The application of heavy indicator mineralogy in mineral exploration with emphasis on base metal indicators in glaciated metamorphic and plutonic terrains

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Abstract: Indicator mineralogy is used to explore for a wide variety of mineral commodities. The method utilizes minerals which are sufficiently heavy to be readily concentrated in the laboratory, often colourful and possess other useful physical and chemical properties. The minerals also must be source specific. Some indicator minerals are true resistate minerals. The others, although less resistant, are stable in oxidized glacial drift and many non-glacial sediments. A few, such as gold grains, are silt sized but most are coarse grained. Grain size has a major impact on indicator mineral dispersal patterns in glacial drift.

The coarse-grained indicator minerals are of two main types: (1) kimberlite indicator minerals (KIMs); and (2) metamorphosed or magmatic massive sulphide indicator minerals (MMSIMs). KIMs are enriched in Mg and Cr and most MMSIMs are enriched in Mg, Mn, Al or Cr. These indicator elements cannot be diagnosed geochemically in anomalous heavy mineral concentrates because the concentrates contain other, more plentiful non-indicator minerals containing the same elements in the same chemical form. Chalcopyrite is also a very useful MMSIM but the number of surviving grains in a dispersal train is too low for detection by selective geochemical analysis.

MMSIMs are derived from three main types of base metal deposits and their associated alteration or reaction zones: (1) volcanosedimentary massive sulphides (encompassing volcanogenic, Sedex and Mississippi Valley subtypes) in medium to high grade regional metamorphic terrains; (2) skarn and greisen deposits; and (3) magmatic Ni–Cu sulphides. The variety of MMSIMs associated with Ni–Cu deposits is astonishing, apparently reflecting mineral hybridization related to assimilation of sulphurous sedimentary rocks by ultramafic magmas. Cr–diopside is one of the best indicators of fertile Ni–Cu environments although not necessarily of the actual Ni–Cu deposits.

Heavy indicator mineralogy is much more sensitive than heavy mineral geochemical analysis and offers many exploration benefits in regional exploration programs including: (1) sampling efficiencies; (2) enlargement of both the bedrock target and dispersal train; (3) coverage of a wider range of mineral commodities; (4) undiminished sensitivity in areas of overabundant non-indicator heavy minerals; (5) visual evidence of points of origin of dispersal trains; and (6) indications of the economic potential of the source mineralization. It is most effective as a reconnaissance exploration tool and is particularly well suited for testing gneissic volcanosedimentary and plutonic terranes where base and precious metal deposits are highly modified and difficult to recognize by other prospecting methods.

Laboratory processing of drift samples for heavy minerals is often employed on geochemical exploration programs in glaciated terrains to enhance the geochemical signature of glacially dispersed metallic mineralization and thereby enlarge the geochemical target. Unweathered glacial drift obtained by drilling is an ideal heavy mineral sampling medium because base metals remain in primary sulphide minerals which are readily concentrated and analysed. However, weathered surface samples lacking sulphides can be used to search for selected metals such as Au, Pt, Sn and W that occur in chemically resistant minerals.

In addition to enhancing geochemical signatures, heavy mineral processing offers many potential benefits available through mineralogical examination of the concentrate. Two well

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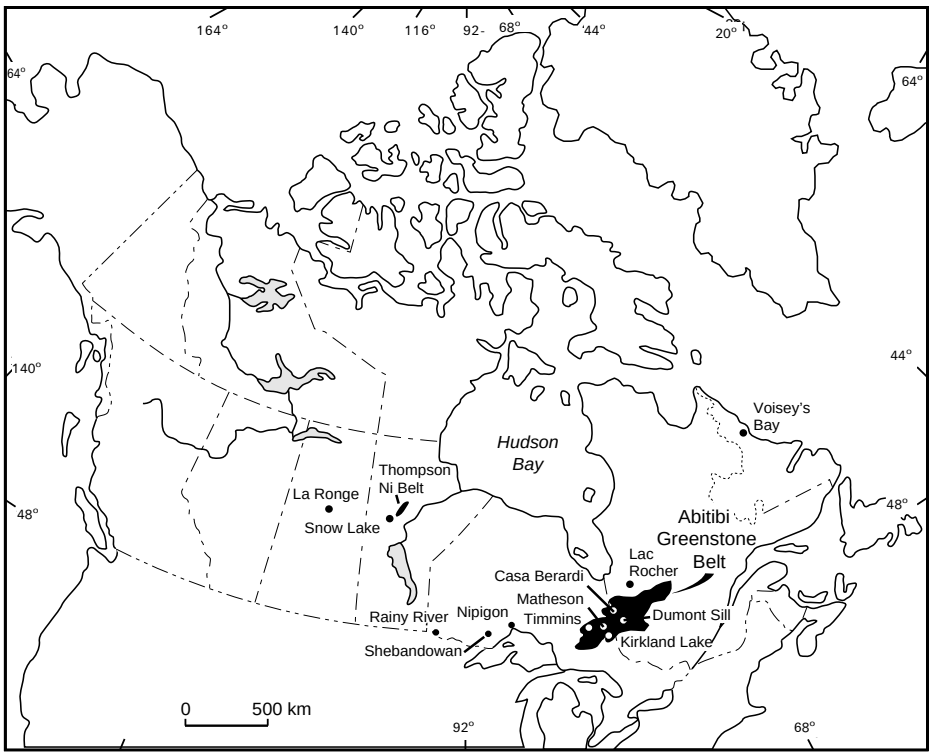

Fig. 1. Index to Canadian localities referenced in the text.

known examples are: (1) determining the sources of gold dispersal trains from the degree of wear of gold grains (Averill 1988; DiLabio 1990); and (2) identifying kimberlite pipes and their diamond potential from kimberlite indicator minerals (KIMs) (Gurney & Moore 1993; Fipke *et al.* 1995). In the case of gold grains, the anomaly signature in the concentrate is both geochemical (i.e. analytical) and mineralogical (i.e. visual). In the case of KIMs, it is strictly mineralogical because the number of indicator grains in the concentrate is small and these grains are enriched only in elements such as Mg and Cr which are overwhelmed by the higher Mg and Cr contributions of common non-indicator heavy minerals.

