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(e-mail: jessica.pollitt@geolsoc.org.uk)

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Cover illustration: Dave Kelley taking water samples in the forefront of the Devil's Tower, about 35 km NW of Sundance, Wyoming. Photo taken by Simon Bolster, Newmont Mining Corporation.

Overview of common processing methods for recovery of indicator minerals from sediment and bedrock in mineral exploration

M. Beth McClenaghan

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

ABSTRACT: Over the past two decades, the application of indicator mineral methods to mineral exploration has expanded significantly such that they are now used to explore globally for a broad spectrum of commodities. Indicator mineral suites have been identified for a variety of ore deposit types including diamond, Au, Ni-Cu, PGE, metamorphosed volcanogenic massive sulphide, porphyry Cu, U, Sn and W. Indicator minerals, which include ore, accessory and alteration minerals, are sparse in unconsolidated sediments, thus sediment samples must be concentrated in order to recover and examine them. Because most indicator minerals have a moderate to high specific gravity, processing techniques involving density separation, in combination with sizing and magnetic separation, are used to recover them from sediment samples. This paper reviews the commonly used processing methods including panning, hydroseparation, tabling, Knelson concentrators, spiral concentrators, dense media separators, jigs and various types of magnetic separators, as well as mineral selection and mineral chemistry determinations. Monitoring of quality control is essential at each stage in these processing, picking and analytical procedures. When reporting indicator mineral results, processing methods, fraction weights and size ranges, and laboratory name should all be recorded, in addition to indicator mineral abundance data.

KEYWORDS: *indicator mineral, heavy mineral, gravity concentration, overview*

The concentration of heavy minerals and recovery of indicator minerals from surficial sediment is one of the oldest exploration methods, being first applied to stream sediments (Brundin & Bergström 1977). The application of indicator mineral methods has grown and developed significantly over the past two decades such that indicator mineral methods are now applied worldwide to a variety of media including stream sediments, alluvium, colluvium, aeolian sediments, glacial sediments, and regolith in deeply weathered terrains for a broad spectrum of commodities. Indicator minerals are also recovered from weathered and fresh bedrock as well as mineralized float. Heavy mineral suites have been identified for detecting a variety of ore deposit types including diamond, Au, Ni-Cu, PGE, metamorphosed volcanogenic massive sulphide, porphyry Cu, (e.g. Averill 2011) U, Sn and W.

Indicator minerals, including ore, accessory and alteration minerals, are usually sparsely distributed in their host rocks and are commonly even less concentrated in derived unconsolidated sediments. As few as one or two sand-sized grains of a particular 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 (Peuraniemi 1990; Towie & Seet 1995). In reducing the volume of material, processing techniques must be able to retain the indicator mineral(s) and do so without contaminating the sample, without losing indicator minerals, and at a reasonable cost. Most indicator minerals have a moderate to high specific gravity, thus

most processing techniques concentrate indicator minerals using some type of density separation, often in combination with sizing and magnetic separations.

Heavy mineral methods progressed since the early to mid 1900s such that commercial labs now provide consistent heavy mineral recovery services, quality control for processing is well monitored at all stages, and the major, minor and trace element composition of individual mineral grains can be characterized almost instantaneously at the micrometre scale. A variety of processing methods (e.g. Gregory & White 1989; Peuraniemi 1990; Stendal & Theobald 1994; Towie & Seet 1995; Davison 1993; Chernet et al. 1999; McClenaghan *et al.* 1999) may be used to reduce the sample volume, concentrate heavy minerals, and recover indicator minerals (Fig. 1). This paper describes some of the common processing methods used by the exploration industry and government organizations, including those for deposits of diamond, precious and base metals, and U. The methods used will depend on the commodities being sought, deposit type and cost per sample. Most oxide and silicate indicator minerals such as those for kimberlite, Ni-Cu-PGE, and metamorphosed massive sulphide indicator deposits (Averill 2001, 2007) are medium to coarse sand size (0.25–2.0 mm). Thus concentration techniques that recover the sand-sized heavy minerals can be used. Approximately 90% of gold grains, platinum group minerals (PGMs), including native PGMs and PGE bearing sulphides, arsenides/antimonides and tellurides, in source rocks are silt-sized (<0.063 mm), thus concentration of these minerals requires preconcentration techniques that

