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Basic indicator mineral math: Why visual analysis of the entire heavy mineral fraction of large sediment samples is required on indicator mineral exploration programs in glaciated terrains

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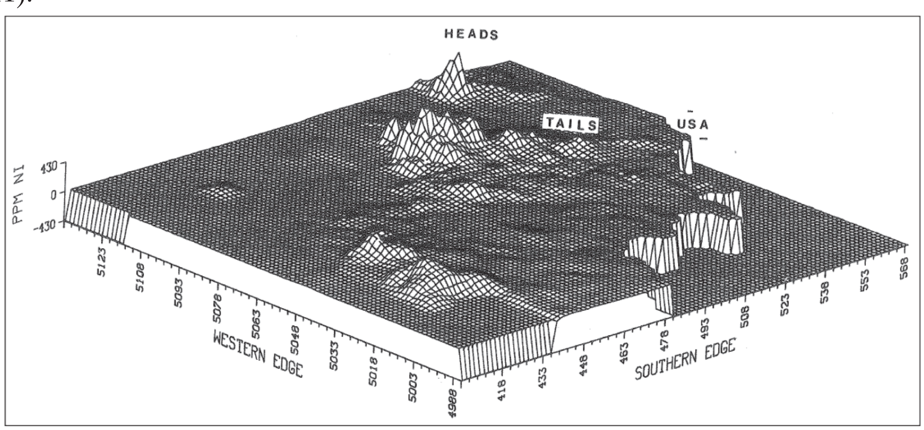
Introduction

Mineral exploration in Canada has become increasingly reliant on identifying and tracing to a bedrock source anomalous concentrations of dispersed indicator mineral grains in till and, to a lesser degree, in glaciofluvial and alluvial gravel. Gold grains, for example, have been employed successfully in many exploration programs (*e.g.* Averill 1988, 2001, 2013, 2015) since the watershed discovery in northern Quebec in 1984 of the Casa Berardi gold deposits by following gold grain anomalies in till beneath thick clay cover (Sauerbrei *et al*. 1987). As well, many of the kimberlites that were discovered in the 1990s and the first decade of this century, including the pipes that host Canada's first diamond mine, Ekati in the Northwest Territories, were found by identifying and tracing kimberlite indicator mineral (KIM) dispersal trains in till (*e.g.* Blusson 1998; Kong *et al*. 1999; Strand *et al*. 2009; Grütter 2016). Now, indicator minerals are being used to explore for deposits of base metals and other commodities (Thorleifson 2009), particularly porphyry Cu, Ni-Cu-PGE and VMS deposits both in Canada (*e.g.* Averill, 2001; Plouffe & Ferbey 2015, McClenaghan *et al*. 2013, 2015a,b; Hashmi *et al*. 2015) and internationally (Averill 2011, Kelley *et al*. 2011).

The greatest strength of indicator mineralogy in exploring glaciated terrains is its ability to detect overburden-covered mineral deposits from afar with very widely spaced samples, thereby greatly reducing exploration costs. The Casa Berardi gold deposits in northern Quebec, Canada were found at a total cost of just $248,000 CAN (1984 figures) using till samples from reverse circulation drill holes spaced 400 m apart (Sauerbrei *et al*. 1987). The gold grain dispersal train from the Rainy River gold deposit in northwestern Ontario, Canada is 15 km long (Averill 2013) and was initially detected by the Ontario Geological Survey in till samples collected from holes drilled ~3 km apart across a previously untested clay belt (Bajc 1991). Most remarkably, Chuck Fipke and Stewart Blusson discovered the Ekati kimberlite field by tracing a KIM dispersal train for 600 km using alluvial and glaciofluvial (esker) gravel samples collected up to 40 km apart (Blusson 1998).

Shilts (1973, 1993) showed by sampling till up to 50 km down-ice from the large Thetford Mines (asbestos) ophiolite complex in Quebec that the concentration of ophiolite indicator minerals, clasts and elements in the till decreased exponentially with increasing distance from the ophiolite source; i.e. the glacial dispersal train had a strong but short head followed by an exponentially weaker but much longer tail (Fig. 1) that, in theory, would never completely dissipate. Thus, a mineral deposit can only be identified from

Figure 1. Three-dimensional plot of Ni concentrations in till down-ice from (southeast of) the Thetford Mines ophiolite belt, southeastern Quebec. Note the strong, short heads and exponentially weaker but much longer and very slowly dissipating tails of the Ni dispersal trains. Excerpted from Shilts (1993) under copyright licence No. 3907820314085.