Heavy indicator mineralogy is dependent upon the minerals being source specific and having various useful properties that complement their high specific gravity. In the case of kimberlite indicators, the minerals are: (1) found in few if any rocks other than kimberlite; (2) coarse-grained; (3) visually distinctive (colourful and/or uniquely textured, altered or fractured); (4) sufficiently heavy (S.G. > 3.2) to be readily concentrated by gravity means; (5) amenable to further concentration by electromagnetic separation; and (6) relatively resistant to weathering, especially in immature glaciated terrains. Kimberlite pipes also tend to be large relative to metallic mineral deposits. Therefore even a pipe that is relatively KIM poor can be a significant KIM source. Moreover, KIMs are so source specific that only a few grains are needed in glacial sediments to recognize the presence of kimberlite. Consequently, KIM dispersal trains tend to be tens of kilometres long whereas the heavy mineral geochemical signatures of base metal dispersal trains in weathered, sulphide-depleted glacial drift are generally measured in hundreds of metres.

Recently it has been recognized that base metal indicator minerals with properties similar to KIMs are present in large alteration and reaction zones associated with certain types of deposits including: (1) volcanosedimentary massive sulphides (encompassing volcanogenic, Sedex and Mississippi Valley subtypes) in medium

Table 1. *Selected gold grain dispersal trains in glaciated terrains in Canada*

Fold belt	Deposit name	Train length* (m)		Gold grains	Average gold grain
		Traced	Est. total	per kg	diameter μm)
Abitibi	Belore	400	400	2	50–100
Abitibi	Cooke Mine†	800	1000	Encapsulated	–
Abitibi	Golden Pond West	400	‡400	3	50–100
Abitibi	Golden Pond	400	‡500	2	50–75
Abitibi	Golden Pond East	800	‡1000	6	25–75
Abitibi	Orenada	100	200	2	25–75
Abitibi	Kiena	100	300	3	10–75
Abitibi	Chimo	600	1000	4	50–75
La Ronge	EP** (Waddy Lake)	600	2000	10	10–100
La Ronge	Star Lake	300	800	2	10–50
La Ronge	Tower Lake	7000	‡7000	10	10–50
La Ronge	Bakos	2000	2000	20	25–50
Lynn Lake	Farley Lake	400	400	1	25–75
Humber	Devil's Cove	2000	2000	6	10–100
Rainy River	17 Zone	2000	††15 000	10	10–50

* Based on minimum ten gold grains of similar size and shape per standard 10 kg sample for free gold trains and coincident high gold and base metal assays in unweathered till for encapsulated gold trains.
† Encapsulated gold deposit.
‡ Train shortened and/or gapped by erosion in last ice advance.
** Deposit orientated parallel to glacial ice flow.
†† Train length enhanced by a 5 km^2 Au-bearing alteration zone surrounding Au deposit.

to high-grade (upper greenschist to granulite facies) regional metamorphic terrains; (2) skarn and greisen deposits; and (3) magmatic Ni–Cu sulphides. The author's company, Overburden Drilling Management Limited (ODM), has invoked the acronym MMSIMs® (for metamorphic or magmatic massive sulphide indicator minerals) for these mineral species and has tested several thousand samples from exploration projects worldwide for MMSIM anomalies. Many of these MMSIM projects included gold grain and KIM components, and many thousands of additional samples have been tested for gold grains alone or for KIMs plus gold grains. Most of the samples weighed 10 to 20 kg. Their < 2 mm fraction was processed by gravity tabling followed by heavy liquid refining, typically at a specific gravity of 3.20 g cm^3. In some cases, samples of the source rocks supplying the indicator minerals were also processed. The indicator minerals were roughly sorted with an electromagnetic separator and visually identified by geologists using a binocular microscope, with resolution of difficult grains by energy dispersive x-ray spectrometer (EDS) analysis using a scanning electron microscope (SEM). Gold grains were micropanned from the table concentrates and counted, measured and classified by binocular microscope with further examination by SEM/EDS on special projects. ODM's original 1970s morphological classification scheme for these gold grains (delicate/irregular/abraded; Averill & Zimmerman 1986; Averill 1988) was updated by DiLabio (1990) with the author's assistance using more generic terms (pristine/modified/reshaped) which allow for chemical as well as physical changes to gold grain morphology.

This paper describes the indicator minerals employed in the above surveys and the types of dispersal patterns observed with emphasis on MMSIMs in weathered glacial drift. The reader will appreciate that the MMSIM method is relatively new and most of the MMSIM survey results are confidential; therefore few explicit case histories are cited and emphasis has been placed on describing broad, repetitive dispersal patterns of general use to explorationists.

Gold grains

Numerous gold deposits in Canada have been discovered by identifying gold grain dispersal trains in glacial drift, primarily till. Examples (Fig. 1) include the Golden Pond East and West deposits at Casa-Berardi, Quebec (Sauerbrei *et al.* 1987), the Aquarius deposit at Timmins, Ontario (Gray 1983), the 17 Zone at Rainy River, Ontario (Averill 1998) and at least four

