Viable indicator minerals in surficial sediments for two major base metal deposit types: Ni-Cu-PGE and porphyry Cu

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ABSTRACT: Indicator minerals are known for many types of base metal deposits but the high temperatures and pressures associated with magmatism and prograde metamorphism are needed to raise mineral density and grain size in order to produce diverse and abundant indicators. Therefore those base metal deposits that are associated with very large magmatic-hydrothermal systems have the most viable indicator mineral suites, in some cases sufficient to produce anomalies in surficial sediments comparable to the regional-scale anomalies associated with kimberlite fields. Two deposits of this type are Ni-Cu-PGE and porphyry Cu. Most sulphide mineral grains dispersed from these deposits are quickly degraded by weathering, increasing the dependence on more stable alteration minerals. The significance and properties of these minerals are described and examples of anomalies are shown for Ni-Cu-PGE indicator minerals in glacial till and post-glacial gravel in Canada and for porphyry Cu indicator minerals in nonglacial sheet wash gravel in Chile.

KEYWORDS: *indicator minerals, Ni-Cu-PGE, porphyry Cu*

The discovery of the diamondiferous Lac de Gras kimberlite field in northern Canada in 1991 by tracing anomalous concentrations of glacially dispersed kimberlite indicator minerals in surficial sediments 600 km up-ice (Krajick 2002) stimulated the development of indicator mineral technology for other commodities, particularly base metals (Averill 2001). This technology is now well proven for some types of base metal deposits, particularly those containing Ni, Cu and platinum group elements (PGE) as the basic indicator minerals for these deposits are closely linked to kimberlite indicators (Averill 2009).

The concentration of indicator mineral grains in anomalous surficial sediments is generally low, in some cases <1 grain per kg, and large samples typically 10–20 kg are generally needed to obtain a useful and representative number of grains. The potential number of indicators available from a base metal deposit is dependent on the specific deposit type and is further governed by three key properties that are common to all indicator minerals. First, the minerals must be heavy so that they can be concentrated sufficiently to be found in 10 to 20 kg samples. Second, unless they are so heavy and vivid that they can be panned from the concentrate and readily seen, e.g. gold grains and PGE-bearing minerals (PGMs), they must be of a sufficient grain size – typically >0.25 mm – to be readily seen *within* the concentrate using an optical (binocular) microscope. Third, if samples are collected from weathered sediments, as is the case on most surveys, the minerals must be resistant to oxidation. These characteristics eliminate most base metal sulphide minerals.

The general unsuitability of sulphide minerals as base metal indicators greatly increases dependence on the associated alteration minerals. Unfortunately, the alteration minerals associated with some types of base metal deposits, for example the sericite and chlorite associated with volcanogenic massive sulphide (VMS) deposits in greenstone belts, are neither heavy nor coarse grained and thus cannot be used as indicator minerals. The higher pressures and temperatures associated with magmatism or prograde regional metamorphism are needed to raise mineral density and grain size above the thresholds for indicator minerals. By extension, those base metal deposits that are associated with the largest magmatic–hydrothermal systems tend to yield the most indicator minerals and to have the largest dispersal anomalies, in some cases comparable in size to the regional-scale anomalies associated with kimberlite fields. Two deposits of this type are Ni-Cu-PGE and porphyry Cu. This paper describes indicator minerals that have proven useful for each of these deposit types and shows examples of dispersal anomalies for some of these minerals.

METHODS

All of the indicator mineral data presented herein were obtained from samples processed in the heavy mineral laboratory of Overburden Drilling Management Ltd. (ODM) in Ottawa, ON, Canada. The interpretations presented are based mainly on ODM's empirical analysis of mineralogical patterns observed repeatedly within the extensive sample database. Most of the Ni-Cu-PGE test samples were collected in Canada and were either of till or post-glacial alluvial gravel. They were collected mainly on programs conducted by federal or provincial geological surveys, details of which can be obtained from published reports issued by these agencies (e.g. Thorleifson & Garrett 1993; Matile & Thorleifson 1997; Bajc & Hall 2000; Bajc & Crabtree 2001; Searcy 2001; Crabtree 2003; Barnett & Dyer 2005; Ames *et al.* 2007). The porphyry Cu samples were obtained from nonglacial sediments, mainly *chusca* (dry, powdery soil) developed on sheet wash alluvium in semi-arid to arid regions of Chile, Peru and western USA. They were typically collected at a depth of 0.2–0.3 m, taking care to avoid surface sediment potentially containing wind-blown mineral contamination from mining or drilling activity. A few surveys were conducted in humid tropical rather than arid regions and utilized gravel samples from active streams. All of the samples were supplied by mining companies conducting mineral exploration programs. Permission has been obtained to publish only one case study but similar indicator mineral results were obtained from other surveys.

