

Overview of indicator mineral recovery methods for sediments and bedrock: 2013 update

M. Beth McClenaghan

Geological Survey of Canada, 601 Booth Street, Ottawa, Ontario, Canada K1A 0E8
(e-mail: bmcclena@nrcan.gc.ca)

These short course notes are a summary of a more detailed paper (McClenaghan 2011) describing common sample processing methods (Fig. 1) used to reduce sample volume, concentrate heavy minerals, and recover indicator minerals in support of mineral exploration. It is an updated version of previously published workshop notes presented in 2009 and 2011 (McClenaghan 2009, 2011).

The application of indicator mineral methods to mineral exploration has expanded and developed significantly over the past two decades and these methods are now used around the world to explore for a broad spectrum of deposit types including kimberlite (diamonds) (e.g. McClenaghan & Kjarsgaard 2007), lode gold (e.g. McClenaghan & Cabri 2011; Moles & Chapman 2011), magmatic Ni-Cu-PGE (e.g. Averill, 2001, 2011; McClenaghan *et al.* 2011), metamorphosed VMS (e.g. Heiman *et al.* 2005), porphyry Cu (e.g. Kelley *et al.* 2011; Averill 2011), Mississippi Valley-type Pb-Zn (e.g. Paulen *et al.* 2011), U, Sn, W, IOCG (e.g. McMartin *et al.* 2011), and rare metals (e.g. Averill 2001).

Indicator minerals, including ore, accessory and alteration minerals, are usually sparsely distributed in their host rocks. In sediments derived from rocks, these indicator minerals may be even sparser, thus sediment samples must be concentrated in order to recover and examine the indicators. Most indicator minerals have a moderate to high specific gravity; therefore most processing techniques use some type of density separation, often in combination with sizing and/or magnetic separations, to concentrate the minerals. The presence of specific indicator minerals in unconsolidated sediments provides evidence of a bedrock source and, in some cases, the chemical composition of the minerals may reflect the ore grade of the bedrock source. As few as one sand-sized grain of a specific indicator mineral in a 10 kg sample may be significant. To recover such potentially small quantities (equivalent to ppb) of indicator minerals, samples are processed to reduce the volume of material that must be examined. The processing techniques employed must retain the indicator mineral(s) without contaminating the sample and must have a reasonable cost.

Indicator minerals can be recovered from a variety of sample media, including stream, alluvial, glacial, beach, or eolian sediments, and residual soils. They can also be recovered from weathered and fresh bedrock, as well as mineralized float. The combinations of processing techniques used for recovering indicator minerals by exploration companies and government agencies are quite variable (e.g. Gregory & White 1989; Peuraniemi 1990; Davison 1993; Towie & Seet 1995; Chernet *et al.* 1999; McClenaghan *et al.* 1999; Gent *et al.* 2011; Plouffe *et al.* in press). The processing methods used will depend on the commodities being sought as well as the cost per sample. Most oxide and silicate indicator minerals are easily recovered from

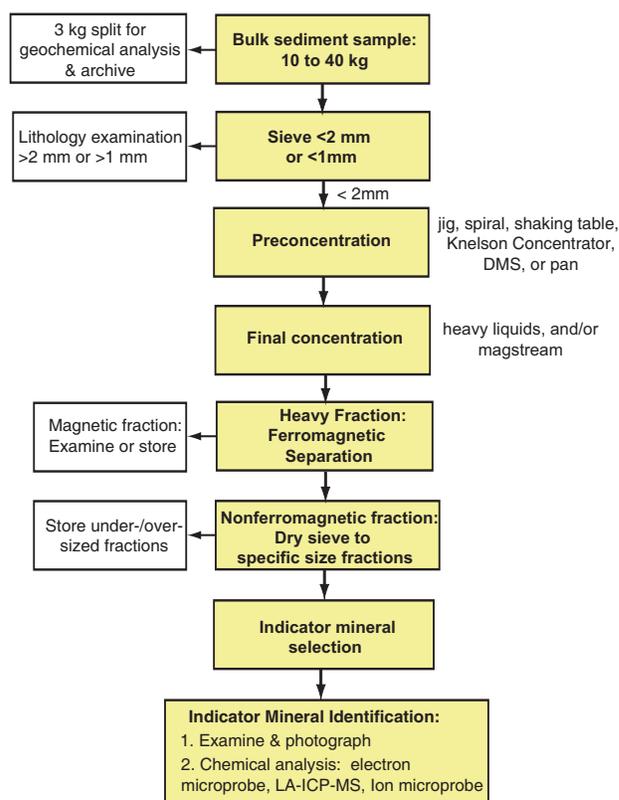


Fig. 1. Generalized flow sheet showing steps in sample processing used to reduce sample weight, concentrate heavy minerals, and recover indicator minerals.

the medium to coarse sand-sized (0.25–2.0 mm) fraction. Therefore, concentration techniques that recover the sand-sized heavy minerals can be used. In contrast, a significant proportion of gold, platinum group minerals (PGM), sulphide minerals, and rare metal minerals (Laukkanen *et al.* 2011) are silt-sized (<0.063 mm), thus concentration of these indicators requires a preconcentration technique that includes recovery of the silt- as well as the sand-sized fractions.

