last decade, the numerous geochemical surveys of Fennoscandia and Canada have dramatically increased our knowledge of the regional distribution, composition and origin of till, established regional backgrounds, identified geochemical anomalies, and documented the effects of weathering on till geochemistry. The greatest challenge to drift exploration in Canada continues to be in areas of thick glacial sediments consisting of multiple tills related to complex ice flow, such as the Abitibi Greenstone Belt. Bajc (1991) and McClenaghan (1994) demonstrated that mineral exploration in these areas is possible by conducting three-dimensional till geochemical surveys in conjunction with studies of regional till stratigraphy and ice flow patterns.

Case studies

Several geochemical studies have been conducted around gold deposits to document the nature of gold dispersal in till (e.g., Sibbick and Fletcher, 1993; Huhta, 1993) with fewer papers on other commodities such as PGE (Coker *et al.*, 1990; 1991; Cook and Fletcher, 1993, 1994; DiLabio, 1995), base metals (Hoffman and Woods, 1991), and tungsten (Coker *et al.*, 1988a). At Farley Lake, Manitoba, for example, Brereton *et al.* (1988) detected gold dispersal patterns at least 300 m down-ice from an iron-formation-hosted gold deposit. Sibbick and Kerr (1995) detected glacial dispersal up to 5 km down-ice from the Mount Milligan porphyry Cu-Au deposit in central British Columbia. Bell and Franklin (1993) and Bell and Murton (1995) have demonstrated that lead isotope ratios of glacial sediments can be used to detect glacial dispersal from volcanogenic massive sulphide (VMS) deposits. Several orientation studies have compared geochemical responses of till to soil, vegetation, lake sediments and water or stream sediment and water around known mineral occurrences in order to evaluate the relative effectiveness of various media in mineral exploration. Geochemical responses in the till reflect clastic dispersal of the ore while the response in the other media reflects the ore zone, and in some cases the dispersal train (e.g., Ford *et al.*, 1988; Coker *et al.*, 1990, 1991; Peuraniemi, 1991; Cook and Fletcher, 1993, 1994; MacDonald and Boner, 1993). For example, the Strange Lake Zr-Nb-Y-Be-REE deposit in northern Labrador has a 6 km wide and 40 km long dispersal train trending down-ice from the deposit that is detectable using till geochemistry (Figure 1), airborne gamma ray spectrometry, boulder mapping, lake sediment (Figure 1) and water geochemistry, and stream sediment and water geochemistry (McConnell and Batterson, 1987; Batterson, 1989a,b). Clastic glacial dispersal of ore from the East Kemptville tin deposit in Nova Scotia is well defined by tin anomalies in till (Figure 2) and lake sediments (Rogers and Garrett, 1987; Rogers *et al.*, 1990) as well as airborne gamma ray spectrometry (Boyle, 1988). At the Mill Shaft gold occurrence in Nova Scotia, gold in till, B horizon soil and red spruce bark define a 100 m wide, 3 km long dispersal train (Figure 6) trending southeast from the ore zone (Coker *et al.*, 1988b; Dunn *et al.*, 1991). In contrast to most papers that describe multimedia studies around known mineral deposits, Chapman *et al.* (1990) used till and soil geochemistry to follow up a lake sediment anomaly and discover the Bakos gold deposit in Saskatchewan.

DIAMOND EXPLORATION

Diamond exploration in glaciated terrain differs from precious or base metal exploration in that it uses indicator minerals and boulders, instead of till geochemistry, to detect glacial dispersal from a kimberlite. Kimberlites are small (few hundred metres across), circular point sources. They are relatively soft rocks that have been preferentially eroded by preglacial weathering and glacial scouring to deeper levels than the surrounding bedrock surface and as a consequence are covered by lakes or thick glacial sediments (Figure 7). Recent discoveries of kimberlite on the Canadian Prairies and in the Northwest Territories (Pell, 1997) have sparked unprecedented levels of diamond exploration in Canada and Finland. Several short course notes, government reports and books provide comprehensive background information on kimberlite genesis, tectonic setting, mineralogy, geophysical characteristics, and glacial sediment sampling methods, that are essential to understanding kimberlite exploration in glaciated terrain (e.g., Mitchell, 1986; DiLabio and Thorleifson, 1993; Sheahan and Chater, 1993; Averill and McClena-