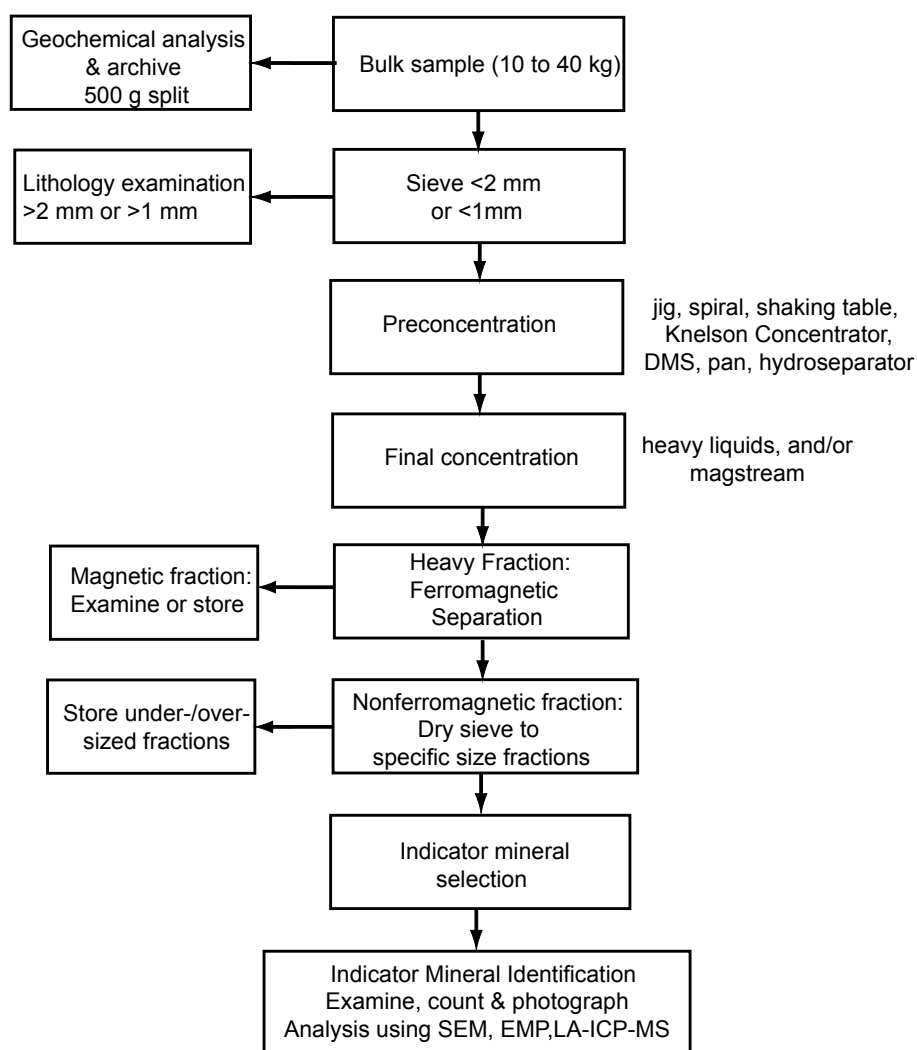


Fig. 1. Generalized flow sheet showing steps in sample processing used to reduce sample weight, concentrate heavy minerals, and recover indicator minerals.

include recovery of the silt-sized fractions. The description of processing methods for recovery of indicator minerals provided in this paper will be valuable to mineral exploration companies and prospectors, government agencies and other researchers that need to select cost-effective and efficient methods for the recovery of specific indicator minerals.

METHODS

Sample weight

The weight of material collected for indicator mineral studies will depend on the type of surficial sediment collected, the grain size characteristics of the sample material, the exploration target and shipping costs (Table 1). For example, in glaciated terrain clay-rich till samples may be 30–60 kg, or more, in order to recover a sufficient weight of sand-sized heavy minerals (Table 2, Buffalo Head Hills). Coarse-grained silty sand till typical of shield terrain requires smaller (10–20 kg) samples because it contains more sand-sized material in the matrix (Table 2). Alluvial sand and gravel samples collected for recovery of porphyry Cu indicator minerals (PCIM) need only be \approx 0.5 kg because porphyry Cu alteration systems are large and rich in indicator minerals (Averill 2007). Bedrock and float samples usually vary from 1–5 kg.

Bedrock preparation

Bedrock and float samples often need to be disaggregated or crushed prior to processing to reduce rock fragment/mineral

grain size to <2 mm or to the average size of mineral grains in the sample. Electric pulse disaggregation (EPD) (e.g. Cabri *et al.* 2008a, b) provides a fast and efficient means of liberating mineral grains from a rock irrespective of lithology or grain-size. Using EPD, rocks are disaggregated by applying an electric current from a high-voltage power source to a sample in a water bath. The major advantage of this method is that the rapid distribution of electric pulses through the sample leads to ‘explosions’ that occur preferentially along grain boundaries (zones of weakness). As a result, individual, undamaged mineral grains can be recovered in their original shape and form regardless of grain size (CNT-MC 2009). This technology is now available worldwide in research labs and commercial heavy mineral processing labs. Conventional rock crushers may also be used; however, they are more difficult to clean between samples and thus pose a higher risk of cross-contamination, often break rock fragments across grain boundaries, and mark/damage grains as they are liberated. Barren quartz should be disaggregated or crushed as a blank between samples to reduce and monitor contamination. Rock sample weights will depend on the deposit type and grade of ore samples.

Preconcentration

If sample shipping costs are a significant issue, samples may be partly processed in the field to reduce the weight of material shipped to the lab, thus lowering shipping costs. Samples may be sieved to remove the coarse (>1 or >2 mm) fraction, which

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

Exploration Target	Typical Sample Weight (kg)	Number of Shaking Table Passes?	Required Separations			
			Micropanning?	Heavy Liquid (Specific Gravity)	Ferro-Magnetic 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 (PGE only)	3.2	Yes	Yes
	0.5	No	No	2.8, 3.2	Yes	Two
	10	Single	Yes	3.3	Yes	No
	20	Triple	No	3.3	Yes	Optional
Heavy mineral sands (grade evaluation)						
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

Table 2. Weight of each fraction generated using a combination of shaking table and heavy liquid separation in methylene iodide to reduce till sample weight, concentrate heavy minerals, and recover indicator minerals in till samples from various locations across Canada: (A) initial sample weight; (B) sieving off <2 mm; (C) & (D) tabling; (E) heavy liquid separation; (F) magnetite separation; (G) final heavy mineral concentrate weight. Locations: (1) South Pit, Thompson Ni Mine, Thompson, Manitoba; (2) Broken Hammer Cu-PGE resource, Sudbury, Ontario; (3) Pamour Au Mine, Timmins, Ontario; (4) Triple B kimberlite, Lake Timiskaming field, Ontario; and (5) Buffalo Head Hills kimberlite field, Alberta

GSF Sample Number	Location	Sediment type and Texture	A: Total sample weight (kg)	B: Weight >2 mm Clasts (kg)	C: Weight put across shaking table (kg)	D: Weight shaking table concentrate produced (g)	E: Weight heavy liquid light fraction (g)	F: Weight ferromagnetic fraction (g)	G: Weight non-magnetic heavy mineral concentrate (g) 0.25–2.0 mm	Data source
05-MPB-009	(1) Thompson Ni Belt	silty sand till	15.0	3.0	12.0	1016	105	36.4	47.9	McClenaghan et al. 2009
06MPB-012	(2) Sudbury North Range	very sandy till	15.0	5.6	9.4	1125	403	13.0	18.9	GSC, unpublished data
96MPB6080A	(3) Timmins Au camp	silty sand till	11.8	2.3	9.5	353	320	5.2	28.1	McClenaghan et al. 1998
MPB-02-1008	(4) Lake Timiskaming Kimberlite field	silty sand till	9.8	1.2	8.6	439	377	22.0	35.8	McClenaghan & Kjarsgaard 2003
03-MPB-001	(5) Buffalo Head Hills Kimberlite field	clay till	67.4	2.4	65.0	1307	1235	5.6	11.5	GSC, unpublished data

may reduce weights from a few % to 30% (e.g. Table 2: columns B–C). Preconcentrating may be carried out in the field to further reduce the weight of material to be shipped. Preconcentrates produced in the field offer the advantage of significantly reducing the time to obtain results for follow-up. However, preconcentrating in the field may be expensive and time-consuming and the available methods may not provide consistent or optimal recovery of the indicator minerals of interest.