SAMPLE WEIGHT

The sample weight of material required for indicator mineral studies will vary depending on the type of surficial sediment collected, the grain size characteristics of the sample material, the commodity being sought, and shipping costs (Table 1). For example, in glaciated terrain clay-rich till samples may have to be 20 to 30 kg (or more) to recover a sufficient weight of sand-sized heavy minerals (Table 2, #5) (e.g. Spirito *et al.* 2011). In contrast, coarse-grained silty sand till typical of shield terrain

Table 1. Examples of variation in sample weight and processing procedures with sample and target type at Overburden Drilling Management Ltd.'s heavy mineral processing laboratory (Averill & Huneault 2006).

Target	Typical Sample Weight	Required Separations				
		Table	Micropan	Heavy Liquid (specific gravity)	Ferromagnetic separation?	Paramagnetic separation?
A. Sediment Samples						
Gold	10	Single	Yes	3.3	Yes	No
Kimberlite	10–30	Double	No	3.2	Yes	Yes
Massive sulphides (Ni-Cu-PGE, BHT, VMS, IOCG, MVT, skarn)	10	Single	Yes (PGM only)	3.2	Yes	Yes
Porphyry Cu	0.5	No	No	2.8, 3.2	Yes	Two
Uranium	10	Single	Yes	3.3	Yes	No
Heavy mineral sands (grade evaluation)	20	Triple	No	3.3	Yes	Optional
Tampering (investigation)	Variable	Optional	Yes	3.3	Yes	Optional
B. Rock Samples						
Gold, PGE, base metals	1	Optional	Yes	3.3	Yes	Optional
Kimberlite	1–10	Optional	No	3.2	Yes	Yes
Tampering (investigation)	1	No	Yes	3.3	Yes	Optional

requires smaller (10 to 15 kg) samples because it contains more sand-sized material in the matrix (Table 2, #1 to 4) (Spirito *et al.* 2011). Alluvial sand and gravel samples collected for recovery of porphyry Cu indicator minerals (PCIM) can be as small as ~0.5 kg because porphyry Cu alteration systems are large and rich in indicator minerals (Averill 2007). Bedrock and float samples usually vary from 1 to 10 kg.

BEDROCK PREPARATION

Bedrock or float (mineralized boulders) samples often need to be disaggregated or crushed prior to processing to reduce rock fragment/mineral grain size to <2 mm. Electric pulse disaggregation (EPD) using an electric current from a high-voltage power source in a water bath is an efficient means of liberating mineral grains from a rock (Cabri *et al.* 2008). The major advantage of this method is that individual mineral grains can be recovered in their original shape and form regardless of grain size. Conventional rock crushers may also be used, however, they 1) are more difficult to clean between samples and thus pose a higher risk of cross contamination, 2) often cause rock fragments to break across grain boundaries, and 3) mark/damage grains as they are liberated. Barren quartz can be disaggre-

gated or crushed as a blank between routine rock samples to reduce and monitor contamination.

PRECONCENTRATION

If sample shipping costs are an issue, samples may be partly processed in the field to reduce the weight of material shipped to the processing laboratory. Samples may be sieved to remove the coarse (>1 or >2 mm) fraction, which may reduce weights from a few % to 30% (e.g. Table 2, columns B–C). Preconcentrating samples using a pan, jig, sluice box or centrifugal concentrator also may be carried out in the field to further reduce the weight of material to be shipped. Preconcentrates may be examined in the field, significantly reducing the time to obtain results for follow up. However, preconcentrating in the field can itself be expensive and time consuming and the available methods may not provide optimal recovery of the indicator minerals of interest. Field setup of concentrating equipment may be more rudimentary than at the processing laboratory, thus extra care is required to avoid cross contamination or material loss during the pre-concentration procedures.

Whether sieved off in the field or in the laboratory, the coarse >2 mm fraction may be examined to provide additional infor-

Table 2. Weight of each fraction generated by a combination of tabling and heavy liquid separation to reduce till sample weight, concentrate heavy minerals, and recover indicator minerals: A) initial sample weight; B) sieving off <2 mm; C & D) tabling; E) heavy liquid separation; F) magnetic separation; G) final heavy mineral concentrate weight. Till samples are from (1) the South Pit of the Thompson Ni Mine, Thompson, Manitoba; (2) Broken Hammer Cu-PGE deposit, Sudbury, Ontario; (3) Pamour Mine, Timmins, Ontario; (4) Triple B kimberlite, Lake Timiskaming field, Ontario; and (5) Buffalo Head Hills, northern Alberta.

Location	Texture	A: total sample weight (kg)	B: weight >2 mm clasts (kg)	C: weight of sample put across shaking table (kg)	D: weight shaking table concentrate produced (g)	E: weight of heavy liquid fraction (g)	F: weight magnetic fraction (g)	G: weight of non-magnetic heavy mineral concentrate (g) 0.25–2.0 mm
1. Thompson Ni Belt	silty sand till	15.0	3.0	12.0	1015.9	104.5	36.4	47.9
2. Sudbury	sandy till	15.0	5.6	9.4	1125.1	402.6	13.0	18.9
3. Timmins Gold camp	silty sand till	11.8	2.3	9.5	353.1	319.8	5.2	28.1
4. Triple B kimberlite	silty sand till	9.8	1.2	8.6	438.7	377.0	22.0	35.8
5. Northern Alberta	clayey till	67.4	2.4	65.0	1,307.0	1,235.2	5.6	11.5

mation about sample provenance and transport distance. The <2 (or <1 mm) fraction is preconcentrated most commonly using sieving and/or density methods (e.g. jig, shaking table, spiral concentrator, dense media separator, pan, centrifugal concentrator) to reduce the weight of material to be examined without losing indicator minerals. Some of the more common preconcentration equipment and techniques are described below.