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afar with a wide sample spacing, as in the Rainy River and Ekati examples, if the sampling method is sufficiently sensitive to detect the weak tail of the train with a high level of confidence. The required sensitivity is attained by (a) collecting large samples; and (b) employing a sample treatment method that provides a very low detection limit of one grain per sample for each targeted indicator mineral in the principal grain size fraction (*e.g.* 250-500 μm) within which that mineral would be expected to occur. A further caveat is that the indicator minerals must have a specific gravity sufficient to be concentrated to a level at which a single grain can be identified at a practical cost. While gravity concentrates can be refined by other means to further concentrate some indicator minerals and thereby ease their identification, not all minerals benefit from this treatment. Therefore the final caveat is that the grain size fractions of the heavy mineral concentrate (HMC) that match the expected sizes of the targeted indicator minerals must be examined in full to obtain the benefit of collecting a large sample.

Kimberlite is such a rare rock that the till in most regions of Canada contains no KIMs. A sample size of 10 to 20 kg is generally adequate for detecting KIMs at very low concentrations in the distal parts of glacial dispersal trains (Grütter 2016). Gold grains, in contrast, are rather ubiquitous in till because: (a) auriferous bedrock is much more common than kimberlite; and (b) gold grains do not physically break down during glacial transport because gold is malleable – the grains simply become reshaped (Averill 2001). On gold exploration programs, therefore, a till sample containing 10 kg of <2 mm (-10 mesh) material will be sufficient. The gold background in a sample of this size can range from just 0 to 5 grains in infertile regions to as much as 40 grains on the down-ice end or side of a long or wide auriferous belt such as the Abitibi Greenstone Belt in Ontario and Quebec (Averill 1988). In areas where the gold background of the till is high, anomalous populations of gold grains derived from nearby mineralized zones of potential economic interest are recognizable by: (a) their more uniform grain size; and (b) limited modification of their primary pristine morphology (Averill 1988, 2001, 2013).

The indicator mineral surveys that contributed to the discovery of the Casa Berardi, Rainy River and Ekati mines adhered closely to the above sample collection and treatment protocols. Large samples were collected, their heavy mineral fraction was extracted, either the entire concentrate or its most prospective grain size fractions were studied and the number of grains of each indicator mineral was established. The grains were identified and classified visually using stereoscopic microscopes (Fig. 2a), a process that requires ~15 minutes for gold grains and 2 hours for a full suite of kimberlite, base metal and other types of indicator minerals.

In recent years, software programs such as MLA® and QEMSCAN® have been developed that allow rapid,

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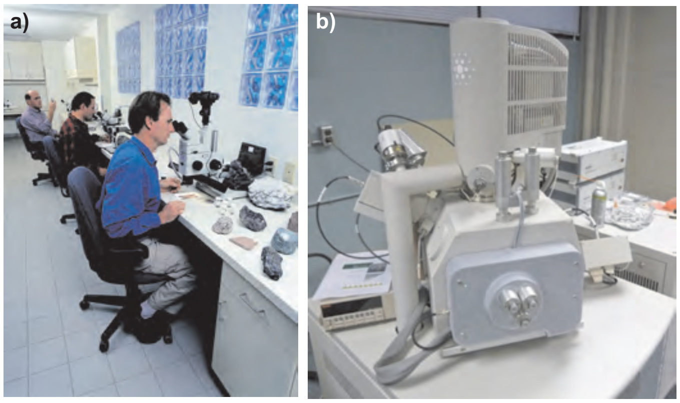

Figure 2. Examples of: (a) visual and (b) automated (MLA) methods of indicator mineral identification. Sources: (a) laboratory of Overburden Drilling Management Limited, Nepean, Ontario; (b) Queens University, Kingston, Ontario.

automated identification and analysis of the minerals in a HMC using scanning electron microscopy (SEM) (Fig. 2b) and energy dispersive x-ray spectroscopy (Sylvester 2012; Agnew 2015; Layton-Matthews *et al*. 2015). In this article, it is shown mathematically that the effectiveness of these automated techniques for indicator mineral surveys in glaciated terrains, where a large sample is required and its entire heavy mineral component or the most prospective grain size fractions thereof must be analyzed at a 1-grain detection limit, is presently constrained by: (a) the surface area of the block on which the grains are mounted, polished and analyzed being too small to hold the large numbers of mineral grains that are present in a typical HMC; (b) the tendency of many indicator minerals to be relatively coarse grained, further limiting the number of grains that can be analyzed per block; and (c) the impracticality of analyzing multiple blocks per sample on a routine basis.

Preferred Natural Grain Sizes of Indicator Minerals

Till is an unsorted sediment deposited directly by glaciers (Goldthwait 1971; Dreimanis 1976). Within its <2000 μm (<2 mm) matrix, the particles range in size upward (Fig. 3) from clay (<2 μm) through very fine to very coarse silt (2-63 μm) to very fine to very coarse sand (63-2000 μm). For each successive particle size class shown in Figure 3, the width is double that of the adjacent smaller class. For example, the range for medium sand grains is 250-500 μm, twice the 125-250 μm range for fine sand grains.