Whether sieved off in the field or in the lab, the coarse >2 mm fraction may be examined (pebble counts) to provide additional information about sample provenance and transport distance. The <2 (or <1 mm) fraction is preconcentrated most commonly using sieving and gravity concentration methods (e.g. jig, shaking table, spiral, dense media separator, pan, Knelson Concentrator) to reduce the weight of material to be examined without losing indicator minerals. Most gold, PGM, and sulphide minerals are silt-sized (Averill & Huneault 2006) and best recovered from this size fraction by panning or hydroseparation.

Panning

Panning is the oldest method used to recover indicator minerals, primarily for gold and PGM. Panning techniques have been described in detail by several users of the technique (e.g. Mertie 1954; Waters 1983; Silva 1986; English *et al.* 1987; Muggeridge 1995; Ballantyne & Harris 1997). Sediment is placed in a pan and shaken sideways in circular motion while being held just under water, the heavy minerals sink to the pan bottom and light minerals are carried upwards in suspension and spill out over the pan sides. Pans are of varying shapes (flat bottomed or conical) and sizes, and may be made out of plastic, metal or wood (e.g. Stendal & Theobald 1994; Muggeridge 1995). The advantages of panning include ease of use, low capital cost, adaptability to both field or lab-based operations, and ability to greatly reduce weight of field samples and thus the cost of shipping them to the laboratory. Panning is often used in combination with other preconcentration methods to recover silt-sized precious metal grains (e.g. Gleeson & Boyle 1980; Grant *et al.* 1991; Leake *et al.* 1991, 1998; Ballantyne & Harris 1997; Pueraniemi & Gehör 2000; Wierchowicz 2002). The disadvantages of this method are that it is slow, can process only small volumes of material at one time, and is highly dependent on the experience and skill of operator and therefore requires consistent personnel to perform the panning. It is a considered to be a rough concentrating method when used in the field and is followed up with further lab-based concentration techniques (Stendal & Theobald 1994; Muggeridge 1995).

Hydroseparation

Hydroseparators (HS) may be used to produce heavy mineral concentrates of grains from sediment samples that follow Stokes Law when settling in an upward flowing pulsating water stream (Fig. 2). Hydroseparators consist of two separate parts: a water flow regulator (WFR) to modulate the water flow, pulse intensity and pulse rate, and a glass separation tube (GST). Sample material is introduced at the top of the GST. Light minerals move upwards in the GST, eventually flowing over the top into a collecting container outside the GST. Heavy minerals collect inside the GST at its base and are washed out after separation is completed. Ideally, mineral grains processed in a HS should have densities from 3–20 g/cm³ and be <0.3 mm. Different sizes of GST are used for separation, depending on the grain-size and the required productivity of processing and

the amount of loaded sample. For bench-top sized set-ups, typical aliquots to be separated are 10 g to 2 kg; however, 100–300 g each of various size fractions (e.g. <45 µm, 45–75 µm, 75–150 µm, 150–250 µm) are recommended, especially for the finest fractions (CNT-MC 2009). Processing an aliquot of *c.* 100 g usually results in a final concentrate of 5 to 20 mg. The HS method is optimal for recovery of silt-sized precious metal minerals from small (10s to 100s of g) samples. Recent examples of applying this technique include PGM recovery from ultramafic rocks (e.g. Rudashevsky *et al.*, 2002; Cabri *et al.* 2006, 2008a, b; Grammatikopoulos *et al.* 2007). HS could be useful for gold, PGM and sulphide recovery from the <0.25 mm fraction of till heavy mineral concentrates, a fraction often not examined in detail for these minerals.

Shaking table

Preconcentration using a shaking table is a commonly used method for separating minerals on the basis of density (Silva 1986; Wills 1988; Towie & Seet 1995). 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; de Souza 2006). A brief description of the method is summarized below from Silva (1986). The table consists of a deck covered with up to 1-cm high riffles covering over half the surface (Fig. 3a). 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 and water is fed along the top of the table perpendicular to the direction of the table motion. The table is shaken sideways lengthwise using a slow forward stroke and a fast return strike that causes the grains to crawl along the deck parallel to the direction of motion. The shaking motion combined with the water wash moves grains diagonally across the deck from the feed end and separates them on the table according to size and density (Fig. 3b). The water flow rate, tilt of the table, and intensity of the shaking motion must be adjusted properly for effective mineral recovery. If kimberlite indicators are targeted, the sample may be tabled twice to ensure higher recovery of the key lower density minerals such as Cr-diopside and forsteritic olivine, and the coarsest grains. The advantages of this method are its moderate cost, ability to recover indicator minerals for a broad spectrum of commodities, high visibility of mineral grains being separated, and ability to recover silt as well as sand-sized indicators. Use of a shaking table is a well-established method for the recovery of gold (e.g. English *et al.* 1987; McClenaghan *et al.* 1998, 2004; McMartin 2009), platinum group minerals (e.g. Bajc & Hall 2000; Searcy 2001), and kimberlite indicator minerals (e.g. Towie & Seet 1995; McClenaghan & Kjarsgaard 2003). The disadvantages of this method include some loss of the largest and lightest heavy minerals, a relatively slow processing rate of 40–60 minutes per sample including the extra time required to isolate and describe any contained gold and PGM grains, and significant dependence on the skill of the table operator.

Dense media separator

A gravity method commonly used to preconcentrate kimberlite indicator minerals is the micro-scale dense media separator (DMS) (Fig. 4). An overview of this method is summarized below from Baumgartner (2006). Heavy mineral concentration is carried out using a gravity-fed high-pressure cyclone. The <1 mm fraction of a sample is mixed with fine-grained ferrosilicon (FeSi) to produce a slurry that has a controlled density. The slurry is fed into a cyclone where the grains travel radially and