Pans

Panning is the oldest method used to recover indicator minerals, primarily for gold and PGM. Sediment is placed in a pan and shaken sideways in circular motion while being held just under water. Heavy minerals sink to the pan bottom and light minerals rise and spill out over the top (Zeschke 1961; Silva 1986; English *et al.* 1987; Ballantyne & Harris 1997). Pans have varying shapes (flat bottomed or conical) and sizes, and can be made out of plastic, metal or wood. The advantages of this technique include that it can be a field or laboratory-based operation, is inexpensive in terms of equipment costs, and if used in the field it reduces sample shipping weight and thus cost. If field based, indicator minerals can be examined immediately and results can be used to guide on going exploration while still in the field. Panning is often used in combination with other preconcentration and/or heavy liquid methods to recover silt-sized precious metal grains (e.g. Grant *et al.* 1991; Leake *et al.* 1991, 1998; Ballantyne & Harris 1997; Wierchowicz 2002). The disadvantages of this method are that it is slow, is highly dependent on the experience and skill of operator and therefore requires consistent personnel to perform the panning. It is considered to be a rough concentrating method when used in the field and is followed up with further laboratory-based concentration techniques (e.g. Zantop & Nespereira 1979; Stendal & Theobald 1994).

Shaking tables

Preconcentration using a shaking (e.g. Wilfley) table is another one of the oldest methods for concentrating and separating heavy minerals on the basis of density. It recovers silt- to coarse sand-sized heavy minerals for a broad spectrum of commodities including diamonds, precious and base metals, and uranium (Averill & Huneault 2006). A brief description of the method is summarized below from Sivamohan & Forsberg (1985), Silva (1986), and Stewart (1986). The table consists of a deck with up to 1 cm high riffles covering over half the surface. A motor mounted on one end drives a small arm that shakes the table along its length. A slurry of <2.0 mm sample material is put across the shaking table to prepare a preconcentrate. If kimberlite indicators are targeted, the sample is tabled twice to ensure higher recovery of the key lower density minerals (Cr-diopside and forsteritic olivine) and the coarsest grains. The advantages of this method are the ability to recover both silt- and sand-sized indicator minerals for a broad spectrum of commodities at a moderate cost. It is a well established method for the recovery of precious metal mineral grains as well as kimberlite indicator minerals (e.g. English *et al.* 1987; McClenaghan *et al.* 1998, 2004). The disadvantages of this method include the loss of some coarse heavy minerals as well as the finer <0.10 mm grains (Gent *et al.* 2011), the lengthy time required to process each sample; and its dependency on the skill of the operator.

Dense Media Separators

A micro-scale dense media separator (DMS), which is used in commercial labs, employs a gravity-based method to preconcentrate kimberlite indicator minerals. An overview of the method described by Baumgartner (2006) is presented below. Heavy mineral concentration is carried out using a gravity-fed high-pressure cyclone. The <1 mm fraction of the sample is mixed with fine-grained ferrosilicon (FeSi) to produce a slurry of a controlled density. The slurry is fed into the cyclone where the grains travel radially and helically, forcing the heavier particles toward the wall of the cyclone and the lighter particles toward the centre (Gent *et al.* 2011). The lighter and heavier particles exit the cyclone through different holes, with the light fraction discarded and the heavy fraction collected on a 0.25 or 0.3 mm screen. The heavy mineral concentrate on the screen is then dried and screened to remove residual FeSi. A Tromp curve is used to define the efficiency and precision of the DMS separation. The DMS is calibrated to recover the common kimberlite indicator minerals that have a specific gravity (SG) >3.1: pyrope garnet, chrome-spinel, Mg-ilmenite, Cr-diopside, forsteritic olivine, and diamond. It is tested using synthetic density tracers before processing samples. The density settings and cut points are checked once per day. The advantages of the micro DMS system are that it is fast, less susceptible to sample contamination than other heavy mineral concentrating techniques, and is not operator dependent. The method, however, is more expensive than other methods described here and it does not recover the silt-sized precious and base metal indicator minerals.

Centrifugal concentrators

Centrifugal concentrators were originally designed for concentrating gold and platinum from placer and bedrock samples. However, in recent years they have also been used to recover kimberlite indicator minerals from sediment samples (e.g. Chernet *et al.* 1999; Lehtonen *et al.* 2005). They can handle particle sizes from >10 µm to a maximum of 6 mm. The general processing procedure is summarized below for one type of centrifugal concentrator, the Knelson Concentrator, from the manufacturer's website (www.knelsongravitysolutions.com). In summary, water is introduced into a concentrate cone through a series of holes in rings on the side of the cone. The sample slurry is then introduced into the concentrate cone from a tube at the top. When the slurry reaches the bottom of the cone, it is forced outward and up the cone wall by the centrifugal force generated by the spinning cone. The slurry fills each ring on the inside of the cone wall to capacity, creating a concentrating bed. High specific gravity particles are captured in the rings and retained in the concentrating cone. At the end of the concentrate cycle, concentrates are flushed from the cone into the sample collector. The advantages of centrifugal concentrators are that they are fast, inexpensive, and can be mobilized to the field and used to reduce the weight of material that must be shipped to the laboratory. However, recovery of kimberlite indicator minerals from silt-poor material such as esker sand or stream sediments is difficult due to the absence of fine-grained material to keep the slurry in suspension (Chernet *et al.* 1999). Alternatively, too much fine-grained material can impede the settling of fine-grained heavy minerals. Centrifugal concentrators are optimal for the recovery of gold and PGM.