Most oxide, sulphide and silicate indicator minerals occur preferentially as sand-sized grains (Averill 2001, 2011; McClenaghan *et al*., 2013, 2015a, b) but ~90% of gold grains and platinum group minerals (PGMs) occur as silt-sized or smaller grains (<63 μm wide; Averill 2001). KIMs are relatively coarse grained, ranging up to 2 mm (Fig. 3), because they originally crystallized as macrocrysts in the mantle. The principal grain size targeted on KIM surveys is medium sand – i.e. 250-500 μm – because this is the peak grain size for most KIMs (Averill & McClenaghan 1994) including Cr-pyrope garnet as illustrated in Figure 3. Most of the base metal indicator minerals that are currently being

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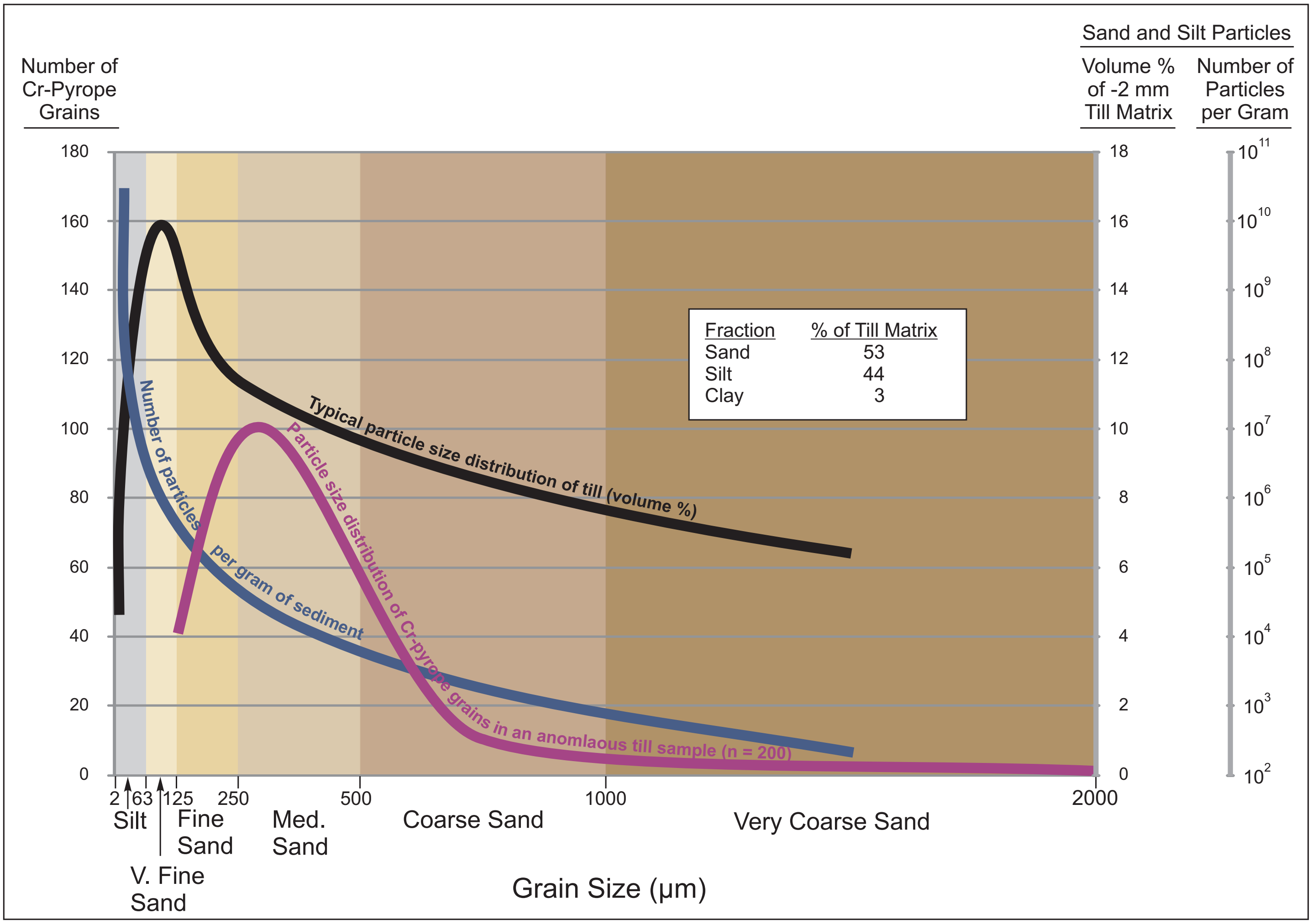