For Ni-Cu-PGE projects, heavy mineral concentrates were prepared from the medium to coarse sand fraction (0.25–2.0 mm) of *c.* 10 kg samples by tabling followed by heavy liquid separation in methylene iodide diluted to specific gravity (SG) 3.20. These procedures are in common use (McClenaghan 2011) and are the same as those that ODM employs for concentrating kimberlite indicators which are of a similar specific gravity range. Recovery rates were not established for the individual Ni-Cu-PGE mineral species but probably varied from *c.* 80–95% with increasing specific gravity based on regular testing of kimberlite indicator mineral recovery rates using samples spiked with natural grains extracted from anomalous surficial sediment samples. Finer gold grains and PGMs were separated by micropanning using a small gold pan and bowls in series.

Magnetite was removed from the 0.25–2.0 mm concentrates and the finest, 0.25–0.5 mm portion of the nonferromagnetic fraction, which typically contains >90 % of the mineral grains, was further partitioned by paramagnetic susceptibility into four mineralogically simpler subfractions successively containing the strongly, moderately, weakly and nonparamagnetic minerals. Any contained indicator minerals were identified under a binocular microscope by geologists thoroughly familiar with all common heavy minerals and indicators of many mineral deposit types. Ambiguous grains, if present, were resolved by scanning electron microscope analysis.

For porphyry Cu projects, 10 kg samples were used only if the samples were collected from active streams. Much smaller, 0.5 kg samples were found to suffice for dry sheet wash in arid regions due to the shorter dispersal distance and consequent higher indicator mineral concentration in this type of sediment. The small sample size facilitated collection and also greatly reduced shipping costs such that it was practical to conduct surveys in regions remote from the laboratory. The small samples were treated by direct heavy liquid concentration with no table preconcentration. For both the large and small samples, however, a mid-density separation employing methylene iodide diluted to SG 2.8 was required in addition to the standard SG >3.2 separation because porphyry Cu indicators have a wider SG range than Ni-Cu-PGE and kimberlite indicators. The extra cost of examining both the SG 2.8–3.2 and >3.2 concentrates for indicator mineral grains offset the savings from processing smaller samples such that laboratory costs were similar to those experienced on Ni-Cu-PGE and kimberlite indicator mineral programs.

NI-CU-PGE INDICATOR MINERALS

Indicators of a fertile melt: the mantle connection with kimberlite indicators

Most Ni-Cu-PGE deposits are ultimately derived from garnet peridotite horizons in the mantle (Naldrett 2005; Mungall 2005; Sproule *et al.* 2005), as are some kimberlite indicator minerals. This mantle connection is described in detail in Averill (2009) and illustrated in Figure 1. The mineralogy of garnet peridotite is well known from xenoliths transported from the mantle to surface in kimberlite volcanoes (Mitchell 1986). Up to five major minerals are contained in garnet peridotite: orthopyroxene (enstatite), olivine (forsterite), Cr-diopside, chromite and Cr-pyrope garnet. All of these minerals are enriched in Mg and/or Cr. The kimberlite melt originates at greater depth than the peridotite and, during its ascent through the peridotite to surface, physically harvests both xenoliths of the peridotite and xenocrysts of the five contained minerals, along with diamond if present. These xenocrysts, if subsequently eroded from the kimberlite and dispersed into surficial sediments, can be used as kimberlite indicators.

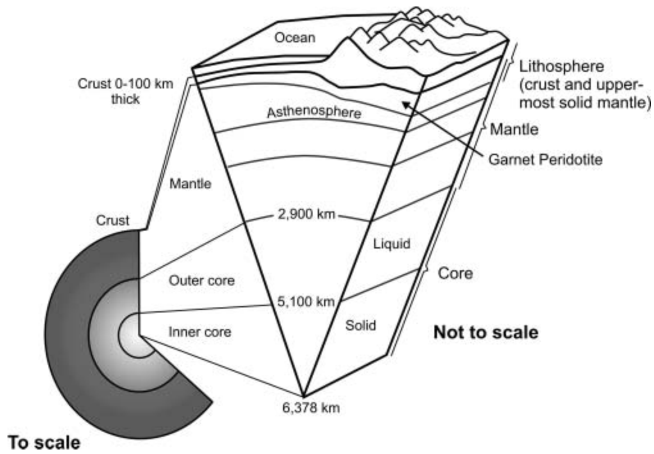

Fig. 1. Position of garnet peridotite layers in the lithospheric upper mantle. Most kimberlite indicator mineral xenocrysts and Ni-Cu-PGE-fertile melts are derived from this garnet peridotite Diagram modified from unpublished source-Bruce Kjarsgaard, Geological Survey of Canada.