Spiral concentrators

Heavy minerals can be recovered using a rotary spiral concentrator, which consists of a flat circular stainless steel bowl with rubber ribs that spiral inward; a detailed description of its use is reported by Silva (1986). A spiral concentrator is mounted on a frame so it can be tilted and has a water wash bar extending laterally from one side of the bowl to the center. As the bowl spins, water is sprayed from the bar and heavy mineral grains move up and inward along the spirals to the central opening where they are collected in a container behind the bowl. The water washes light minerals down to the bottom of the bowl. The heaviest minerals are recovered first. The advantages of the spiral concentrator are that it can be field-based and thus used to reduce sample weight to be shipped, it is inexpensive to acquire and operate, it requires little time if the material is sandy, and it recovers indicator minerals across a broad size range, from silt- to sand-sized grains. The method, however, is dependent on the experience and skill of the operator, the lower density threshold is variable, there is some loss of heavy minerals, and the method is slow if the sample is clay-rich. It is used mainly for gold recovery (e.g. Maurice & Mercier 1986; Silva 1986; Sarala *et al.* 2009) but in the past 10 years it also has been used for the recovery of kimberlite indicator minerals (e.g. Sarala & Peuraniemi 2007).

Jigs

Jigging is one of the oldest gravity concentration methods; this method separates heavy minerals based on differential settling velocities of mineral grains in water (Stendal & Theobald 1994). Jigging is performed by hand or by mechanically jerking a partially filled screen of material up and down underwater for several minutes. While submersed in water, mineral grains separate through suspension and gravity effects into layers of varying specific gravity. Heavier grains concentrate on the surface of the screen, with the heaviest generally concentrated towards the centre of the screen forming an 'eye'. Very heavy minerals, such as ilmenite and magnetite, will be found at the very centre of the screen and lighter heavy mineral, such as garnet and pyroxene, will concentrate at the periphery of the eye. Diamonds tend to concentrate towards the centre, despite their moderate specific gravity (SG 3.51). A spoon is used to remove the heavy minerals in the eye for more detailed examination. For optimal recovery, the jig tailings should be re-jigged 2 to 3 times until no eye forms. The method is typically used for recovery of gold (e.g. Silva 1986) and kimberlite indicator minerals (Muggeridge 1995). The advantages of using a jig are that it can be field-based and thus used to reduce the weight of the samples to be shipped, is inexpensive to operate, is relatively fast, and works best for fine to coarse sand-sized grains. However, it is best used in a fixed, laboratory-based setting with an experienced operator.

FINAL CONCENTRATION

Heavy liquid separation

A preconcentrate is usually further refined using heavy liquids of a precise density (Gent *et al.* 2011) to further reduce the size of the concentrate prior to heavy mineral selection (Table 2-column E). Heavy liquid separation provides a sharp separation between heavy (sink) and light minerals (float) at an exact known density. However, it is slow and expensive, and there-

fore is not economical for large volumes of sample material; hence, it is advantageous to use the preconcentration procedures described above to reduce sample volume before this step (Stendal & Theobald 1994). It is common to remove the finer fraction (<0.063 mm) of a sample by sieving before using heavy liquid separation, as this material can be difficult to separate due to its small size (M. Lehtonen, pers. comm. 2013).

The most common heavy liquids used include methylene iodide (MI) with a SG of 3.3 and tetrabromoethane (TBE) or the low-toxicity heavy liquid lithium heteropolytungstates (LST), both with SG of 2.9. The density of the heavy liquid required will depend on the indicator minerals being sought. Some laboratories use a combination of both heavy liquids, separating first using the lower density heavy liquid at about SG 2.9 to reduce the volume of material to be further separated at SG 3.2 or 3.3 (e.g. Le Couteur & McLeod 2006; de Souza 2006; Mircea 2006). The recovery of kimberlite and magmatic Ni-Cu-PGE indicator minerals requires heavy liquid separation at SG 3.2 using dilute methylene iodide to include the lowest density indicators, Cr-diopside and forsteritic olivine. Recovery of porphyry Cu indicator minerals requires separation at SG 2.8 to 3.2 to recover the mid-density indicators tourmaline (dravite), alunite, jarosite, and turquoise (Averill 2007). Some indicator minerals, such as apatite and fluorite, are of intermediate density but are recovered mainly from the mid-density rather than the heavy fraction.

Magnetic separation

Magnetic separation may be used to further refine heavy mineral concentrates and reduce concentrate volume for picking of mineral species with specific magnetic susceptibilities (Towie & Seet 1995). The most common magnetic separation involves splitting the ferromagnetic from the non-ferromagnetic fraction. Ferromagnetic minerals can comprise a considerable proportion of the concentrate (e.g. Table 2, column F) and therefore removing the ferromagnetic minerals decreases concentrate size prior to indicator mineral selection and removes any steel contaminants derived, in most instances, from sampling tools or drilling equipment. The ferromagnetic fraction may then be (1) set aside, (2) examined to determine the abundance and mineral chemistry of magnetite (e.g. Beaudoin *et al.* 2011), pyrrhotite (McClenaghan *et al.* 2012), or magnetic Mg-ilmenite, as is the case for some kimberlites (e.g. McClenaghan *et al.* 1998), or (3) analyzed geochemically (e.g. Theobald *et al.* 1967). A hand magnet or plunger magnet is most commonly used to carry out this separation.