Figure 3. Typical size distribution of Cr-pyrope grains in an anomalous till sample in relation to the average proportion (%) of silt and sand-sized particles in till and the number of particles per gram of silt and very fine to very coarse sand. Note that fewer Cr-pyrope grains are present in the fine sand fraction than the medium sand fraction even though fine sand constitutes a higher proportion of the till and contains eight times more particles per gram than medium sand. Till particle distribution data from northern Quebec courtesy of Beth McClenaghan (Geological Survey of Canada).

utilized are sand sized because the main types of base metal sulphide deposits being targeted by indicator minerals are either magmatic (*e.g.* porphyry, skarn, IOCG, Ni-Cu) or metamorphosed (*e.g.* Broken Hill-type deposits and VMS and SEDEX deposits in amphibolite-facies terranes) and thus relatively coarse grained (Averill 2011; McClenaghan 2013, McClenaghan *et al*. 2013).

The Grain Deficit Issue of Automated Analyzers

If an automated analyzer is used to identify and count the indicator mineral grains present in a HMC, grains of a similar size are mounted in an epoxy block, typically 25.4 x 25.4 mm, which is then polished to expose the grains. Only ~2000 grains of the commonly used 250-500 μm size fraction can be mounted on one 25 mm square block (Agnew 2015). However, each gram of 250-500 μm heavy minerals contains ~11,000 grains (Table 1), requiring analysis of 5.5 epoxy blocks to identify and count all of the contained indicator mineral grains. Moreover, the 250-500 μm heavy mineral fraction of a 10 kg till sample typically weighs ~20 g (Fig. 4) and thus contains ~220,000 mineral grains.

If a single, 25 mm square, 2000-grain epoxy block from the 220,000-grain, 250-500 μm fraction of the HMC is analyzed, the only representative analyses that are obtained will be for minerals that comprise >0.1 percent (1 grain in

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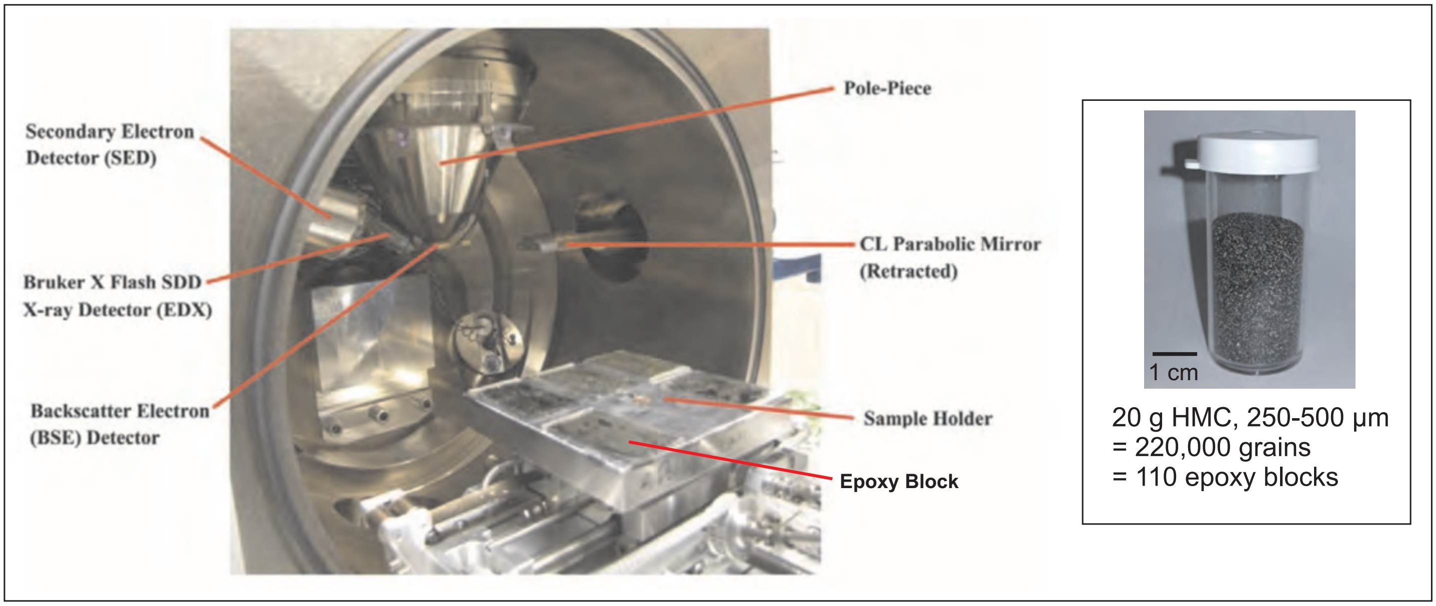

Figure 4. Grain capacity of an automated mineral analyzer. Each epoxy block in the sample tray will hold ~2,000 grains of 250-500 µm (medium sand) size or 8,000 grains of 125-250 µm (fine sand) size. However, a typical 10 kg till sample contains ~20 g of heavy minerals of each size and each gram contains 11,000 or 88,000 mineral grains, respectively, for a total of 220,000 or 1,760,000 grains requiring 110 or 220 epoxy blocks to be analyzed completely.