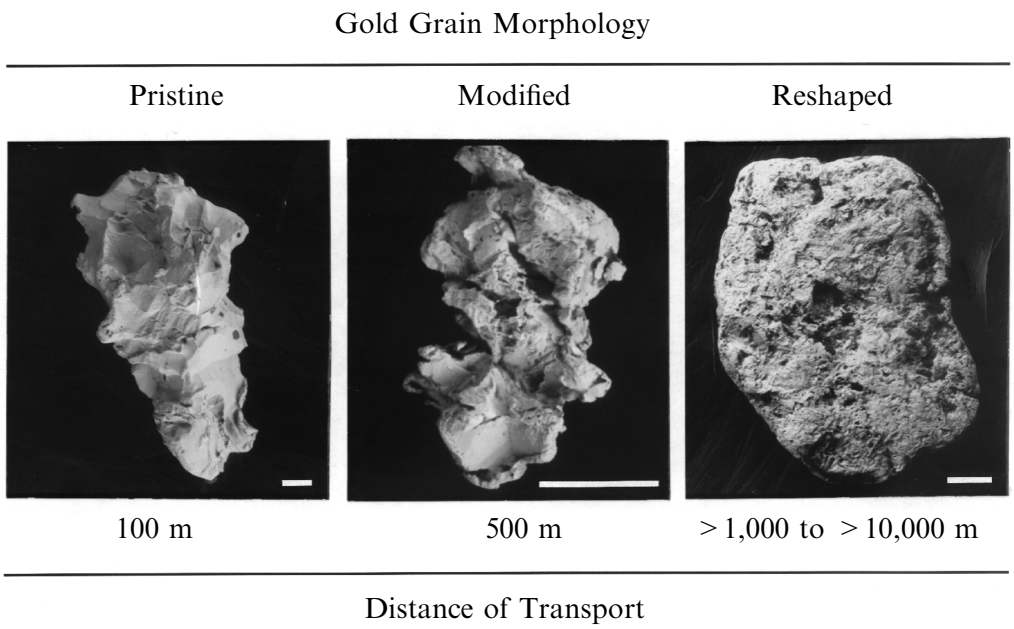

Fig. 2. Backscatter electron images of gold grains from till illustrating the relationship between grain wear and distance of glacial transport. The wear processes are compressional (infolding and compaction) and do not reduce the mass of the gold grain. Scale bars = 50 μm.

deposits in the La Ronge Belt, Saskatchewan (Averill & Zimmerman 1986; Sopuck *et al*. 1986; Chapman *et al*. 1990; Lehnert-Thiel 1998). Case studies have also been performed at several gold mines, primarily by reverse circulation drilling (Table 1) but in some cases by rotasonic drilling or backhoe sampling (McClenaghan 2001). Data of a more regional nature have been obtained from many government surveys (e.g. Thorleifson & Kristjansson 1990; Bajc 1991; Thorleifson & Matile 1993; McClenaghan 1994; Plouffe 1995; Morris *et al*. 1998). The principal gold grain dispersal patterns observed are:

(1) Gold grains are present in tills everywhere in Canada (Averill 1988). Their background abundance ranges from less than one grain per standard 10 kg exploration sample (0.1 grains/kg) in regions of thick Phanerozoic cover such as the central Prairies to more than 20 grains per sample (2 grains/kg) on the down-ice margins of large volcanosedimentary terrains such as the Abitibi Greenstone Belt (Fig. 1).
(2) Eighty to 90% of gold grains in till are silt sized (< 63 μ wide), mirroring the grain size of the parent bedrock mineralization.
(3) Most gold geochemical anomalies obtained from analysing the sieved fine sand and silt fractions of raw (unconcentrated) till or soil samples are due to these gold grains, not to gold chemically adsorbed on clay minerals or limonite. This relationship is easily demonstrated by micropanning anomalous samples that have previously been analysed by the non-consumptive instrumental neutron activation method.
(4) Being soft and malleable, gold grains are deformed rapidly during ice transport (Fig. 2), progressively transforming them from pristine to modified and reshaped forms (DiLabio 1990). This deformation occurs by infolding and compaction; the original mass of the grains does not change. The reshaping process is typically complete after 1 km of transport but required 5 to 10 km of transport at Rainy River (Fig. 1) where buoyant ice flowed rapidly through glacial Lake Agassiz (Averill 1998). That is, gold grain wear appears to be more closely related to transport time than to transport distance.
(5) Most gold grain dispersal trains related to significant mineralization are < 1 km long (Table 1); therefore their gold grains are primarily of the pristine and modified classes. The anomaly strength midway along the train is typically 2 to 4 grains/kg but in a

few trains, especially in the La Ronge Belt (Fig. 1), it reaches ten grains per kilogram.

(6) Esker sediments are depleted in gold grains relative to tills. This depletion occurs in part because esker sediments consist mainly of sorted medium to coarse sand grains whereas gold grains by nature are mostly silt sized. Although heavy, these small gold grains tend to be flushed from coarse esker sands and gravels into distal outwash silty sands due to the effective reduction in specific gravity that occurs with decreasing grain size (Stokes' law). Also the rapid rate of deposition of esker sediments does not permit the few available coarse gold grains to be concentrated into placer beds. Reported occurrences of placer gold such as in the Munro Esker in the Matheson district (Fig. 1) of the Abitibi Greenstone Belt (Ferguson & Freeman 1978) are generally hosted by glaciolacustrine beach deposits developed on eskers rather than in true esker sediments.

Kimberlite indicator minerals

KIMs are described in detail elsewhere in this volume (McClenaghan & Kjarsgaard 2001) and therefore will be mentioned only briefly here. Three garnet species are commonly used as KIMs (Dawson & Stephens 1975; Fipke *et al.* 1995): (1) peridotitic Cr–pyrope; (2) eclogitic pyrope-almandine; and (3) megacrystic Cr-poor pyrope. The other prime indicators are Mg–ilmenite, chromite and Cr–diopside. Mg-rich olivine (forsterite) and orthopyroxene (enstatite) are supplemental indicators; they are of limited use alone as they occur in peridotites and some metamorphic rocks in addition to kimberlite.

The chemistry of certain KIM species is a useful guide to the diamond potential of their source kimberlites (Gurney & Moore 1993; Fipke *et al.* 1995). Specifically, Ca-poor, harzburgitic 'G10' Cr–pyrope, Na-rich pyrope–almandine and ultra Cr-rich chromite indicate sampling of diamond-fertile layers in the mantle by the kimberlite magma and ultra Mg-rich ilmenite indicates reducing conditions favouring diamond preservation during the magma's ascent through the crust.