A specific size fraction of the non-ferromagnetic heavy mineral fraction may be further separated electromagnetically into fractions with different paramagnetic characteristics to help reduce the volume of material to be examined for indicator minerals (Averill & Huneault 2006). Minerals such as diamond are nonparamagnetic; pyrope garnet, eclogitic garnet, Cr-diopside and forsteritic olivine are nonparamagnetic to weakly paramagnetic; and Cr-spinel and Mg-ilmenite are moderately to strongly paramagnetic (see Table 1 in McClenaghan & Kjarsgaard 2007). If the non- or paramagnetic portion of the concentrate contains a significant amount of almandine garnet it may be processed through a magstream separator to separate the orange almandine from similar looking eclogitic or pyrope garnet grains. In this case, magstream separation divides the concentrate into (1) a fraction containing most of

the silicates (e.g. pyrope and eclogitic garnet) and no almandine, and (2) a fraction containing ilmenite, chromite, and other moderately magnetic minerals such as almandine (Baumgartner 2006).

INDICATOR MINERAL SELECTION AND EXAMINATION

The non-ferromagnetic fraction is commonly sieved into two or three (e.g. 0.25–0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm) size fractions for picking of indicator minerals; however the final size range will depend on the commodity sought. For example, kimberlite indicator minerals are most abundant in the 0.25 to 0.5 mm fraction (McClenaghan & Kjarsgaard 2007) and thus, to maximize recovery and minimize counting time and cost, the 0.25 to 0.5 mm fraction is most commonly picked.

Indicator minerals are selected from non-ferromagnetic heavy mineral concentrates during a visual scan, in most cases, from the finer size (e.g. 0.25–0.5 mm, or 0.3–0.5 mm, 0.25–0.86 mm) fractions using a binocular microscope. The grains are counted and a selection of grains is removed from the sample for analysis using an electron microprobe (EMP) to confirm their identification. Methods for examining a sample for counting/picking vary from rolling conveyor belts to dishes/paper marked with lines or grids. If a concentrate is unusually large, then a split is examined and the indicator mineral counts are normalized to the total weight of the concentrate. If a split is picked, the weight of the split and the total weight should both be recorded. Not all grains counted in a sample will be removed for EMP analyses. If this is the case, the total number of grains counted and the number of grains removed should both be recorded.

Indicator minerals are visually identified in concentrates on the basis of colour, crystal habit, and surface textures, which may include features such as kelyphite rims and orange peel textures on kimberlitic garnet (e.g. Garvie 2003; McClenaghan & Kjarsgaard 2007). Scheelite and zircon in a concentrate may be counted under shortwave ultraviolet light. Gold and PGM grains may be panned from concentrates that were prepared such that the silt-sized fraction has been retained (e.g. tabling). The grains may be counted and classified with the aid of optical or scanning electron microscopy. Commonly, gold grains are classified according to their shape/degree of wear (e.g. DiLabio 1990; Averill 2001), which are characteristics that can provide information about relative transport distances (McClenaghan & Cabri 2011).

INDICATOR MINERAL CHEMISTRY

Mineral chemical analysis by EMP, scanning electron microprobe (SEM), laser ablation-ICP-MS, or secondary ion mass spectrometry (SIMS) may be carried out to determine major, minor and trace element contents of specific indicator minerals because mineral chemistry is used to confirm identity, establish mineral paragenesis, and in some cases deposit grade (e.g., Ramsden *et al.* 1999; Belousova *et al.* 2002; Scott 2003; Heimann *et al.* 2005). For example, kimberlite indicator minerals are characterized by a specific range of compositions that reflect their mantle source and diamond grade (e.g. Fipke *et al.* 1995; Schulze 1997; Grütter *et al.* 2004; Wyatt *et al.* 2004). Gold, PGM and sulphide grains may be analyzed to determine their trace element chemistry or isotopic compositions (e.g. Grant *et*

al. 1991; Leake *et al.* 1998; Chapman *et al.* 2009). Prior to indicator mineral grains being selected from a heavy mineral concentrate, newer techniques such as mineral liberation analysis (MLA), computer-controlled scanning electron microscopy (CCSEM), or quantitative evaluation of materials by scanning electron microscopy (QEMSCAN) may provide quantitative mineralogical analysis and identification of indicator minerals in a portion of the heavy mineral concentrate that has been prepared as a polished epoxy grain mount, in the 0.25 to 2.0 mm fraction of the rarely examined <0.25 mm fraction. These methods can be used to identify indicator minerals of interest and prioritize grains for further detailed and more costly EMP analysis, thus reducing EMP analytical costs. The cost per sample for these new techniques is, in general, more expensive than conventional methods.

QUALITY CONTROL

Project geologists may use a combination of blank samples (which contain no indicator minerals), spiked samples (which are known to contain a quantity of specific indicator mineral species or density blocks/beads (e.g. Gent *et al.* 2011)), and field duplicates, as well as repicking of 10% of the heavy mineral concentrates to monitor a laboratory's potential for sample contamination and quality of mineral grain selection. In addition, heavy mineral processing and identification laboratories can be asked to report their own quality control monitoring procedures and test results. Quality assurance and control measures implemented at the Geological Survey of Canada for indicator mineral surveys are described in Spirito *et al.* (2011) and Plouffe *et al.* (in press).