1000) of the HMC, i.e. minerals that would be obvious from a simple visual inspection of the HMC. The analyses obtained for the most commonly targeted indicator minerals will not be representative because these minerals normally occur at ppb levels in till and ppm levels in till HMCs (Averill 2001). In fact, grains of these minerals would seldom be detected by automated analysis of a single 2000 grain block even where present in significantly anomalous numbers in the HMC. Analysis of the entire 250-500 µm fraction of the HMC, or 110 epoxy blocks, would be required to determine the number of grains of each indicator mineral species that are present, if any. If this were not done, there would be no point in collecting such a large sample as the ability to detect mineralization from afar would be lost. Unfortunately,

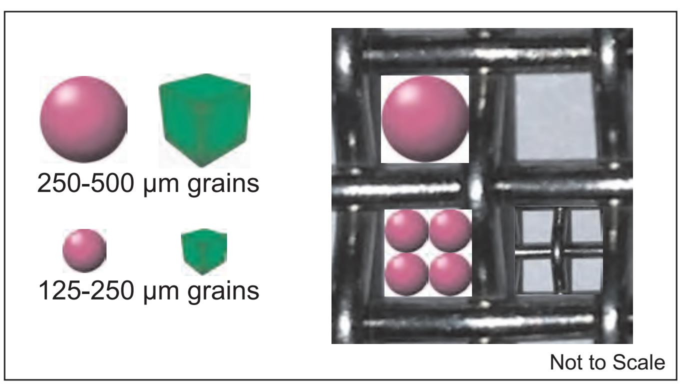

Figure 5. Relationships between grain diameter, area and volume. Halving the size of a spherical or cubic mineral grain from 250-500 µm (medium sand) to 125-250 µm (fine sand) quarters the surface area that the grain occupies on an epoxy block (area = πr^2 or d^2). However the volume of the grain decreases by a factor of eight (volume = $4/3\pi r^3$ or d^3) such that eight times more grains and twice as many epoxy blocks must be analyzed per gram of sample.

it is presently impractical to analyze multiple grain blocks from a large till sample on a routine basis because from 30 minutes (Agnew 2015) to 1-2 hours (Layton Matthews *et al*. 2015) are required to identify the targeted indicator minerals in each block. This time estimate does not include time required for mounting and polishing the grains and subsequent interpretation of the acquired analytical data.

In theory, analyzing the fine, 125-250 µm rather than medium, 250-500 µm sand fraction of the HMC would improve the detection limit of an automated analyzer because four times as many grains could be mounted on an epoxy block (Fig. 5, Table 1). However till generally contains a higher proportion of 125-250 µm grains than of 250-500 um grains (~12% versus 10%; Fig. 3) and thus a greater weight of heavy minerals requiring examination. Furthermore, each 125-250 grain has only one-eighth the volume of a 250-500 um grain (Fig. 5). Consequently, even if the weight of the 125-250 µm HMC does not exceed the 20 g weight of the 250-500 µm HMC, eight times as many grains and twice as many grain blocks (220) would need to be examined to identify the targeted indicator mineral grains in the 125-250 µm grain size fraction despite the fourfold increase in grain capacity per block for this fraction (Fig. 4, Table 1). Finally, the 125-250 µm fraction commonly contains fewer grains of coarse-biased indicator minerals such as Cr-pyrope (Fig. 3); i.e. the frequency of these mineral grains is less than one-eighth that in the 250-500 µm fraction, compounding the time and effort required to identify them among the many non-indicator mineral grains in the HMC.

Detection Limits for Gold Grains

As noted above, ~90% of gold grains in till are silt sized. While one 25-mm-square epoxy mount will hold up

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Particle Size		Approximate Number of Heavy Mineral Grains		Approximate No. of Epoxy Blocks per Gram
Class	µm	Per Gram	Per Expoxy Block	
Very coarse sand	1000-2000	170	125	1.5
Coarse sand	500-1000	1,400	500	3
Medium sand	250-500	11,000	2,000	5.5
fine sand	125-250	88,000	8,000	11
Very fine sand	63-125	700,000	32,000	22
Very coarse silt	32-63	5,600,000	130,000	45
Coarse silt	16-32	45,000,000	500,000	90

Table 1. Variation with particle size in the number of epoxy blocks required for automated analysis of 1 gram of heavy minerals.