All KIM species are chemically stable in immature glacial drift; Cr–diopside and garnet are not selectively destroyed as in mature non-glacial terrains (Mosig 1980). However certain KIMs, especially garnets, tend to occur as highly fractured grains in kimberlite as a consequence of hydration either during volcanism or by preglacial weathering, and their subsequent grain size and relative abundance in glacial drift are controlled in part by this preparatory fracturing (Averill & McClenaghan 1994; McClenaghan & Kjarsgaard 2001). Fracture-prone Cr–pyrope macrocrysts, for example, tend to break into large numbers of medium sand sized (0.25–0.5 mm) grains whereas fracture-resistant Mg–ilmenite generally remains at coarse sand size (0.5–1.0 mm) and therefore tends to be less abundant. In the dispersal train of the C14 pipe near Kirkland Lake, Ontario (Fig. 1), unfractured but cleavable Cr–diopside grains appear to have broken after fractured, uncleavable Cr–pyrope as the ratio of Cr–diopside to Cr–pyrope grains increases down-ice (Averill & McClenaghan 1994). Being naturally medium to coarse grained rather than silt sized like gold grains, KIMs are concentrated rather than depleted in esker sediments relative to tills, typically tenfold. Furthermore, medium sand sized Cr–pyrope tends to collect in sand beds and coarse sand sized Mg–ilmenite in gravel beds.

Metamorphic/magmatic massive sulphide indicator minerals

MMSIMs are heavy, coarse-grained, weathering-resistant minerals formed by any of the following processes: (1) recrystallization of volcanosedimentary massive sulphide deposits and their hydrothermal alteration halos by medium to high-grade regional metamorphism; (2) high-temperature magmatic metasomatism (skarns and greisens); or (3) reactions associated with the separation of Ni–Cu–Fe sulphides from ultramafic magmas and komatiites. Their resistance to weathering reflects enrichment in elements such as Mg, Mn, Al and Cr which are concentrated in acid-leached 'aluminous' hydrothermal alteration zones (Lydon 1989), introduced by magmatic metasomatism (Dawson & Kirkham 1996) or united through the assimilation of felsic, sulphurous sedimentary rocks by ultramafic magmas and lavas during the formation of Ni–Cu deposits (Naldrett 1989; Naldrett *et al.* 1996).

MMSIM dispersal trains tend to be large (sometimes as large as KIM trains) because the indicator minerals reflect both the deposit and its alteration envelope and some of the minerals are as unique as KIMs. However, some MMSIMs, such as kyanite, sillimanite, staurolite and orthopyroxene, are less useful than others because they are common throughout certain high-grade regional metamorphic terrains as

well as in hydrothermal alteration zones. On the other hand, a few MMSIMs are enriched in ore metals instead of (or in addition to) alteration zone elements and thus are doubly useful indicators in the manner of G10 Cr–pyrope on KIM surveys. Common examples are gahnite ($ZnAl_2O_4$), zincian staurolite ($(Fe,Mg,Zn)_2Al_9(Si,Al)_4O_{22}(OH)_2$), willemite ($Zn_2SiO_4$) and franklinite ($(Zn,Mn,Fe)(Fe,Mn)_2O_4$) in metamorphosed massive sulphide alteration zones, and scheelite ($CaWO_4$) and cassiterite (SnO_2) in skarns and greisens. If the mineral deposit contains accessory precious metals, native indicator minerals such as gold grains and PGE alloys may also be present in its dispersal train although the fine-grained fraction of the samples must be processed to utilize these minerals.

Arsenides such as sperrylite ($PtAs_2$), rammelsbergite ($NiAs_2$) and loellingite ($FeAs_2$) are also relatively stable, even in sediments in unglaciated terrains, and can be used as MMSIMs. Most sulphide minerals, in contrast, are very unstable. However, ODM has observed that chalcopyrite (and to a lesser degree sphalerite) is nominally stable in surficial sediments worldwide. In Cu-fertile regions it is not unusual to find 50 to 100 chalcopyrite grains in a till or alluvial sediment sample that does not contain pyrite, even if pyrite is ten times more plentiful than chalcopyrite in known Cu-deposits in the area. More research on mineral stabilities is needed to explain this useful phenomenon. However, the observed chalcopyrite grains are clearly survivors of a once-larger sulphide mineral population and the Cu anomalies are much stronger than the grain counts suggest.

Perhaps the earliest documented usage of chalcopyrite as a MMSIM was in 1994 at the Voisey's Bay Ni–Cu–Co deposit in Labrador (Fig. 1) as chronicled by McNish (1998). The first indications of the deposit were found the previous year by prospectors Al Chislett and Chris Verbiski when they examined a rusty outcrop while sampling stream sediments for KIMs on behalf of Diamond Field Resources Inc. The prospectors assayed their outcrop samples for Cu but not Ni and the full significance of their discovery was not recognized. Moreover, Diamond Fields was interested in diamonds, not copper. Consequently the project was refocused on kimberlite in 1994 and ODM was contracted to process the stored 1993 stream sediment samples. Much to the consternation of Diamond Fields, no KIMs were found. Three directors, Mike McMurrough, Richard Garnett and Rod Baker, placed a telephone conference call to the author on May 13, 1994, seeking an explanation. Following is McNish's (1998, p. 75) account of that conversation:

'*The lab, Overburden Drilling of Ottawa, reported confusion over the test results. It was supposed to be testing for diamonds, but the results showed unusually high levels of sulphides, a chemical compound that typically indicates the presence of base metals. What did Diamond Fields want the lab to do about the sulphides? The three officials agreed that the lab should keep tracking the sulphide occurrences and send its reports to Garnett.*

Garnett kept track of the extensive data by marking the occurrences in different colours, green highlights for copper showings and yellow for pyrite. After a few weeks, the area surrounding Voisey's Bay was so full of green and yellow spots that it looked like a crude pointillist painting. Surprised by the heavy concentration of sulphides, Garnett began to research the few geological reports about the region. He grew more intrigued after he read an eight-year-old report by Newfoundland government geologist Bruce Ryan about the strange orange gossan on a hill now claimed by the prospectors. There was something very unusual about Voisey's Bay.'

The discovery of MMSIMs in surficial sediments at Voisey's Bay while searching for KIMs illustrates the extended versatility of heavy indicator mineralogy compared to heavy mineral geochemical analysis. Moreover, the chalcopyrite grains were observed despite the fact that the heavy mineral concentrates were grossly oversized, weighing up to 2 kg rather than the usual 25 to 50 g, due to an overabundance of garnet and other heavy minerals eroded from the underlying Archean gneisses of the Nain Province. With so much heavy mineral dilution, the Cu in the chalcopyrite would represent only a few ppm Cu in the concentrates and thus would not be considered geochemically anomalous even if the analysis employed a sulphide-selective extraction.