SUMMARY

These workshop notes describe some of the procedures available for processing surficial media and rocks to recover indicator minerals for mineral exploration. The processing method used will depend on: sample media, commodities being sought, budget, bedrock and surficial geology of the survey area, as well as processing methods used for previous batches. When reporting indicator mineral results in company assessment files, government reports, or scientific papers, it is helpful to report the laboratory name, processing methods used, and sample weights. A complete list of metadata that should be reported so that the indicator mineral data can be fully understood, interpreted, and archived is reported in Plouffe *et al.* (in press). Monitoring of quality control is essential at each stage in the processing, picking, and analytical procedures described here and should be monitored both by the processing laboratories and clients. Geologists are encouraged to visit processing and picking laboratories so they have a clear understanding of the procedures being used and can discuss customizations needed for specific sample batches.

REFERENCES

- AVERRILL, S.A. 2001. The application of heavy indicator minerals 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. (eds) *Drift Exploration in Glaciated Terrain*. Geological Society of London, Special Volume **1985**, 69–82.
- AVERRILL, S.A. 2007. Recent advances in base metal indicator mineralogy: An update from Overburden Drilling Management Limited. *EXPLORE, Newsletter of the Association of Applied Geochemists*, **134**, 2–6.

- 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. & HUNECAULT, R. 2006. Overburden Drilling Management Ltd: Exploring heavy minerals. *EXPLORE, Newsletter of the Association of Applied Geochemists*, **133**, 1–5.
- BALLANTYNE, S.B. & HARRIS, D.C. 1997. Alluvial platinum-group minerals and gold in Alberta: Results from the “Orientation Studies Project” and their significance to exploration. In: MACQUEEN, R.W. (ed), *Exploring for Minerals in Alberta*. Geological Survey of Canada Geoscience Contributions, Canada-Alberta Agreement on Mineral Development (1992–1995), Geological Survey of Canada, Bulletin **500**, 279–329.
- BAUMGARTNER, M. 2006. Industry leading laboratory services for diamond explorers. *EXPLORE, Newsletter of the Association of Applied Geochemists*, **133**, 5–10.
- BEAUDOIN, G., DUPUIS, C., MCCLENAGHAN, B., BLAIN, J., & McMARTIN, I. 2011. Application of iron-oxide discriminant diagrams in mineral exploration. In: MCCLENAGHAN, M.B., PEURANIEMI, V. & LEHTONEN, M.L. (Convenors), *Indicator Mineral Methods in Mineral Exploration, Workshop 3*. 25th International Applied Geochemistry Symposium, August 21, 2011, 35–40.
- BELOUSOVA, E.A., GRIFFIN, W.L., O'REILLY, S. & FISHER, N.I. 2002. Apatite as an indicator mineral for mineral exploration: Trace element compositions and their relationship to host rock type. *Journal of Geochemical Exploration*, **76**, 45–69.
- CABRI, L.J., RUDASHEVSKY, N.S., RUDASHEVSKY, V.N. & OBERTHÜR, T. 2008. Electric-Pulse Disaggregation (EPD), Hydroseparation (HS) and their use in combination for mineral processing and advanced characterization of ores. In: *Proceedings. Canadian Mineral Processors 40th Annual Meeting*, Paper **14**, 211–235.
- CHAPMAN, R.J., LEAKE, R.C., BOND, D.P.G., STEDRA, V. & FAIRGRIEVE, B. 2009. Chemical and mineralogical signatures of gold formed in oxidizing chloride hydrothermal systems and their significance within populations of placer gold grains collected during reconnaissance. *Economic Geology*, **104**, 563–585.
- CHERNET, T., MARMO, J. & NISSINEN, A. 1999. Technical note. Significantly improved recovery of slightly heavy minerals from Quaternary samples using GTK modified 3” Knelson preconcentrator. *Minerals Engineering*, **12**, 1521–1526.
- DAVISON, J.G. 1993. Diamond exploration samples: laboratory processing. In: SHEAHAN P. & CHATER, A. (Chairmen) *Diamond: Exploration, Sampling and Evaluation*. Prospectors and Developers Association of Canada, Short Course Proceedings, Toronto, March 27, 1993, 315–341.
- DE SOUZA, H. 2006. Indicator mineral processing at SGS Minerals Services. *EXPLORE, Newsletter of the Association of Applied Geochemists*, **133**, 13–15.
- DiLABIO, R.N.W. 1990. Classification and interpretation of the shapes and surface textures of gold grains from till on the Canadian Shield. In: *Current Research, Part C*. Geological Survey of Canada, Paper **90-1C**, 323–329.
- ENGLISH, B.L., DESBOROUGH, G.A. & RAYMOND, W.H. 1987. *A mechanical panning technique for separation of fine-grained gold and other heavy minerals*. United States Geological Survey, Open File Report **97-0364**.
- FIPKE, C.E., GURNEY, J.J. & MOORE, R.O. 1995. *Diamond exploration techniques emphasizing indicator mineral geochemistry and Canadian examples*. Geological Survey of Canada, Bulletin **423**.
- GARVIE, O.G. 2003. Surface textures found on kimberlite indicator minerals. In: *Indicator Mineral Methods in Mineral Exploration*. Prospectors and Developers Association of Canada, Short Course **2**, March 8, p. 23.
- GRANT, A.H., LAVIN, O.P. & NICHOL, I. 1991. The morphology and chemistry of transported gold grains as an exploration tool. *Journal of Geochemical Exploration*, **40**, 73–94.
- GREGORY, G.P. & WHITE, D.R. 1989. Collection and treatment of diamond exploration samples. In: ROSS, J. (ed) *Kimberlites and Related Rocks Volume 2 Their Crust/Mantle Setting, Diamonds and Diamond Exploration*. Geological Society of Australia, Special Publication **14**, Blackwell Scientific Publications, Oxford, 1123–1134.