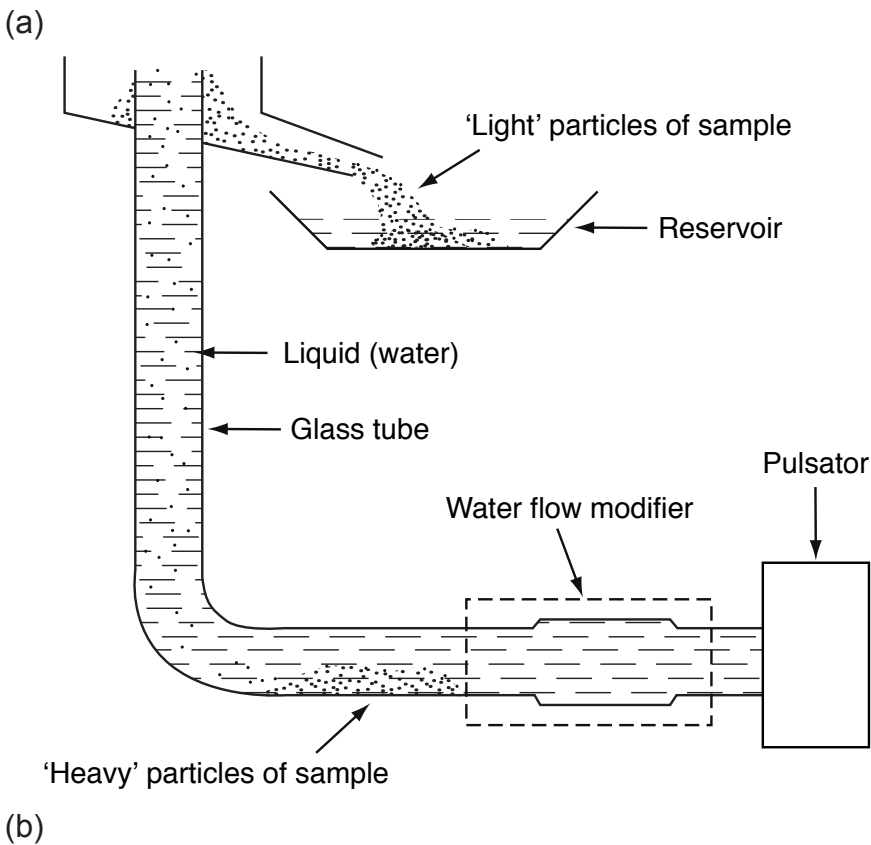


Fig. 2. (a) Schematic cross-section of a hydroseparator (modified from Rudaskevsky *et al.* 2002); and (b) photograph of hydroseparator model HS-11 set up. Light minerals collect in container outside the glass separation tube (GST) and heavy minerals collect inside the tube (photo courtesy of CNT-MC website, <http://www.cnt-mc.com/services/hs.html>).

helically, forcing the heavier particles toward the wall of the cyclone and the lighter particles toward the center. 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 >0.25 or 0.3 mm heavy fraction is then dried and screened to remove residual FeSi. The cut-point or threshold for accepting or rejecting minerals spans a density range of 0.2 g/cm³ at \approx 3.1 g/cm³ and is calibrated to recover the common kimberlite indicator minerals that have a specific gravity

>3.1: pyrope garnet, eclogitic garnet, Cr-spinel, Mg-ilmenite, Cr-diopside, forsteritic olivine and diamond. The required cut-point is tested using synthetic density beads before proceeding with processing the samples. Density settings and cut-points should be checked once per day to maintain accurate specific gravity thresholds. The advantages of the micro DMS system are that it is fast, less susceptible to sample contamination than other heavy mineral concentrating techniques due to ease of cleaning the equipment and is not operator dependent. The method,

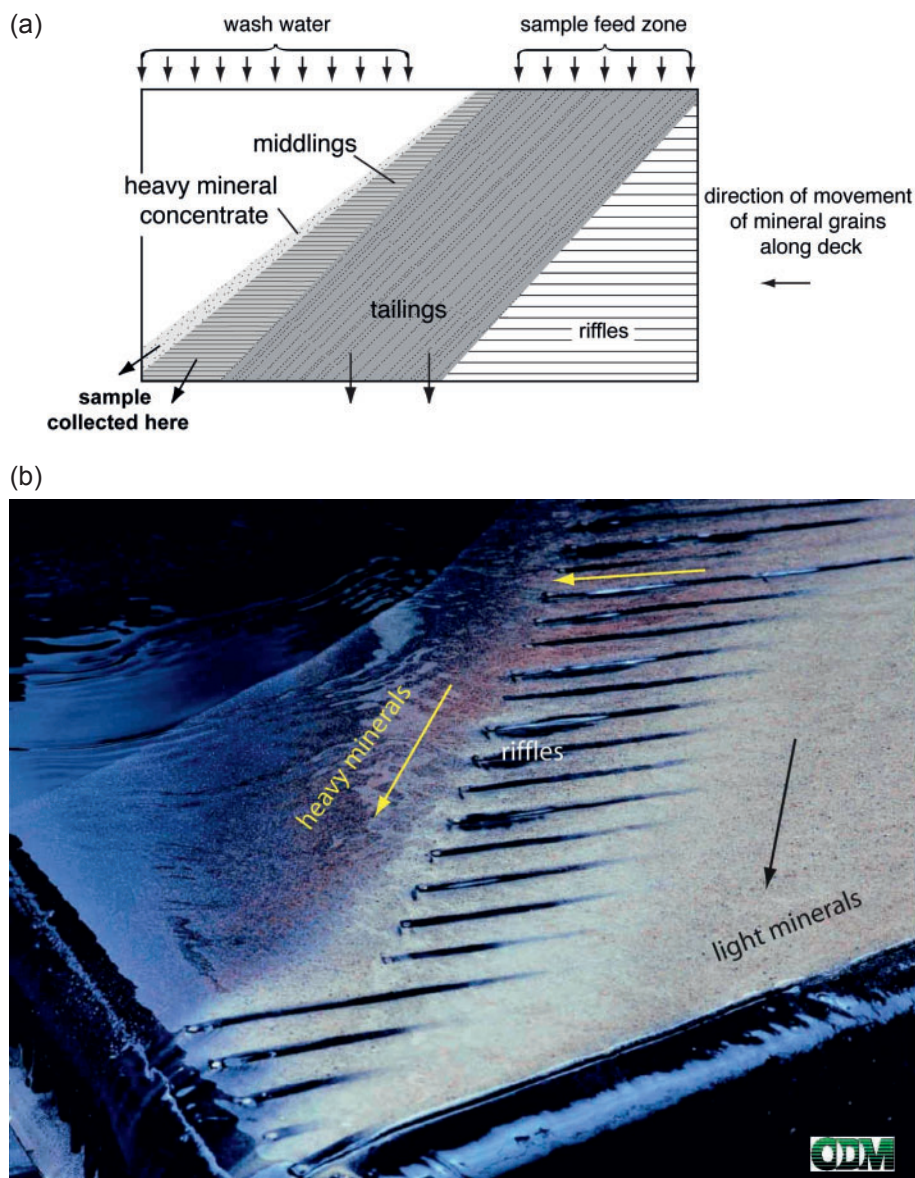


Fig. 3. (a) Schematic plan view of a shaking table (modified from Silva 1986); (b) close-up of heavy minerals separating from light minerals on a shaking table (photo provided by Overburden Drilling Management Ltd).

however, is more expensive than other methods described here and it does recover <0.25 mm indicator minerals.