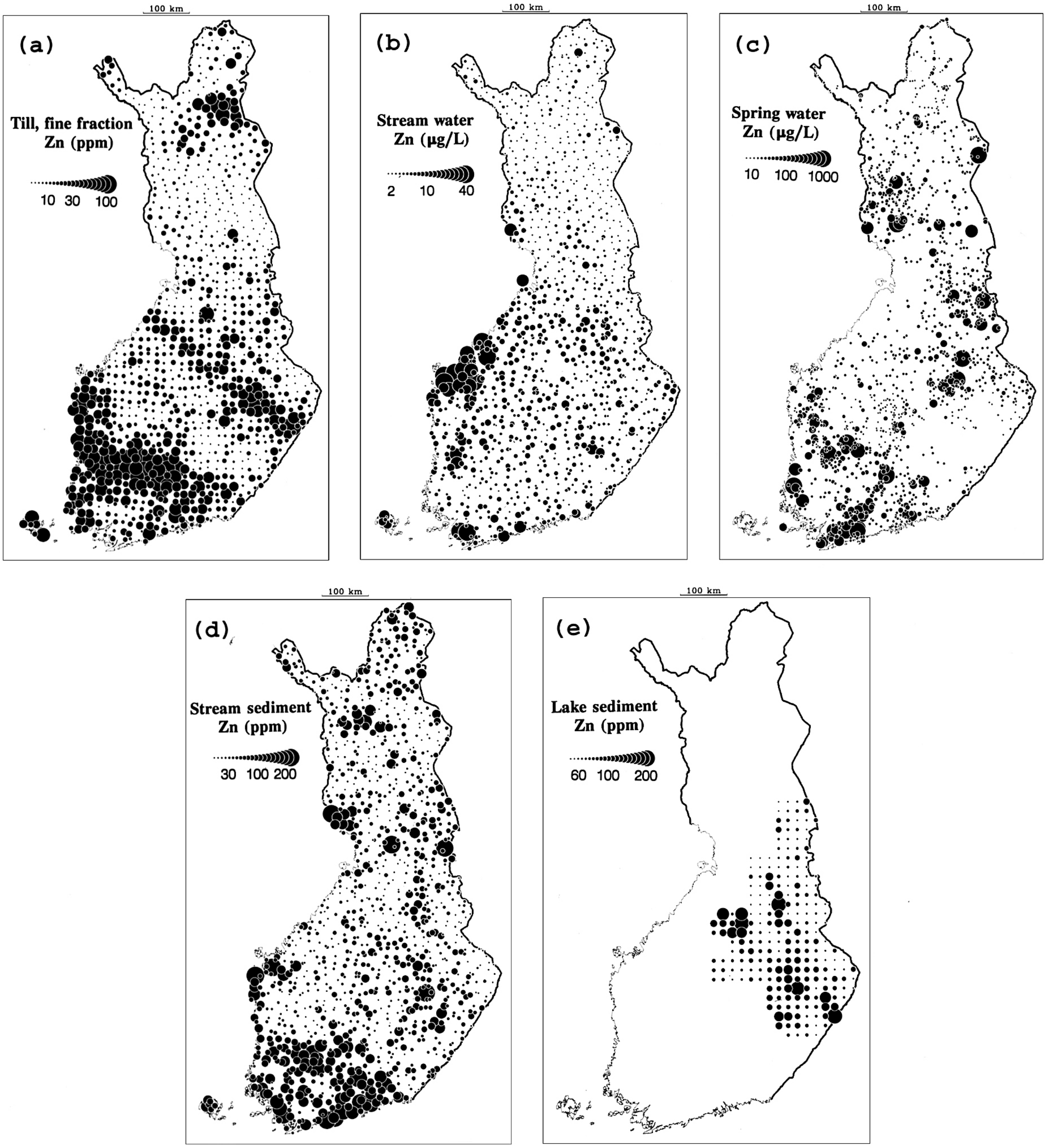

Figure 5: *Zinc concentrations in sample media from regional geochemical surveys of Finland: (**a**) <0.06 mm till; (**b**) stream water; (**c**) groundwater from natural springs; (**d**) organic stream sediments; (**e**) organic lake sediments (from Salminen and Tarvainen, 1995).*