- GRÜTTER, H.S., GURNEY, J.J., MENZIES, A.H. & WINTER, F. 2004. An updated classification scheme for mantle-derived garnet, for use by diamond explorers. *Lithos*, **77**, 841–857.
- GRÜTTER, H.S., THIS VOLUME**
- HEIMANN, A., SPRY, P. & TEALE, G.S. 2005. Zincian spinel associated with metamorphosed Proterozoic base-metal sulfide occurrences, Colorado: A re-evaluation of gahnite composition as a guide in exploration. *Canadian Mineralogist*, **43**, 601–622.
- KELLEY, K.D., EPPINGER, R.G., LANG, J., SMITH, S.M. & FEY, D.L. 2011. Porphyry copper indicator minerals (PCIMs) in glacial till samples as an exploration tool: example from the giant Pebble porphyry Cu-Au-Mo deposit. *Geochemistry: Exploration, Environment, Analysis*, **11**, 321–334.
- LAUKKANEN, J., LEHTONEN, M. & SARALA, P. 2011. Exploring RE and REE mineralization using indicator minerals. In: *Workshop 3: Indicator Mineral Methods in Mineral Exploration*. 26th International Applied Geochemistry Symposium, Association of Applied Geochemists, 13–18.
- LEAKE, R.C., BLAND, D.J., STYLES, M.T. & CAMERON, D.G. 1991. Internal structure of Au-Pd-Pt grains from south Devon, England, in relation to low temperature transport and deposition. *Transactions of the Institute of Mining and Metallurgy*, Section B, Applied Earth Sciences, **100**, B159–B178.
- LEAKE, R.C., CHAPMAN, R.J., BLAND, D.J., STONE, P., CAMERON, D.G. & STYLES, M.T. 1998. The origin of alluvial gold in the Leadhills areas of Scotland: evidence from interpretation of internal characteristics. *Journal of Geochemical Exploration*, **63**, 7–36.
- LEHTONEN, M.L., MARMO, J.S., NISSINEN, A.J., JOHANSON, B.S. & PAKKANEN, L.K. 2005. Glacial dispersal studies using indicator minerals and till geochemistry around two eastern Finland kimberlites. *Journal of Geochemical Exploration*, **87**, 19–43.
- LE COUTEUR, P.C. & MCLEOD, J.A. 2006. Heavy mineral processing at Vancouver Indicator Processors Inc./Teck Cominco Global Discovery Lab. *EXPLORE, Newsletter of the Association of Applied Geochemists*, **133**, 15–18.
- MAURICE, Y.T. & MERCIER, M.M. 1986. A new approach to sampling heavy minerals for regional geochemical exploration. In: *Current Research Part A*. Geological Survey of Canada, Paper **86-1A**, 301–305.
- MCCLENAGHAN, M.B. 2009. Processing methods for recovery of indicator minerals from sediment and bedrock. In: *Workshop B Indicator Mineral Methods in Mineral Exploration*. 26th International Applied Geochemistry Symposium, Association of Applied Geochemists, 13–20.
- MCCLENAGHAN, M.B. 2011. Overview of common processing methods for recovery of indicator minerals from sediment and bedrock in mineral exploration. *Geochemistry: Exploration, Environment, Analysis*, **11**, 265–278.
- MCCLENAGHAN, M.B. & CABRI, L.J. 2011. Review of gold and platinum group element indicator minerals methods for surficial sediment sampling. *Geochemistry: Exploration, Environment, Analysis*, **11**, 251–263.
- MCCLENAGHAN, M.B. & KJARSGAARD, B.A. 2007. Indicator mineral and surficial geochemical exploration methods for kimberlite in glaciated terrain, examples from Canada. In: GOODFELLOW, W.D. (ed.) *Mineral Resources of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces and Exploration Methods*. Geological Association of Canada, Special Publication No. **5**, 983–1006.
- MCCLENAGHAN, M.B., PAULEN R.C., AYER, J.A., TROWELL, N.F. & BAUKE, S. 1998. *Regional till and bumus geochemistry of the Timmins-Kamiskotia (NTS 42A/11, 12, 13, 14) area, northeastern Ontario*. Geological Survey of Canada, Open File **3675**.
- MCCLENAGHAN, M.B., KJARSGAARD B.A., KJARSGAARD I.M., & PAULEN, R.C. 1999. *Mineralogy and geochemistry of the Peddie kimberlite and associated glacial sediments, Lake Timiskaming, Ontario*. Geological Survey of Canada, Open File **3775**.
- MCCLENAGHAN, M.B., KJARSGAARD, I.M. & KJARSGAARD, B.A. 2004. *Kimberlite indicator mineral chemistry and till geochemistry around the Seed and Triple B kimberlites, Lake Timiskaming, Ontario*. Geological Survey of Canada, Open File **4822**.
- MCCLENAGHAN, M.B., AVERILL, S.A., KJARSGAARD, I.M., LAYTON-MATTHEWS, D. & MATILE, G. 2011. Indicator mineral signatures of magmatic Ni-Cu deposits, Thompson Nickel Belt, central Canada. In: *Workshop 3: Indicator Mineral Methods in Mineral Exploration*. 26th International Applied Geochemistry Symposium, Association of Applied Geochemists, 67–72.
- MCCLENAGHAN, M.B., BUDULAN, G., AVERILL, S.A., LAYTON-MATTHEWS, D. & PARKHILL, M.A. 2012. *Indicator mineral abundance data for bedrock and till samples from the Halfmile Lake Zn-Pb-Cu volcanogenic massive sulphide deposit, Bathurst Mining Camp, New Brunswick*. Geological Survey of Canada, Open File **7076**.
- McMARTIN, I., CORRIVEAU, L. & BEAUDOIN, G. 2011. An orientation study of the heavy mineral signature of the NICO Co-Au-Bi deposit, Great Bear magmatic zone, NWT, Canada. *Geochemistry: Exploration, Environment, Analysis*, **11**, 293–307.
- MIRCEA, C. 2006. Kimberlite indicator mineral services offered by SRC Geoanalytical Laboratories. *EXPLORE, Newsletter of the Association of Applied Geochemists*, **133**, 10–13.
- MUGGERIDGE, M.T. 1995. Pathfinder sampling techniques for locating primary source of diamond: recovery of indicator minerals, diamonds and geochemical signatures. *Journal Geochemical Exploration*, **53**, 183–204.
- PAULEN, R.C., PARADIS, S., PLOUFFE, A. & SMITH, I.R. 2011. Pb and S isotopic composition of indicator minerals in glacial sediments from northwest Alberta, Canada: implications for Zn-Pb base metal exploration. *Geochemistry: Exploration, Environment, Analysis*, **11**, 309–320.
- PLOUFFE, A., MCCLENAGHAN, M.B., PAULEN, R.C., McMARTIN, I., CAMPBELL, J.E. & SPIRITO, W.A. In press. Processing of glacial sediments for the