A similar situation occurs in till over the Shebandowan Greenstone Belt (Figs 1 and 3) of northwestern Ontario (Bajc 1999, 2000) except that heavy mineral dilution here is due to pyroxene glacially transported from the laterally extensive, pyroxene-rich (40 to 50%) Nipigon Diabase intrusion 70 km to the northeast (Fig. 3). The local bedrock of the Shebandowan Greenstone Belt is well represented in the pebble fraction of the till but the rocks contain $< 0.5\%$ heavy minerals and therefore are minor contributors to the overall heavy mineral fraction of the till. The relative paucity of locally derived

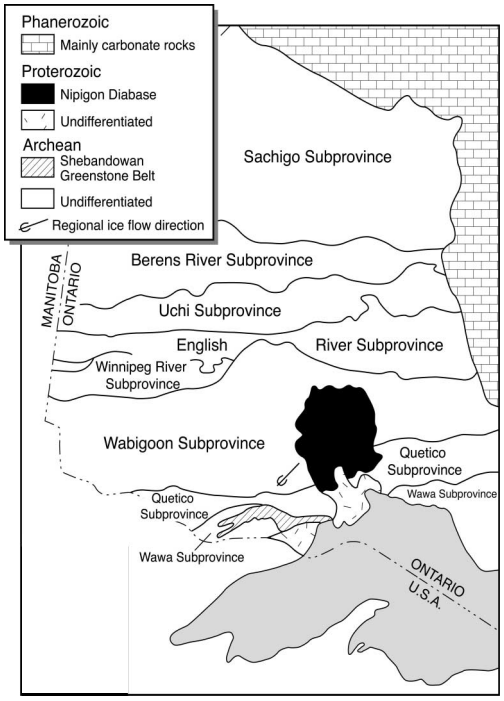

Fig. 3. Bedrock geology map of northwestern Ontario showing the location of the Shebandowan Greenstone Belt relative to Nipigon Diabase. Ice flow was towards the southwest across the diabase, polluting the till with pyroxene which suppresses heavy mineral geochemical responses of local mineralization in tills in the Shebandowan area.

heavy minerals has no bearing on the indicator mineral signature of local mineral deposits – indeed several significant gold grain and MMSIM dispersal trains are present – but the geochemical signatures of these trains are greatly suppressed by the exotic pyroxene. This type of dilution is seldom encountered in non-glacial terrains because the heavy mineral sources are geographically more restricted.

MMSIMs regularly observed by ODM geologists in dispersal trains from metamorphosed volcanosedimentary massive sulphide deposits, skarns/greisens and magmatic Ni–Cu sulphide deposits are described sequentially in the following sections. Only primary MMSIMs found in weathered immature glacial drift are included. Many of these primary minerals are also found in mature non-glacial sediments along with secondary base metal oxides, silicates, carbonates, sulphates and phosphates.

Metamorphosed volcanosedimentary massive sulphide indicator minerals

MMSIM species regularly observed in glacial dispersal trains associated with metamorphosed volcanosedimentary massive sulphide mineralization are listed in Table 2 together with the indicator elements in which the minerals are enriched. The minerals are diverse because they include species from all parts of the alteration zone as well as the actual sulphide deposit. In a Mn-bearing volcanogenic massive sulphide system, for example, metamorphism of the proximal, chalcopyrite-veined chloritic alteration pipe (Lydon 1989) would tend to increase the grain size of the chalcopyrite and produce anthophyllite ($(Mg,Fe)_7Si_8O_{22}(OH)_2$) + spessartine ($Mn_3Al_2Si_3O_{12}$) whereas metamorphism of the distal, semiconformable, epidote-quartz alteration zone would tend to produce red Mn–epidote ($Ca_2(Al,Fe,Mn)_3Si_3O_{12}OH$). The minerals observed in dispersal trains and their associated indicator elements include chalcopyrite (Cu, S), barite (Ba, S), gahnite (Zn, Al), spinel–staurolite–sapphirine (Mg, Al), kyanite–sillimanite (Al), anthophyllite–orthopyroxene (Mg), spessartine (Mn, Al), red epidote (Mn), red rutile (Cr) and loellingite (As). Note that most of the indicator elements are common to other, non-indicator heavy minerals and are too tightly bonded to respond to selective extraction in the analytical laboratory. Thus the anomalies, like KIM anomalies, are seldom discernible by geochemical analysis of the concentrates. Even Cu in chalcopyrite and Zn in gahnite are difficult to detect because anomalous concentrations of these minerals are in the order of just tens of grains per sample (50 chalcopyrite grains in 50 g of 0.25 to 0.5 mm concentrate approximates 15 ppm Cu). The only indicator minerals in Table 2 commonly reaching percentage levels in heavy mineral concentrates are kyanite, sillimanite, staurolite, spessartine, anthophyllite, orthopyroxene and barite.

As with KIM anomalies, the best MMSIM anomalies include two or more mineral species. Common mineral associations observed in the dispersal trains of metamorphosed volcanosedimentary massive sulphide deposits are tourmaline–barite, chalcopyrite–spessartine (or Mn–epidote), gahnite–chalcopyrite–staurolite (or anthophyllite), and red rutile–spinel–kyanite (or sillimanite).