Knelson concentrator

The Knelson concentrator is a fluidized centrifugal separator (Fig. 5) that was originally designed for concentrating gold and platinum from placer and bedrock samples. However, in recent years it has also been used to recover kimberlite indicator minerals from sediment samples (e.g. Chernet *et al.* 1999; Lehtonen *et al.* 2005). The concentrator can handle particle sizes from >10 µm up to a maximum of 6 mm. The general processing procedure is summarized below from the Knelson Concentrator website (<http://www.knelsongravitysolutions.com/>). Briefly, pressurized water is introduced into a spinning 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 centrifugal force from the spinning cone. Heavy mineral grains are captured in the rings and retained in the concentrating cone and light minerals are carried by water flow out the top. At the end of the concentrate cycle, concentrates

are flushed from the cone into the sample collector. The procedure of Chernet *et al.* (1999) for kimberlite indicator minerals takes 5–11 minutes per sample. The advantages of the Knelson concentrator are that it is fast, inexpensive, and can be used in a lab or mobilized to the field to reduce the weight of material to be shipped to the lab. 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). Knelson concentrators are optimal for recovery of gold and PGM.

Rotary spiral concentrator

Heavy minerals can be recovered using a rotary spiral concentrator which consists of a flat circular stainless steel or plastic bowl with ribs that spiral inward (Fig. 6), a detailed description of which 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

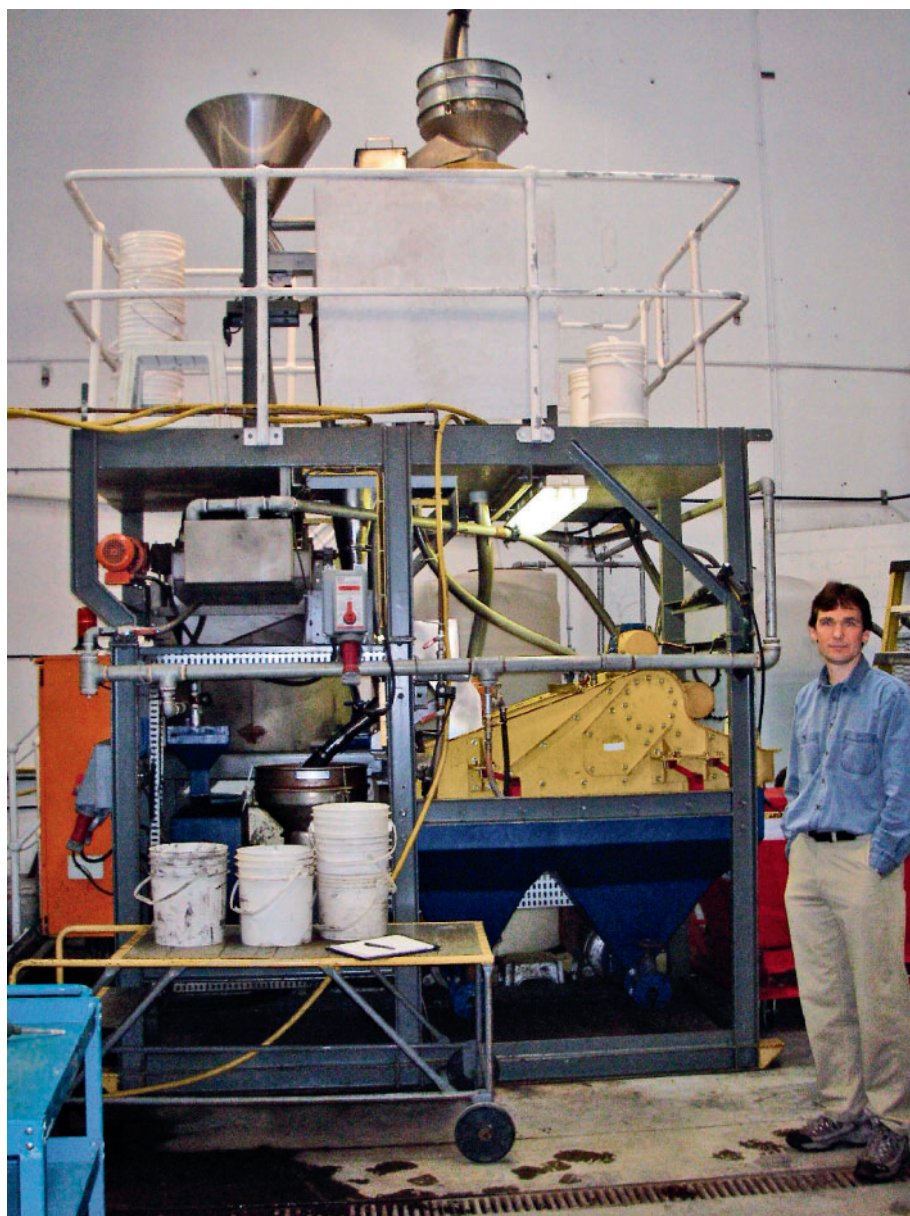


Fig. 4. Micro dense media separator used at Mineral Services Canada to separate kimberlite indicator minerals (photo provided by Mineral Services Canada).

bowl. Water washes light minerals down and over the lower side of the bowl. The heaviest minerals are recovered first. The speed of rotation, tilt of the bowl and water flow rate require adjustments for the separation to be efficient. The advantages of the spiral concentrator are that it can be field-based and thus reduce sample weight to be shipped, it is inexpensive to acquire and operate, it is fast if the material is sandy, and it recovers indicator minerals across a broad grain size range from silt to sand size 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 (Silva 1986; Wills 1988). It separates heavy minerals based on

differential settling velocities of mineral grains in water, induced either by pulsing water through the sample or pulsing the sample within 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 center of the screen forming an 'eye'. The screen is inverted in order to examine and sample this base layer of heavy minerals. Very heavy minerals such as ilmenite and magnetite will be found the very center 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 center despite their moderate specific gravity (3.52). A spoon or specialized tool is used to scoop up the heavy minerals in the eye for more detailed processing and examination. For optimal recovery, the jig tailings should be re-jigged 2 to 3 times until no eye exists. The method is typically used for recovery of gold (e.g. Silva



Fig. 5. Lab-based Knelson concentrator used to prepare a preconcentrate for recovery of kimberlite indicator minerals by the Geological Survey of Finland (photo provided by M. Lehtonen, Geological Survey of Finland).