to 200,000 mineral grains of this size (Agnew 2015), silt is a major component of till, typically comprising ~44% of the matrix of samples collected over the crystalline rocks of the Canadian Shield (Fig. 3). Moreover, a single gram of silt contains ~50 million mineral grains (Table 1, Fig. 3). Consequently, a typical 10 kg till sample contains 4400 g or ~220 billion grains of silt and one gold grain in this silt – the required detection level – represents just 0.0045 ppb or 4.5 ppt by volume. If the 4400 g of silt were simply reduced to a routine >3.2 specific gravity heavy mineral concentrate weighing 20 g, the targeted gold grain would still represent only 1 ppb by volume of the HMC and thus be essentially impossible to find either visually or with an automated mineral analyzer. However, since gold has a much higher specific gravity (~19 vs. 3.2-5.5) than most of the other minerals in HMCs, gold grains can be further concentrated to as much as 1000 ppm (1 grain in 1000). They can then be identified either visually in a few minutes or instrumentally by analysis of a single epoxy block.

Identifiable Mineral Associations and Grain Morphologies

When conducting an indicator mineral exploration program, it is important to recognize potentially useful associations between and physical features of the various minerals in the HMCs, including: (1) the major minerals that comprise the background suite in the HMC, particularly their implications for the main source rocks of the till and hence for the locations of the bedrock sources of any indicator minerals that the till contains; (2) the morphology of the indicator mineral grains, particularly their degree of wear relative to their susceptibility to wear (*e.g.* hardness, malleability, cleavage); and (3) any other indicators of the provenance of these grains such as the presence or absence of surface alteration, inclusions or mineral intergrowths. Also, as illustrated by the major Voisey's Bay Ni-Cu-Co discovery which ensued from the observation of anomalous concentrations of chalcopyrite grains in a KIM survey (McNish 1998), it is important to recognize minerals indicative of any type of mineral deposit, not just the type being targeted in the survey.

While most KIMs are sufficiently distinctive to be recognized visually in HMCs by a trained indicator mineral technician, visually analyzing a HMC for a full range of both background and indicator minerals while simultaneously evaluating the significance of these minerals, as described above, requires an attentive geologist/mineralogist with an aptitude for mineral exploration and good knowledge of rock-mineral associations and ore deposit and hydrothermal alteration models. The grains are examined whole and thus can be turned and studied from any angle and compared to one another. If a SEM is available, any mineralogical uncertainties can be resolved in minutes by qualitative analysis of the natural (unpolished) surfaces of the problematic grains. Timely decisions such as placing more (or less) emphasis on specific minerals and mineral associations can be made based on the patterns observed in the initial samples of the survey. Significant trends normally become apparent as the work proceeds; therefore little further interpretation is required.

In the case of automated investigation of HMCs at the above level, all of the minerals grains of the most prospective sizes must be analyzed; it is not sufficient to selectively search for and analyze grains of the targeted indicator minerals. While the beneficial human element of a visual analysis is lost, a more precise and objective analysis is obtained, either as an actual grain count by analyzing the centre of each particle as is done with MLA® or as a modal mineral count by analyzing grid points as is done with QEMSCAN® (Layton-Matthews *et al*. 2015). As well, the chemical compositions of the grains are measured and the mineralogy of any small inclusions can be determined. Due to the need for a finely polished section of the grains, however, no information is obtained on their natural surface features. As well, the acquired data must still be interpreted in depth by a geologist with broad experience in both indicator mineralogy and mineral exploration.

Conclusions

Detecting a mineral deposit from afar with widely spaced till samples, as is required for practical, cost-effective indicator mineral exploration in glaciated terrains, requires: (a) large samples, typically 10 kg of the -2 mm till matrix; (b) extraction of the heavy mineral fraction from the sample to concentrate the indicator minerals; (c) an ultra-sensitive detection limit of one grain in the particle size fraction of the HMC within which the targeted indicator minerals preferentially reside; and (d) examination of all of this size fraction of the HMC in order to determine how many indicator mineral grains are present, if any.

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While automated methods are now available for analyzing HMCs, only a very small portion of an HMC can presently be analyzed on a practical basis, typically 1 % of the most critical particle size fraction. Therefore traditional visual analysis is still essential to obtain meaningful indicator mineral data for exploration programs. Visual analysis can also provide important information on the physical features of the grains that is lost when grains are mounted and polished for automated analysis. If, however, a till HMC is known from visual analysis to be enriched in an indicator mineral to the 1000 ppm range, or if this mineral is present in a mineralized rock sample at the 10 ppm level and is distributed optimally as very small grains ($<20\ \mu m$; Cabri 2015), automated analysis of a single epoxy block can reliably identify the mineral and determine its concentration in the sample. Automated analysis also determines the composition of each mineral and may identify mineral inclusions that are not apparent visually.