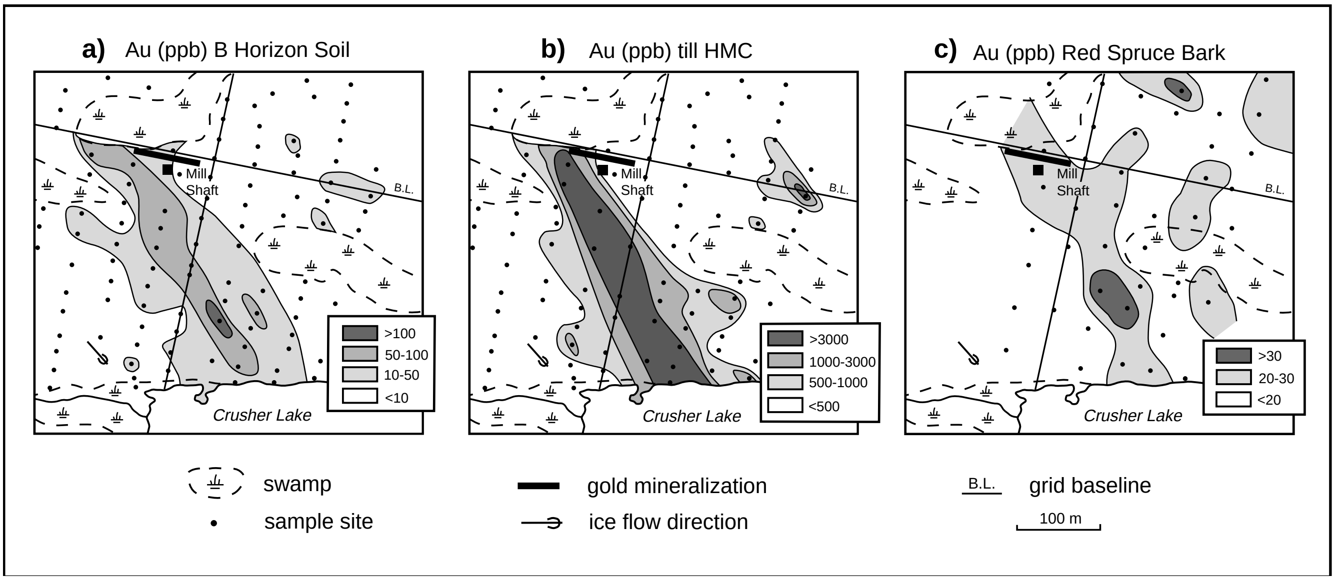

Figure 6: *Gold concentrations in B horizon soil developed on till, heavy minerals in C-horizon till, and red spruce bark at the Mill Shaft gold occurrence, Nova Scotia (modified from Dunn et al., 1991).*