1986) and kimberlite indicator minerals (Muggeridge 1995). The advantages of using a jig are that it can be field-based and thus reduce sample weight to be shipped, is inexpensive to operate, is relatively fast and works best for fine to coarse sand-sized grains. It is best used in a fixed, lab-based setting with an experienced operator.

Final concentration

Heavy liquid separation

A preconcentrate is usually further refined using heavy liquids of a precise density to further reduce the size of the concentrate prior to heavy mineral selection (Table 2, column E). Heavy liquid separation (Fig. 7) provides a sharp separation between heavy (sink) and light minerals (float) at an exact known density. It is slow and expensive and therefore not economical for large volumes of sample material, hence the preconcentration procedures described above are used to prepare a preconcentrate before this step (Stendal & Theobald 1994). The most common heavy liquids used are reported by Towie & Seet (1995) and 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 required of the heavy liquid will depend on the indicator minerals being sought. Some labs use a combination of both heavy liquids, separating first using the lower density heavy liquid at *c.* 2.9 to reduce the volume of material to be further separated at 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 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 2.8–3.2 to recover the mid density indicators tourmaline (dravite), alunite, jarosite, and turquoise (Averill 2007, 2011). Some indicator minerals such as apatite and fluorite, which may contain deposit-specific traces of certain REE, are of an 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). Magnetic properties of minerals are measured in relation to the equipment and settings used for separation, as shown in the example in Figure 8. Minerals normally have narrow ranges of magnetic susceptibility but this range may increase because of variations in their chemical composition, intergrown minerals or inclusions. For example, inclusions of magnetite in olivine increase the paramagnetic susceptibility (e.g. Table 1 in McClenaghan & Kjarsgaard 2007). Diamagnetic minerals (e.g. gold, silver, galena, sphalerite, pyrite, goethite, apatite, zircon, diamond) have a very weak, negative susceptibility to magnetic fields, they are slightly repelled by a magnetic field and do not retain the magnetic properties when the external field is removed. Paramagnetic minerals have a weak, positive susceptibility only to externally applied magnetic fields and do not retain the magnetic properties when the external field is removed. These include garnet, rutile, and Fe-bearing minerals such as garnet, olivine, chromite, ilmenite, and orthopyroxene. Ferromagnetic minerals (e.g. magnetite, pyrrhotite and some PGM alloys) have a large, positive susceptibility to an external magnetic field, and retain their magnetic properties after the external field has been removed. The stronger the current (amperage) applied to the electromagnet the stronger the magnetic field produced will be. For example, at a <0.5 amp setting, strongly paramagnetic to paramagnetic minerals can be separated from a sample. At a higher, >1 amp setting, only the very weakly paramagnetic and non-paramagnetic minerals are left behind.

The most common magnetic separation is splitting the ferromagnetic from the nonferromagnetic fraction because the ferromagnetic minerals can comprise a considerable portion of the concentrate (e.g. Table 2, column F). Removing the ferromagnetic minerals decreases concentrate size prior to indicator mineral selection and removes any steel contaminants. The ferromagnetic fraction may be set aside, examined to determine the abundance and mineral chemistry of magnetite (e.g. Beaudoin *et al.* 2009), pyrrhotite, or magnetic ilmenite, as is the case for some kimberlites (e.g. McClenaghan *et al.* 1998), or this fraction may be analysed geochemically. A hand magnet or plunger magnet (Fig. 8) 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). Indicator 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). The Frantz Isodynamic Separator may be used to separate non-ferromagnetic minerals of varying paramagnetism (e.g. Mircea 2006). It consists of a large



Fig. 6. Lab-based rotary spiral concentrator used by the Geological Survey of Finland (photo from P. Sarala, Geological Survey of Finland).



Fig. 7. Separation of heavy and light minerals is carried out using a specific heavy liquid of known density in separatory funnels, Heavy mineral sink and light mineral float to the top (photo provided by Overburden Drilling Management Ltd).

electromagnet through which heavy mineral concentrates are passed on a metal trough that is divided near its exit end. Varying the strength of the magnetic field and/or slope of the separation trough is used to separate minerals of varying paramagnetism (Jones 1987; Stendal & Theobald 1994). A roll separator is a faster alternative to the Frantz separator and utilizes magnetic force and gravity to capture weakly magnetic materials. It consists of a rotating cylinder around an electromagnet and a hopper that feeds sample material down onto the rotating cylinder (Fig. 10). Varying the strength or amperage of the electromagnetic field applied separates minerals of varying paramagnetism. Non-magnetic minerals are not attracted to the magnet and as a result are thrown off the rotating cylinder by centrifugal force, fall down a chute and are collected in a pan. Paramagnetic minerals are attracted to the magnet, but after rotation past the magnet fall off into a second collection chute (Jones 1987).

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 garnets. Magstream separation divides the concentrate into: (1) a fraction containing most of the silicate indicators (e.g. pyrope and eclogitic garnet) and no almandine; and (2) a fraction containing ilmenite, chromite and other moderately paramagnetic minerals such as almandine (Baumgartner 2006). The magstream separator is a rotation-based separation system that is dependent on specific gravity as well as magnetism. The concentrate to be separated is combined with a ferrofluid and passed downward through a long, vertical column that is surrounded by a magnetic field (Svoboda 2004). The grains rotate in the column at a specific speed. Lighter and/or non-paramagnetic particles move radially inwards through the ferrofluid (Fig. 11) and heavier and/or paramagnetic particles,



Fig. 8. A hand magnet is commonly used to remove the ferromagnetic fraction (black sand on left) from the heavy mineral concentrate prior to indicator mineral picking (photograph courtesy of Overburden Drilling Management Ltd).

experiencing higher centrifugal and magnetic forces, move radially outwards. The two fractions are captured in separate ducts at the bottom of the column (Fig. 11).

Sieving

The non-ferromagnetic fraction is commonly sieved into several size fractions (e.g. <0.25 mm, 0.25–0.5 mm, 0.5–1.0 mm, 1.0–2.0 mm) 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 0.25–0.5 mm fraction (McClenaghan & Kjarsgaard 2007) and thus to maximize recovery and minimize counting time and cost, this fine size fraction is most commonly picked.