The regional-scale abundance of kyanite, sillimanite or staurolite in metasedimentary terrains containing slightly aluminous pelitic horizons, and of orthopyroxene in granulite-

Table 2. *Common heavy indicator minerals of hydrothermal alteration zones associated with metamorphosed volcanosedimentary massive sulphide deposits in glaciated terrains*

Indicator mineral	Chemical composition	Indicator elements
sillimanite	Al_2SiO_5	Al
kyanite	Al_2SiO_5	Al
corundum	Al_2O_3	Al
anthophyllite	$(Mg,Fe)_7Si_8O_{22}(OH)_2$	Mg
orthopyroxene	$(Mg,Fe)_2Si_2O_6$	Mg
Mg–spinel	$MgAl_2O_4$	Mg, Al
sapphirine	$(Mg,Al)_8(Al,Si)_6O_{20}$	Mg, Al
staurolite	$(Fe,Mg,Zn)_2Al_9(Si,Al)_4O_{22}(OH)_2$	Mg (±Zn), Al
tourmaline	$(Na,Ca)(Mg,Fe)_3Al_6(BO_3)_3(Si_6O_{18})(OH)_4$	Al, B
dumortierite	$Al_7(BO_3)(SiO_4)_3O_3$	Al, B
Mn–epidote	$Ca_2(Al,Fe,Mn)_3Si_3O_{12}(OH)$	Mn
spessartine	$Mn_3Al_2Si_3O_{12}$	Mn, Al
gahnite	$ZnAl_2O_4$	Zn, Al
franklinite	$(Zn,Mn,Fe)(Fe,Mn)_2O_4$	Zn, Mn
willemite	Zn_2SiO_4	Zn
Cr–rutile	$(Ti,Cr)O_2$	Cr
barite	$BaSO_4$	Ba, S
chalcopyrite	$CuFeS_2$	Cu, S
cinnabar	HgS	Hg, S
loellingite	$FeAs_2$	As
native gold	Au	Au

Table 3. *Common heavy indicator minerals of skarn and greisen deposits in glaciated terrains*

Indicator mineral	Chemical composition	Indicator elements
SKARN:		
forsterite olivine	Mg_2SiO_4	Mg
knebelite olivine	$(Fe,Mn)_2\ SiO_4$	Mn
vesuvianite	$Ca_{10}Mg_2Al_4(Si_2O_7)_2(SiO_4)_5(OH)_4$	Mg
johannsenite	$CaMnSi_2O_6$	Mn
grossular	$Ca_3Al_2Si_3O_{12}$	Al±Cr
scheelite	$CaWO_4$	W
chalcopyrite	$CuFeS_2$	Cu, S
native gold	Au	Au
GREISEN:		
topaz	$Al_2SiO_4(F,OH)_2$	Al, F
tourmaline	$(Na,Ca)(Mg,Fe)_3Al_6(BO_3)_3(Si_6O_{18})(OH)_4$	Al, B
fluorite	CaF_2	F
cassiterite	SnO_2	Sn
wolframite	$(Fe,Mn)WO_4$	Mn, W
chalcopyrite	$CuFeS_2$	Cu, S

facies terrains, can restrict the role of these minerals to supplemental MMSIMs similar to forsterite and enstatite in diamond exploration. However, this restriction applies only to high-pressure, Barrovian-type metamorphic terrains; it is not a factor in high-temperature, Abukuma-type (Miayashiro 1973) terrains where such minerals are stable only in alteration zones. Moreover, the chemical compositions of hydrothermal alteration zones are often so specific that a particular metamorphic mineral will form only at these sites even in Barrovian terrains. For example, the alteration zones associated with the Snow Lake deposits in Manitoba (Fig. 1) are characterized by staurolite + kyanite (Walford & Franklin 1982) whereas the main aluminous mineral in the neighbouring unmineralized Kisseynew gneisses is sillimanite (Froese

Table 4. *Common heavy indicator minerals of magmatic Ni-Cu massive sulphide deposits in glaciated terrains*

Indicator mineral	Chemical composition	Indicator elements
hercynite	$FeAl_2O_4$	Al
olivine	$(Mg,Fe)SiO_4$	Mg
orthopyroxene	$(Mg,Fe)_2Si_2O_6$	Mg
low-Cr diopside	$Ca(MgCr)Si_2O_6$	Mg, Cr
chromite	$(Fe,Mg)(Cr,Al)_2O_4$	Cr, Mg, Al (±Zn)
uvarovite	$Ca_3Cr_2Si_3O_{12}$	Cr
Cr–rutile	$(Ti,Cr)O_2$	Cr
chalcopyrite	$CuFeS_2$	Cu, S
loellingite	$FeAs_2$	As
rammelsbergite	$NiAs_2$	Ni, As
sperrylite	$PtAs_2$	Pt, As
PGE alloys	PGE	PGE

& Moore 1980). In some cases, such as in the 17 Zone at Rainy River, Ontario (Fig. 1), hydrothermal alteration envelopes are so enriched in Mn or Al that minerals such as spessartine or kyanite will form even under lower greenschist-facies conditions of metamorphism where they would not normally be stable (Averill 1998). Such occurrences are primarily geological curiosities; most hydrothermal alteration zones in greenschist facies terrains are characterized by fine-grained, low-density minerals and therefore cannot be detected by the MMSIM method.

Skarn and greisen indicator minerals

MMSIM species regularly observed in glacial dispersal trains associated with skarn and greisen mineralization are listed in Table 3 together with the indicator elements in which the minerals are enriched. Skarn indicators include forsterite (Mg), knebelite (Mn), johannsenite (Mn), grossular (Al±Cr), chalcopyrite (Cu, S) and scheelite (W). The principal greisen indicators are topaz (Al, F), tourmaline (Al, B), fluorite (F), cassiterite (Sn) and wolframite (Mn, W). No glacial drift sampling has been done near Olympic Dam-type (Cu–Au–U) deposits but high-temperature indicator minerals analogous to those of skarns and greisens would be expected.

Ni–Cu massive sulphide indicator minerals

MMSIM species regularly observed in glacial dispersal trains associated with Ni–Cu massive sulphide mineralization hosted by komatiites and layered mafic/ultramafic intrusions are listed in Table 4 together with the indicator elements in which the minerals are enriched. These minerals include olivine (especially Mg-rich forsterite), orthopyroxene (especially Mg-rich bronzite/enstatite), Cr–diopside (Mg, Cr), chromite (Cr, Mg, Al), uvarovite (Cr), red rutile (Cr), hercynite (Al), chalcopyrite (Cu, S), loellingite (As), rammelsbergite (Ni, As), sperrylite (Pt, As) and native PGE alloys. Olivine, orthopyroxene and chromite occur in unmineralized as well as mineralized ultramafic rocks and therefore are useable only if their chemical compositions are unique or they are accompanied by other, more diagnostic indicator minerals.