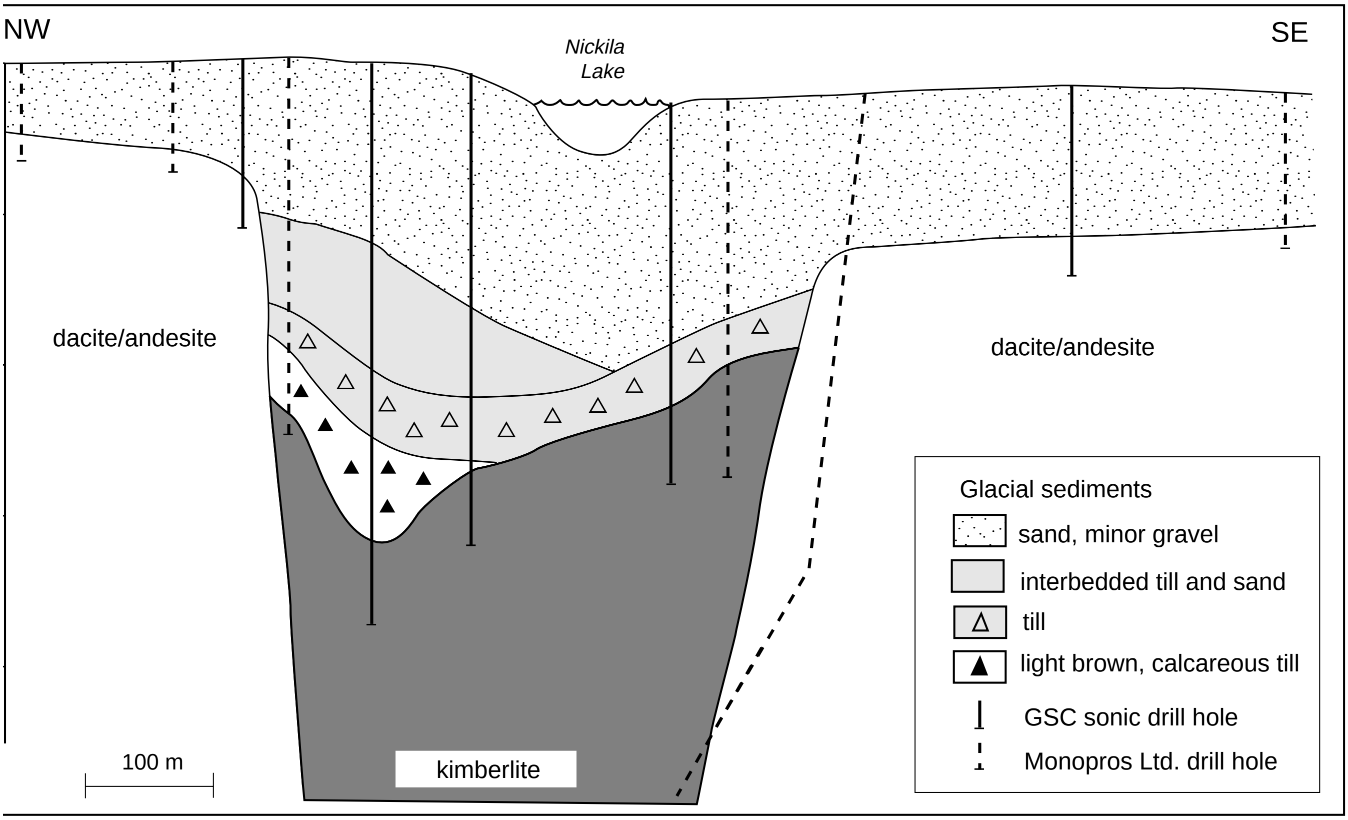

Figure 7: *Schematic north-south cross-section over the B30 kimberlite pipe at Kirkland Lake, Ontario, showing a deep level of erosion and thick glacial sediment cover (from McClenaghan et al., 1996).*

ghan, 1994; Helmstaedt *et al.*, 1995; McClenaghan, 1996; Ward *et al.*, 1996; Morris and Kaszycki, 1997).

Recently published results of regional indicator mineral distributions in various parts of Canada have allowed exploration companies to place their local, more detailed survey results into the broader, regional context. In the Lac de Gras area, where Canada's first diamond mine will go into production in 1998, regional indicator mineral surveys have been completed over an area of 30 000 km^2. A large train of pyrope (Figure 8) and Cr-diopside, 50 km wide and 100 km long, trends northwest from the western part of the Lac de Gras field of approximately 150 kimberlite pipes, parallel to the direction of the main phase of Late Wisconsinan ice flow (Ward *et al.*, 1996; Dredge *et al.*, 1997). The east half of the kimberlite field does not have an indicator mineral signature in the till. Pyrope is the most abundant indicator mineral, followed in decreasing abundance by Cr-diopside, Cr-spinel and Mg-ilmenite (Dredge *et al.*, 1997). Till samples that contain more than five sand-sized pyrope grains in a 10 kg till sample are considered anomalous. Dispersal trains from individual kimberlite pipes within the Lac de Gras field are typically narrow (hundreds of metres), sharp-edged linear ribbons that extend several tens of kilometres down-ice and reflect the relative abundance of indicator minerals in individual pipes. The Strange Lake dispersal train (Batterson, 1989a), although from a larger point source, is a good analogue for the ribbon-shaped kimberlite trains that have been reported in the Lac de Gras region (Figure 1). On the Canadian Prairies, elevated pyrope concentrations in till in western and southwestern Saskatchewan are derived from kimberlites in central Saskatchewan and reworked from Tertiary gravels (Garrett and Thorleifson, 1996). In the Kirkland Lake kimberlite field of northeastern Ontario, eskers contain pyrope and kimberlite boulders several kilometres down-ice (Brummer *et al.*, 1992a,b). Detailed glacial dispersal studies have been completed around the Kirkland Lake kimberlites (Averill and McClenaghan, 1994; McClenaghan *et al.*, 1996; McClenaghan, 1996).