Other testing

Field preconcentrates and/or lab concentrates can also be examined for radioactivity using a scintillometer (e.g. Stendal 1978) to detect the presence of indicator minerals such as uraninite, thorianite, carnotite, and monazite. Concentrates may also be examined for fluorescence with an ultraviolet lamp (e.g. Stendal 1978) to test for the presence of indicator minerals such as scheelite, fluorite, willemite (Zn mineral), sphalerite, zircon, diamond and some U minerals such as uranophane. Fluorescence of diamonds may also be tested under X-ray.

Mineral concentrate cleaning

Prior to indicator mineral selection, heavy mineral concentrates may be subjected to an oxalic acid wash or ultrasonic bath to remove adhering clay or secondary iron oxide coatings. ‘Cleaning’ the grains prior to indicator mineral selection allows for faster and more accurate selection of indicator minerals, thus reducing picking time as well as reducing the time and money spent analysing non-indicator grains that were picked in error.

Indicator mineral selection and examination

Indicator minerals are selected from non-ferromagnetic heavy mineral concentrates during a visual scan, in most cases, of the finer size (e.g. 0.25–0.5 mm, or 0.3–0.5 mm, 0.25–0.86 mm) fractions under a binocular microscope. The grains are counted and a selection of grains is removed from the sample for analysis to confirm their identification. Methods for examining

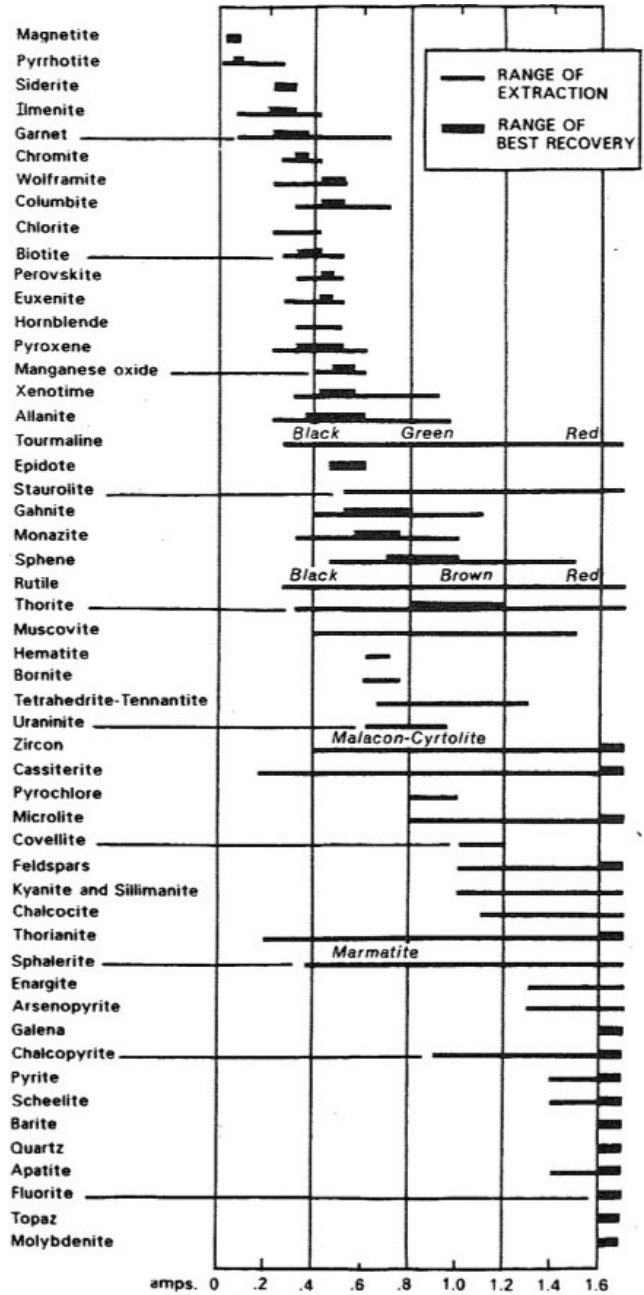


Fig. 9. Magnetic susceptibilities of selected minerals in a Frantz Isodynamic Separator with a side tilt of 15–25° and a forward tilt of 15–25° (from Stendal & Theobald 1994).

a sample for counting and mineral selection vary from rolling conveyor belts to dishes/paper marked with lines or grids (e.g. Kiridzija 2006). The ferromagnetic fraction may also be examined and mineral chemistry determined for selected indicator minerals such as pyrrhotite and magnetite.

If a concentrate is unusually large, then it may be split using a riffle splitter so that a portion of the concentrate can be examined. If a split is examined, the weight of the split and the total weight of the concentrate should both be recorded to allow for the results to be normalized (Baumgartner 2006). Not all grains counted in a sample will be removed for microprobe 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, cleavage and surface textures,

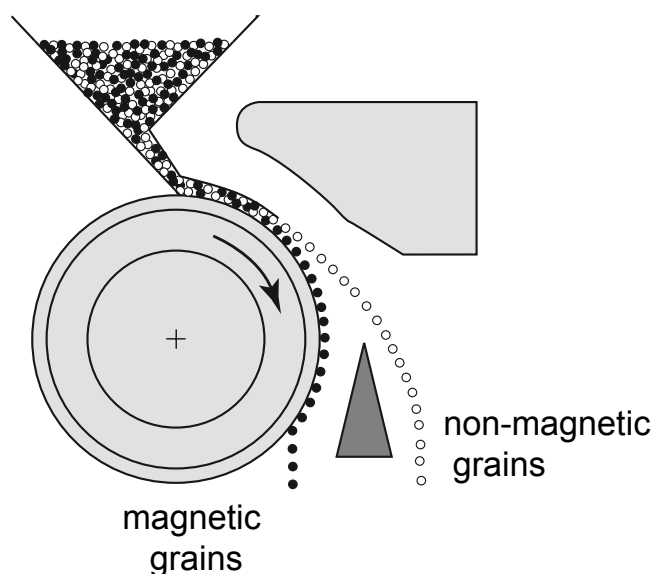


Fig. 10. Schematic of an induced magnetic roll separator (modified from Svoboda 2004).