In summary automated mineral analysis, in its present form, is a useful complement to, not a replacement for visual analysis of HMCs in indicator mineral exploration in glaciated terrains.

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References

AGNEW, P.D. 2015. Micro-analytical innovation for indicator mineral exploration. *In: Application of Indicator Mineral Methods to Mineral Exploration.* The Association of Applied Geochemists, 27th International Applied Geochemistry Symposium, Short Course **SC02**, Tucson, 11-12.

AVERILL, S.A. 1988. Regional variations in the gold content of till in Canada. *In:* MACDONALD, D.R. & MILLS, K.A. (eds) *Prospecting in Areas of Glaciated Terrain – 1988.* Canadian Institute of Mining and Metallurgy, Geological Division, Halifax, 2871-284.

AVERILL, S.A. 2001. The application of heavy indicator mineralogy in mineral exploration with emphasis on base metal indicators in glaciated metamorphic and plutonic terrains. *In:* MCCLENAGHAN, M.B., BOBROWSKY, P.T., HALL, G.E.M. & COOK, S.J. (eds) *Drift Exploration in Glaciated Terrains.* Geological Society, London, Special Publications, **185,** 69-81.

AVERILL, S.A. 2011. Viable indicator minerals in surficial sediments for two major base metal deposit types: Ni-Cu-PGE and porphyry Cu. *Geochemistry: Exploration, Environment, Analysis,* **11,** 279-292.

AVERILL, S.A. 2013. The discovery and delineation of the Rainy River gold deposits using glacially dispersed gold grains sampled by deep overburden drilling: a 20-year odyssey. *In: New Frontiers for Exploration in Glaciated Terrain.* Prospectors and Developers Association of Canada, Workshop, Toronto.

AVERILL, S.A. 2015. The Blackwater gold-spessartine-pyrolusite dispersal train, British Columbia, Canada: Influence of sampling depth on indicator mineralogy and geochemistry. *In: Application of Indicator Mineral Methods to Mineral Exploration.* The Association of Applied Geochemists, 27th International Applied Geochemistry Symposium, Short Course **SC02,** Tucson, 47-60.

AVERILL, S.A. & MCCLENAGHAN, M.B. 1994. Distribution and character of kimberlite indicator mineral in glacial sediments, C14 and Diamond Lake kimberlite pipes, Kirkland Lake, Ontario. *Geological Survey of Canada,* Open File **2819**.

BAJC, A.F. 1991. Till sampling survey, Fort Frances area: Results and interpretation. *Ontario Geological Survey,* Study **56**.

BLUSSON, S.L. 1998. Key steps to discovery of the Slave Craton diamond field, N.W.T., Canada. *In:* WALTON, G. & JAMBOR, J. (eds) *Pathways '98 Abstract Volume.* Cordilleran Roundup, Vancouver, 1998, British Columbia Yukon Chamber of Mines, 25.

CABRI, L.J. 2015. Importance of sample preparation, representivity, and reporting methodologies for quantitative evaluation of precious metal mineralogy. Abstract No. 34332, Geological Association of Canada, Annual Meeting, Abstract Volume No. 38, 277.

DREIMANIS, A. 1976. Tills: Their origin and properties. *In:* LEGGET, R.F (ed) *Glacial Till*. The Royal Society of Canada, Special Publication No. **12**, 11-49.

GOLDTHWAIT, R.P. 1971. Introduction to till, today. *In:* GOLDTHWAIT, R.P. (ed) *Till – A Symposium.* Ohio State University Press, 3-26.

GRÜTTER, H. 2016. Kimberlitic indicator minerals in glaciated terrain: An update on contemporary practices. *In: Exploring Smarter in Glaciated and Covered Terrains.* AMEBC Exploration RoundUp 2016 Short Course **4**, Vancouver, 145-154.

HASHMI, S., WARD, B.C., PLOUFFE, A. LEYBOURNE, M.I. & FERBEY, T. 2015. Geochemical and mineralogical dispersal in till from the Mount Polley Cu-Au porphyry deposit, central British Columbia, Canada. *Geochemistry: Exploration, Environment,* Analysis, **15**, 234-249.

KELLEY, K.D., EPPINGER, R.G., LANG, J., SMITH, S.M. & FEY, D.L. 2011. Porphyry Cu indicator mineral in till as an exploration tool: Example from the giant Pebble porphyry Cu-Au-Mo deposit, Alaska, USA. *Geochemistry: Exploration, Environment,* Analysis, **11**, 321-334.

KONG, J. M., BOUCHER, D.R. & SCOTT-SMITH, B.H. 1999. Exploration and geology of the Attawapiskat kimberlites, James Bay Lowland, northern Ontario, Canada. *In:* GURNEY, J.J., GURNEY, J.L., PASCOE, M.D. & RICHARDSON, S.H. (eds) *The J.B. Dawson Volume, Proceedings of the VIIth International Kimberlite.* Cape Town, 446-448.