Golubev (1995) classified pyrope and Cr-spinel dispersal patterns in Russia as: 1) short-distance, <3 km from source and usually detected in till; 2) long-distance, 10-15 km from source and usually found in glaciofluvial sediments; and 3) detached, unknown distance to source as they have lost their relationship to primary source and usually found in glaciofluvial outwash and modern beach sediments. Indicator minerals are most abundant in the 0.25 to 0.5 mm (medium sand) size fraction of glacial sediments (Averill and McClenaghan, 1994; Dredge *et al.*, 1997; Garrett and Thorleifson, 1996). In contrast to unglaciated regions, all kimberlite indicator minerals survive long distance glacial transport, and the relative abundances of each mineral in a till sample is a function of the

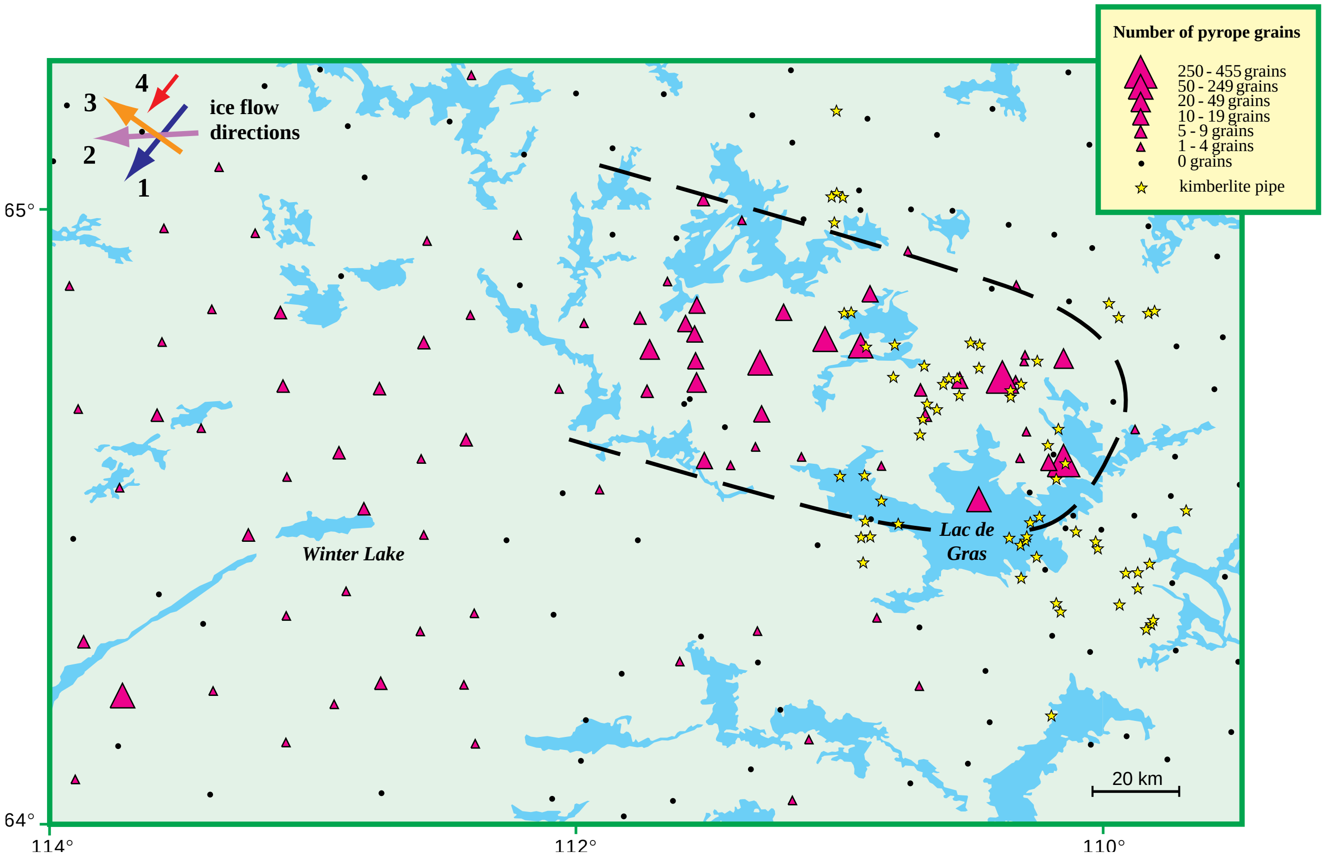

Figure 8: *Distribution and abundance of pyrope in 10 kg till samples in relation to known kimberlite pipe locations in the Lac de Gras region, Northwest Territories. Dashed black line outlines main dispersal train trending northwest. Regional ice flow directions are indicated by the arrows in the top left corner (modified from Dredge et al., 1997).*

primary mineralogy of individual kimberlite pipes. Surface features and morphology of indicator minerals may provide clues as to the distance and nature (glacial versus fluvial) of their transport (McCandless, 1990; Averill and McClenaghan, 1994; Golubev, 1995; Dredge *et al.*, 1996).

APPLICATIONS TO ENVIRONMENTAL RESEARCH

Environmental policies must be based on a knowledge of the natural concentrations of metals and of the natural processes that affect these levels. Till geochemical surveys play important roles in the identification of areas of naturally high metal levels, the development of strategies for remediation and land use management and in addressing issues such as acid rain (Kettles *et al.*, 1991; Kettles and Shilts, 1994), natural versus anthropogenic sources of mercury (Henderson and McMartin, 1995; Plouffe, 1995c) and acid mine drainage (Dyer *et al.*, 1996). Till geochemistry is well suited to address these issues because C horizon till is collected below the depth of obvious anthropogenic effects (Koljonen, 1992; Edén and Björklund, 1995). The Fennoscandian geological surveys (Bölviken *et al.*, 1986, 1990; Edén and Björklund, 1995) have taken the lead by conducting systematic geochemical surveys of their entire countries in support of both mineral exploration and environmental research (Koljonen, 1992; Hari *et al.*, 1991; Nikkarinen *et al.*, 1996) and by evaluating the effectiveness of low density till sampling and of till as the medium.

CONCLUSIONS

- Rapid and inexpensive multi-element geochemical techniques combined with improved and more readily available indicator mineral methods now allow glacial sediment sampling to evaluate the potential of a region to host several mineral deposit types including precious and base metals, tin, tungsten, REE and diamonds.