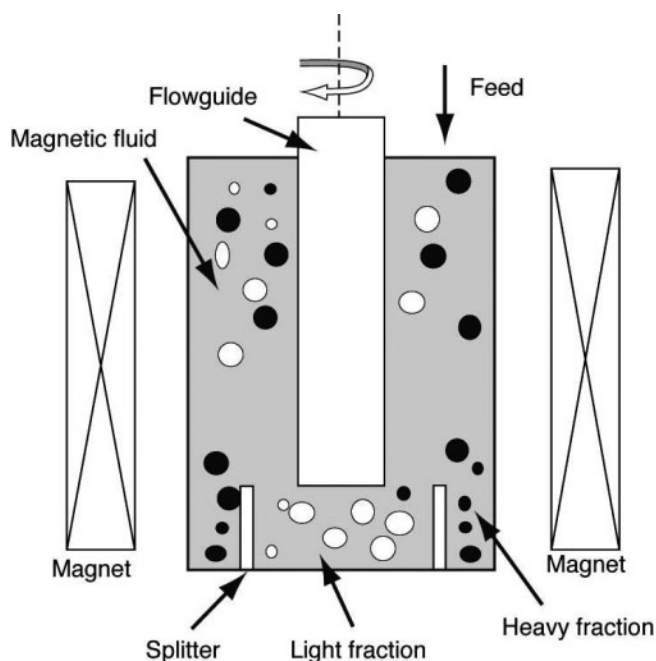


Fig. 11. Schematic cross-section of a Magstream separator used to separate minerals of varying paramagnetism (modified from Svoboda 2004).

which may include features such as kelyphite rims and orange peel textures on kimberlitic garnets (Garvie 2003; McClenaghan & Kjarsgaard 2007). The success of indicator mineral identification at this stage is dependent on the knowledge and experience of the observing mineralogist. Rare or uncommon minerals may not be recognized by an inexperienced mineralogist. A well trained and experienced mineralogist who is able to recognize a broad spectrum of mineral species is necessary.

Gold and PGM grains may be recovered by panning or hydroseparation from concentrates that were prepared in such a way 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 and PGM grains are classified according to their shape/degree of wear

(e.g. DiLabio 1990; Wierchowicz 2002; Podlipsky *et al.* 2007) that can provide information about relative transport distances.

Indicator mineral chemistry

For specific indicator mineral grains, chemical analysis by electron microprobe (EMP), scanning electron microprobe (SEM), proton microprobe, laser ablation ICP-MS, or secondary ion mass spectrometry (SIMS) may be carried out to determine major, minor and trace element contents (e.g. Cabri *et al.* 2003; Ulrich *et al.* 2009; McClenaghan & Cabri 2011) 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 & Radford 2007; Averill 2007; Spry & Teale 2009; Paulen *et al.* 2011; McMartin *et al.* 2011). For example, kimberlite indicator minerals are characterized by specific ranges 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; Grütter 2007). Gold, PGM and sulphide grains may be analysed to determine their trace element chemistry (e.g. Grant *et al.* 1991; McCandless *et al.* 1997; Cabri *et al.* 2003; Mortensen *et al.* 2004; Podlipsky *et al.* 2007; McClenaghan & Cabri 2011) or isotopic compositions (e.g. Hattori & Cabri 1992) in order to determine genesis and source rocks.

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, especially the <0.25 mm fraction. MLA uses a combination of SEM BSE images with EDX spectra to rapidly provide overviews of mineral proportions and assemblages as well as mineral frequency, grain size distribution of individual mineral species, intergrowth relationships, and grain parameters such as roundness (e.g. Lastra & Cabri 2003; Oberthür *et al.* 2008; Keulen *et al.* 2009; Cabri *et al.* 2009). These newer rapid SEM techniques 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. Rapid SEM techniques will also allow for cost-effective examination of the often neglected <0.25 mm fraction, which is costly to examine and pick visually because of the extremely small size of individual grains. Gold and PGM, which are commonly silt size, can be easily detected in the <0.25 mm fraction using these rapid SEM techniques.

Quality control

In some countries, national guidelines have been established for quality assurance and control of sample preparation and analysis for mineral exploration samples and these guidelines apply to heavy mineral samples. In Canada, for example, National Instrument 43–101, through the Best Practices Guidelines, states that a qualified person that plans and supervises exploration programs must “ensure that a quality assurance program is in place and that any required quality control measures are implemented” during sample preparation (including heavy mineral processing) and analysis and testing stages (including mineral chemistry) (www.cim.org/definitions/explorationBESTPRACTICE.pdf).

With these official reporting requirements in mind, project geologists should use a combination of: (1) blank samples

(contain no indicator minerals); (2) samples spiked with known quantities of specific indicator mineral species or density beads with known specific gravities (Towie & Seet 1995; Erlich & Hausel 2002; Baumgartner 2006; Michaud & Averill 2009); and (3) field duplicates, to continuously monitor efficiency of indicator mineral recovery and sample contamination (Doherty 2009). Field duplicates used for these purposes should be thoroughly mixed to limit sediment heterogeneity.

At least 10% of the heavy mineral concentrates that are examined and picked for their indicator mineral content should be re-picked to monitor sample contamination and the quality of the lab's mineral grain selection (Baumgartner 2006; Doherty 2009; Michaud & Averill 2009). This re-picking should be carried out by submitting renumbered samples so that the lab is not aware of which samples have been resubmitted. Monitoring of precision and accuracy of mineral chemistry determinations is also essential, and can be achieved by analysing certified reference mineral standards, in-house standards, and completing replicate grain analysis (De Souza 2006; Doherty 2009). In addition, labs should supply descriptions of heavy mineral processing and selection methods and report results of internal quality control monitoring procedures to their clients (e.g. Mircea 2006).

Data reporting

When reporting indicator mineral results in company assessment files, government reports, or scientific papers, it is essential to report the sample medium, heavy mineral processing lab name, processing methods used, as well as the total weight of sample processed, weight of individual fractions produced, size fractions picked and mineral abundance data for each sample. The abundance of a specific indicator mineral species in each sample should be normalized using the weight of the processed material. For example, a till sample may contain 10 Mg-ilmenite grains in the 0.25–0.5 mm fraction of a 10 kg sample. Quality control procedures used by the lab as well as the client also should be reported.

SUMMARY

This paper has described common procedures used for processing surficial media and rocks to recover indicator minerals. The processing methods chosen for a particular project will depend on sample media, commodities being sought, budget, bedrock and surficial geology of the survey area, and processing methods used for previous batches. When reporting indicator mineral results, it is helpful to report the heavy mineral processing lab name, processing methods used, and weight of individual samples processed. Monitoring of quality control is essential at each stage in the indicator mineral processing, picking and analytical procedures described here and should be monitored both by the processing labs and clients. Geologists are encouraged to visit processing labs so that they have a clear understanding of the procedures being used and can discuss customizations needed for specific sample batches.

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