The great variety of Ni–Cu indicator minerals contrasts with the simplicity of Ni–Cu sulphide deposits. This diversity appears to reflect the hybridization process (voluminous assimilation of sulphurous felsic sedimentary rocks by superheated ultramafic magmas) that separates a Ni–Cu–Fe–S liquid from ultramafic magma. Assimilation is known to generate distinctive hybrid Mg–Al rocks such as olivine and orthopyroxene gabbro (troctolite and norite); therefore it might also be expected to combine Mg, Fe or Cr with Al or Si in distinctive hybrid minerals such as chromite ($(Fe,Mg)(Cr,Al)_2O_4$), uvarovite ($Ca_3Cr_2Si_3O_{12}$) and hercynite ($FeAl_2O_4$). Many other combinations are possible. For example, if excess Cr were available following the crystallization of chromite or uvarovite it would tend to be accommodated in common, Cr-receptive minerals such as diopside ($CaMgSi_2O_6$) and rutile (TiO_2), transforming them into colourful indicator species ($Ca(Mg,Cr)Si_2O_6$ and $(Ti,Cr)O_2$, respectively).

Cr-bearing diopside is the principal clinopyroxene of pyroxenite and peridotite horizons associated with the Ni deposits at Outokumpu, Finland (Papunen *et al.* 1979) and in the Dumont sill (Duke 1986) and Lac Rocher intrusions (Averill 1999*a*, *b*, 2000), Quebec (Fig. 1). Being so plentiful, it is generally the most useful Ni–Cu indicator mineral in glacial drift. For example, a significant dispersal train

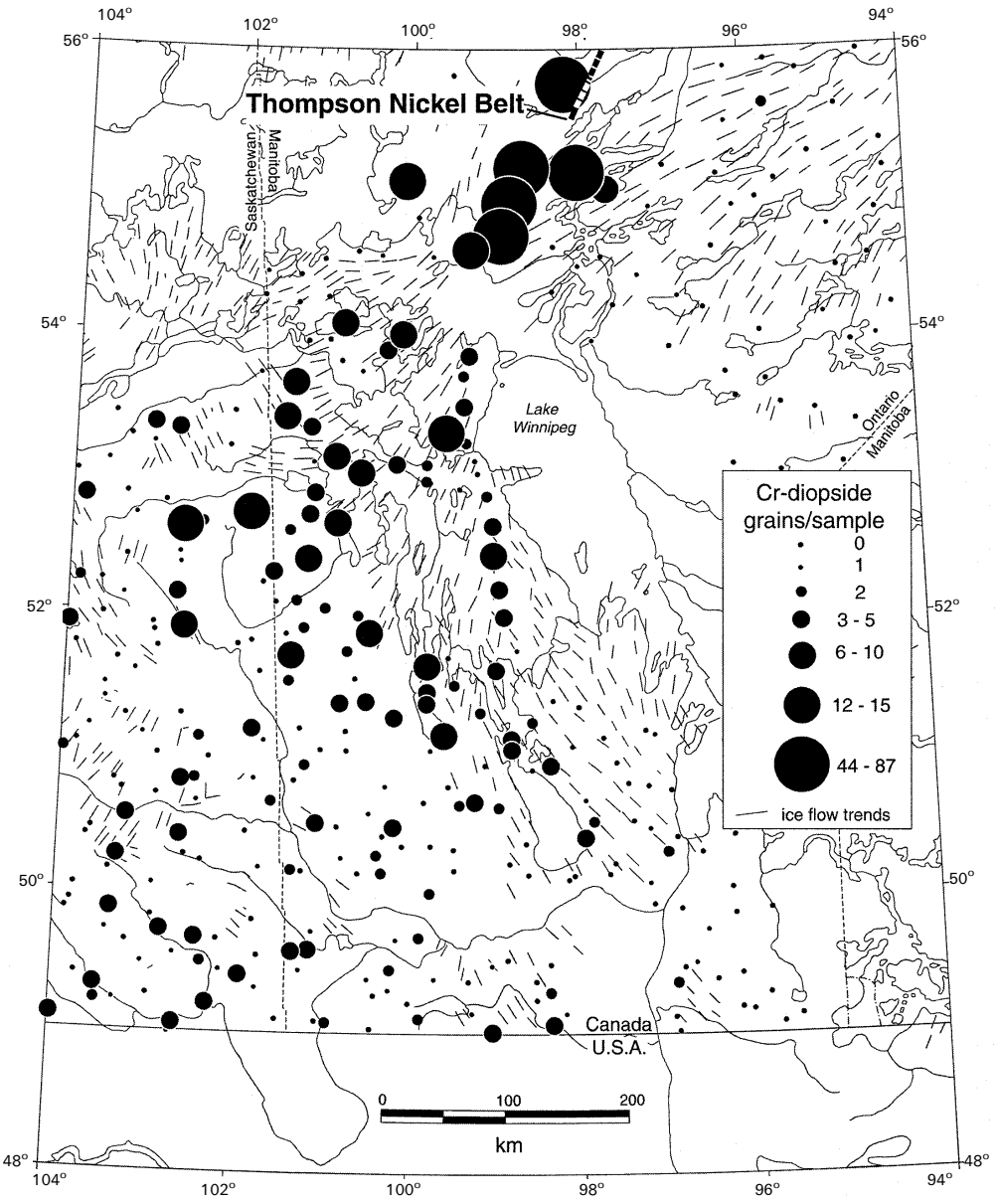

Fig. 4. Distribution of Cr–diopside in surface till in Manitoba, Saskatchewan and Alberta. Note the high concentrations extending 400 km SW (down-ice) from the Thompson Ni Belt (adapted from Thorleifson & Garrett 1993).