- recovery of indicator minerals: protocols used at the Geological Survey of Canada. *Geochemistry: Exploration, Environment, Analysis*.
- PEURANIEMI, V. 1990. Chapter 10. Heavy minerals in glacial sediment. In: KUJANSUU, R. & SAARNISTO, M. (eds), *Glacial Indicator Tracing*. A.A. Balkema, Rotterdam, 165–185.
- RAMSDEN, A.R., GRIFFIN, W.L. & FRENCH, D.H. 1999. Application of resistate indicator mineralogy to metalliferous exploration: tourmaline. In: *Research Review*. CSIRO Exploration and Mining, 49–52.
- SARALA, P. & PEURANIEMI, V. 2007. Exploration using till geochemistry and heavy minerals in the ribbed moraine area of southern Finnish Lapland. *Geochemistry: Exploration, Environment, Analysis*, **7**, 195–205.
- SARALA, P., PULKKINEN, E., JUHANI OJALA, V. & PELTONIEMI-TAIVALKOSKI, A. 2009. Gold exploration using till at Petäjälähtö, northern Finland. *Geochemistry: Exploration, Environment, Analysis*, **9**, 247–255.
- SCHULZE, D.J. 1997. The significance of eclogite and Cr-poor megacryst garnets in diamond exploration. *Exploration and Mining Geology*, **6**, 349–366.
- SCOTT, K. 2003. Rutile geochemistry as a guide to mineralization at the Northparkes porphyry copper deposit, New South Wales, Australia. In: *Programme and Abstract*. International Geochemical Exploration Symposium 2003- North Atlantic Minerals Symposium 2003, 44.
- SILVA, M. 1986. *Placer gold recovery methods*. California Department of Conservation, Division of Mines and Geology, Special Publication **87**.
- SIVAMOHAN, R. & FORSSBERG, E. 1985. Principles of tabling. *International Journal of Mineral Processing*, **15**, 281–295.
- SPIRITO, W., MCCLENAGHAN, M.B., PLOUFFE, A., McMARTIN, I., CAMPBELL, J.E., PAULEN, R.C., GARRETT, R.G. & HALL, G.E.M. 2011. *Till sampling and analytical protocols for GEM projects: from field to archive*. Geological Survey of Canada, Open File **6850**.
- STENDAL, H. & THEOBALD, P.K. 1994. Heavy-mineral concentrates in geochemical exploration. In: HALE, M. & PLANT, J.A. (eds), *Drainage Geochemistry*. Handbook of Exploration Geochemistry, **6**, 185–225.
- STEWART, R. 1986. Routine heavy mineral analysis using a concentrating table. *Journal of Sedimentary Research*, **56**, 555–556.
- THEOBALD, P.K., OVERSTREET, W.C. & THOMPSON, C.E. 1967. *Minor elements in alluvial magnetite from the Inner Piedmont Belt, North and South Carolina*. United States Geological Survey, Professional Paper **554-A**.
- TOWIE, N.J. & SEET, L.H. 1995. Diamond laboratory techniques. *Journal of Geochemical Exploration*, **53**, 205–212.
- WIERCHOWIEC, J. 2002. Morphology and chemistry of placer gold grains – indicators of the origin of the placers: an example from the East Sudetic Foreland, Poland. *Acta Geologica Polonica*, **52**, 563–576.
- WYATT, B.A., BAUMGARTNER, M., ANCKAR, E. & GRÜTTER, H. 2004. Compositional classification of kimberlitic and non-kimberlitic ilmenite. *Lithos*, **77**, 819–840.
- ZANTOP, H. & NESPEREIRA, J. 1979. Heavy-mineral panning techniques in the exploration for tin and tungsten in NW Spain. In: WATTERSON, J.R. & THEOBALD, P.K. (eds) *Geochemical Exploration 1978*. Association of Exploration Geochemists, 329–336.
- ZESCHKE, G. 1961. Prospecting for ore deposits by panning heavy minerals from river sands. *Economic Geology*, **56**, 1250–1257.