LAYTON-MATTHEWS, D., HAMILTON, C. & MCCLENAGHAN, M.B. 2015. Mineral chemistry: Modern techniques and applications to exploration. *In: Application of Indicator Mineral Methods to Mineral Exploration.* The Association of Applied Geochemists, 27th International Applied Geochemistry Symposium, Short Course **SC02**, Tucson, 1-10.

MCCLENAGHAN, M.B. 2013. Till geochemistry and indicator mineral methods for volcanogenic massive sulphide exploration in glaciated terrain. *In: New Frontiers for Exploration in Glaciated Terrain.* Prospectors and Developers Association of Canada, Workshop, Toronto.

MCCLENAGHAN, M.B., KJARSGAARD, I.M., AVERILL, S.A., LAYTON-MATTHEWS, D., CRABTREE, D., MATILE, G., MCMARTIN, I. & PYNE, M. 2013. Indicator mineral signatures of magmatic Ni-Cu deposits, Thompson Nickel Belt, Manitoba part 2- till data. *Geological Survey of Canada,* Open File **7200**.

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MCCLENAGHAN, M.B., PETER, J.M. & LAYTON-MATTHEWS, D. 2015a. Overview of VMS exploration in glaciated terrain using indicator minerals, till geochemistry, and boulder tracing: A Canadian perspective. *In:* PETER, J.M. & MERCIER-LANGEVIN, P. (eds) *Targeted Geoscience Initiative 4 Contributions to the Understanding of Volcanogenic Massive Sulphide Genesis and Exploration Methods Development.* Geological Survey of Canada, Open File **7853**, 81-100.

MCCLENAGHAN, M.B., PARKHILL, M.A., PRONK, A.G., SEAMAN, A.A., MCCURDY, M., POULIN, R.S., MCDONALD, A.M., KONTAK, D.J. & LEYBOURNE, M.I. 2015b. Indicator mineral and till geochemical signatures of intrusion-hosted Sn-W deposits examples from the Sisson W-Mo and Mount Pleasant Sn-W-Mo-Bi-In deposits, New Brunswick. *In:* ROGERS, N. (ed) *TGI 4 Intrusion Related Mineralization Project New Vectors to Buried Porphyry-Style Mineralization.* Geological Survey of Canada, Open File **7843**, 39-58.

MCNISH, J. 1998. *The Big Score: Robert Friedland, Inco, and the Voisey's Bay hustle.* Doubleday Canada Limited, Toronto.

PLOUFFE, A. & FERBEY, T. 2015. Till composition near Cu-porphyry deposits in British Columbia: highlights for mineral exploration. *In:* ROGERS, N. (ed) *TGI 4 Intrusion Related Mineralization Project New Vectors to Buried Porphyry-Style Mineralization.* Geological Survey of Canada, Open File **7843**, 15-37.

SAUERBREI, J.A., PATTISON, E.F. & AVERILL, S.A. 1987. Till sampling in the Casa-Berardi gold area, Quebec: A case history in orientation and discovery. *Journal of Geochemical Exploration,* **28,** 297-314.

SHILTS, W.W. 1973. Glacial dispersal of rocks, minerals and trace elements in Wisconsinan till, southeastern Quebec, Canada. *Geological Society of America*, Memoir **136**, 189-220.

SHILTS, W.W. 1993. Geological Survey of Canada's contributions to understanding the composition of glacial sediments. *Canadian Journal of Earth Sciences,* **30**, 333-353.

STRAND, P., NABAS, A., BAUMGARTNER, M. & BURGESS, J. 2009. Tracing kimberlite indicator mineral dispersal trains: an example from the Churchill Diamond Project, Kivalliq, Nunavut. *In:* PAULEN, R.C. & MCMARTIN, I. (eds) *Application of Till and Stream Sediment Heavy Mineral and Geochemical Methods to Mineral Exploration in Western and Northern Canada.* Geological Association of Canada, GAC Short Course Notes **18**, 167-175.

SYLVESTER, P.J., 2012. Use of the mineral liberation analyzer (MLA) for mineralogical studies of sediments and sedimentary rocks. *In:* SYLVESTER, P.J. (ed) *Quantitative Mineralogy and Microanalysis of Sediments and Sedimentary Rocks.* Mineralogical Association of Canada Short Course **42**, St. John's, 1-16.

THORLEIFSON, L.H. 2009. Till geochemical and indicator mineral methods in mineral exploration: History and status. *In:* LENTZ, D.R., THORNE, K.G. & BEAL, K.L. (eds) *Proceedings of the 24th IAGS, Fredericton.* Volume **2**, 573-576.