containing Cr–diopside but no other indicator minerals (Bajc 2000) is present down-ice from the Shebandowan Ni–Cu–PGE deposit in Ontario (Fig. 1). Also, a major Cr–diopside dispersal train extends 400 km southwest into Saskatchewan from the Thompson Nickel Belt in Manitoba (Fig. 4; Thorleifson & Garrett 1993; Matile & Thorleifson 1997). Closer to Thompson, the Cr–diopside in this train is accompanied by other Ni indicators such as chalcopyrite, hercynite and chromite which occur as minor accessory minerals in the Ni

deposits (de Saboia 1978). Although the dispersal train is clearly related to the nickel belt, the actual source of the Cr–diopside within the belt is poorly constrained because little information is available on the chemistry of clinopyroxene in the peridotite and pyroxenite horizons. The Ni-bearing horizons are mostly harzburgites and orthopyroxenites but unmineralized lherzolites, wehrlites, websterites and clinopyroxenites are present (Peredery 1982). Most of the clinopyroxene in these phases has been altered to amphibole but three grains from the Pipe Mine 2 ultramafic body were analysed by de Saboia (1978) and all are excellent Cr–diopsides (0.47 to 1.09 wt.% Cr_2O_3). Orthopyroxenes from the same rocks also contain significant Cr_2O_3 (0.20 to 0.88 wt.%). At Lac Rocher, Quebec (Fig. 1), the main intrusive phase is clinopyroxenite and most of the clinopyroxene in both mineralized and unmineralized phases is Cr–diopside although it is largely hydrated to tremolite + Cr–magnetite (Averill 1999*a*, *b*, 2000). Orthopyroxene, where present, is also Cr–bearing but the Cr is not colour enhancing as it is in diopside. The Thompson Nickel Belt is much larger than the Lac Rocher intrusions and as little as 1% Cr–diopside in the ultramafic rocks would be sufficient to explain the observed Cr–diopside dispersal train in the till. As well, diopside-bearing carbonate horizons are common in the metasediments that enclose the pyroxenites and peridotites (R. Somerville, Inco Ltd., pers. comm. 2000) and Cr–metasomatism of these carbonate rocks by the ultramafic bodies during emplacement or metamorphism could also have produced considerable Cr–diopside as at Outokumpu (Papunen *et al.* 1979).

Cr–diopside that is used as a Ni–Cu indicator generally contains less Cr_2O_3 (< 1.25 wt.%) than typical kimberlitic Cr–diopside derived from mantle lherzolites (> 1.25 wt.%; Eggler *et al.* 1979) and tends to have a paler green colour. However, considerable overlap in both Cr_2O_3 content and colour between the types does occur. Kimberlites are also known to contain Cr–diopside of at least six parageneses having lower Cr contents than the bright green Cr–diopside of lherzolitic paragenesis that is used as a kimberlite indicator mineral (Mitchell 1986). Cr–diopside grains used as a Ni–Cu indicator are less easily recognized in rock specimens than in heavy mineral concentrates and have seldom, if ever, been recognized in drill core. Ideally any accompanying chromite grains in a Cr–diopside dispersal train are Zn–bearing, indicating that their source rocks have assimilated significant quantities of sedimentary sulphides (Lesher 1989). Thus, in Ni–Cu exploration as in diamond exploration, the chemistry of the chromite grains is as important as their association with other indicator minerals.

Conclusions

Heavy indicator mineralogy has many benefits not found in heavy mineral geochemistry. These benefits arise due to: (1) the high degree of chemical stability of indicator minerals relative to sulphide minerals upon which heavy mineral geochemistry is so dependent; (2) the presence in the indicator minerals of elements such as Mg, Mn, Al and Cr which favourably enhance colour, chemical stability and electromagnetic separability but cannot be detected by geochemical analysis of mineralogically anomalous concentrates; and (3) the opportunity to observe physical features of the mineralization. The benefits of heavy indicator mineralogy over heavy mineral geochemical analysis include:

(1) Major sampling efficiencies in base metal exploration through the substitution of weathered surface sediments for unweathered buried sediments, thereby reducing the need for deep sampling.
(2) Considerable enlargement of the bedrock target by adding the alteration zone to the actual mineralization. Since this enlargement occurs in three dimensions, it may also allow detection of otherwise blind mineralized targets.
(3) Manyfold enlargement of the dispersal train by effectively lowering the detection limit of both alteration elements such as Mg, Mn, Al and Cr and base metals such as Zn, Cu and Ni to the single mineral level (e.g. Mg and Al in staurolite, Mn in spessartine, Cr in diopside, Zn in gahnite, Cu in chalcopyrite, Ni in rammelsbergite).
(4) Undiminished sensitivity in terrains with overabundant non-indicator heavy minerals.
(5) Coverage of a wider range of mineral commodities in a single survey.
(6) Visible evidence of the dispersal distance including the degree of reshaping of gold and platinum grains and the degree of separation of KIMs from their alteration rinds.
(7) Evidence of the worth of the source mineralization including the type and number of indicator mineral species present in the dispersal train and the chemistry of KIMs such as Cr–pyrope or MMSIMs such as gahnite, staurolite and chromite.

With the targets being so large and so many mineral commodities being identifiable from a single set of samples, heavy indicator mineralogy is most effective as a reconnaissance exploration tool. The reconnaissance capabilities are well established for KIMs and are probably even greater for MMSIMs. Extensive, highly metamorphosed, often gneissic Archean and Proterozoic volcanosedimentary and plutonic terrains have undergone negligible base metal exploration due to the difficulty of recognizing fertile protoliths and recrystallized hydrothermal alteration zones beneath their metamorphic masks. Heavy indicator mineralogy offers much promise for the future development of these terrains.

Most of the heavy mineral relationships described in this paper were identified over a 25-year period from tens of thousands of bulk samples submitted to ODM by more than a hundred individual prospectors and corporate and government clients. Many of these samples were from pioneering projects requiring considerable faith in heavy mineral sampling as a viable exploration tool. BHP World Explorations Inc., WMC International Ltd., the Geological Survey of Canada and the Ontario Geological Survey have been particularly helpful in demonstrating the utility of the MMSIM method. R. Somerville and P. Golightly of Inco Ltd. supplied critical information on mineral chemistry in the Thompson Nickel Belt. Nuinsco Resources Ltd. granted permission to use data from the author's consulting reports on the Lac Rocher intrusions. The paper benefited from insightful reviews by J. M. Franklin, L. Hulbert, P. Taufen, and L. H. Thorleifson and thoughtful editing by M. B. McClenaghan.

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