- Application of indicator mineral methods to diamond exploration in glaciated terrain has intensified in the past five years. Diamond exploration in Russia, Finland and Canada uses established sample collection and processing methodologies and is based on an advanced knowledge of indicator mineral chemistry.
- In the last decade, analysis of glacial sediments for gold has improved significantly because of the increased ability to use larger analytical aliquots to avoid the nugget effect, the understanding of partitioning in various size fractions and the ability to analyze for gold using a variety of analytical techniques. Gold grain methods are widely used in Canada, with more refined morphologic classification and smaller grain sizes recovered.
- Case studies around known mineral deposits continue to be crucial sources of information on the geochemical and mineralogical signatures of deposits, on appropriate sampling, and on analytical methods and ice flow patterns.
- During the last decade, regional till surveys conducted in Fennoscandia and Canada have dramatically increased our knowledge of the distribution, composition and origin of till, especially in areas covered by thick glacial sediments, such as the Abitibi Greenstone Belt. This knowledge has had a significant impact on survey design and sampling and analytical methods used in mineral exploration programs.
- Areas affected by alpine glaciation where valleys are filled with thick glacial sediments continue to be an obstacle to mineral exploration because of the lack of case histories and regional surveys.
- Regional geochemical data also can be used to outline areas of natural enrichment or depletion of noxious trace elements as they relate to environmental, agricultural, geomedical and other uses which might not have been considered when the surveys were originally designed.
- Case histories and regional till survey results from private sector exploration programs are noticeably absent from the literature. This shortfall can be remedied by cooperative research between exploration companies and government surveys. Such efforts will directly benefit the exploration companies and at the same time provide new information on regional Quaternary geology and ice flow history.
- Of all the sampling media available for mineral exploration in glaciated terrain, including till, soil, water, lake, stream and overbank sediments, C horizon till continues to have the broadest potential. It also is ideal for environmental studies because it is least affected by anthropogenic and biologic factors, and as such, most closely represents natural element concentrations.

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