The formation of a Ni-Cu-PGE deposit, in contrast, begins with a high degree (up to 70%) of *in-situ* partial melting of the garnet peridotite (Mungall 2005; Sproule *et al.* 2005). Such melts are of a komatiitic composition and fertile in Ni-Cu-PGE. After they rise from the mantle to the crust and undergo fractional crystallization, the Ni-Cu-PGE may, under certain conditions, partition into a sulphide phase and produce economic Ni-Cu-PGE mineralization (Naldrett 2005; Mungall 2005). High-degree komatiitic melts are also enriched in Mg and Cr and their fractional crystallization regenerates four of the Mg and/or Cr-rich minerals – enstatite, forsterite, Cr-diopside and chromite – that were originally present as primary constituents of the garnet peridotite source rock. Hence these four minerals are used as indicators of a Ni-Cu-PGE fertile melt as well as kimberlite indicators – they are ‘crossover’ indicator minerals. The fifth mantle mineral – Cr-pyrope – does not recrystallize due to the much lower temperature and pressure conditions prevailing in the crust. Thus, it is used only as a kimberlite indicator.

While all kimberlite indicator minerals are xenocrysts derived from the mantle, not all are derived from garnet peridotite. Two, pyrope-almandine garnet and omphacite, are derived from eclogite and two others, Cr-poor pyrope and Mg-ilmenite, are megacrystic and thought to be cumulus crystals derived from fractionated Cr-poor, Ti-rich mantle melts (Harte & Gurney 1981). Thus, there are nine primary kimberlite indicators (Table 1) compared to just four primary Ni-Cu-PGE indicators – the four peridotitic crossover minerals. Nevertheless, it will be shown that there are significantly more useful Ni-Cu-PGE indicators than kimberlite indicators.

Table 1. *Primary Mg and/or Cr-rich minerals used as kimberlite and Ni-Cu-PGE indicators. The kimberlite indicators are mantle xenocrysts derived in part from garnet peridotite and the Ni-Cu-PGE indicators crystallize in the crust during fractionation of partial melts derived from this peridotite*

Kimberlite	Ni-Cu-PGE-Fertile Rocks
orthopyroxene (enstatite)	orthopyroxene (enstatite)
forsterite	forsterite
Cr-diopside	Cr-diopside
chromite	chromite
Cr-pyrope	
pyrope-almandine	
omphacite	
Mg-ilmenite	
Cr-poor pyrope	

The non-kimberlitic and kimberlitic varieties of the four crossover minerals can be differentiated visually. Non-kimberlitic enstatite is pale brown whereas kimberlitic enstatite has a faint green tint, possibly indicating traces of Cr_2O_3. Non-kimberlitic forsterite (Fig. 2a) is as colourless as quartz whereas the kimberlitic variety (Fig. 2b) has the same green tint as kimberlitic enstatite. The non-kimberlitic grains, if derived from mafic to ultramafic igneous rocks rather than from metamorphosed Fe and Cr-poor marble and calc-silicates, also tend to be peppered with minute Cr-magnetite inclusions that render them paramagnetic whereas non-kimberlitic forsterite is nonparamagnetic. In addition, the average size (Table 2) of non-kimberlitic forsterite grains, except for grains derived from marble and calc-silicate rocks, is invariably much smaller than that of kimberlitic forsterite, with 0.25–0.5 mm grains at least 20 times more abundant than 0.5–1.0 mm grains. In contrast, kimberlitic forsterite ratios drop to less than 5:1 with some samples containing as many large grains as small grains.

Non-kimberlitic Cr-diopside (Fig. 2c) contains less Cr_2O_3 – generally <1.25 wt.% – than the kimberlitic variety (Fig. 2d). This lower chrome content visibly reduces the amount of emerald green pigment; therefore the pale, non-kimberlitic grains are referred to by ODM as low-Cr diopside. Indicator mineral surveys conducted in Manitoba by Thorleifson & Garrett (1993) and Matile & Thorleifson (1997) identified a major till-hosted low-Cr diopside dispersal train extending *c.* 400 km down-ice from the Thompson Nickel Belt (Fig. 3).

Non-kimberlitic chromite crystals (Fig. 2e) are sharply angular or rough textured whereas kimberlitic grains (Fig. 2f) are smoothed and rounded by resorption. The non-kimberlitic grains are also much smaller on average than kimberlitic grains, in fact by essentially the same factor (Averill 2009) as for forsterite. However, in tropical regions lateritic weathering can mask chromite's distinguishing surface features (Fig. 2g) and reduce the grain size. A major chromite anomaly with tens to hundreds of grains per 10 kg till sample extends *c.* 100 km down from the Ni-Cu-PGE-fertile komatiite belts of the Timmins district, Ontario (Fig. 4). The chromite background concentration in till in the surrounding area is <5 grains per sample.

Indicators of sulphide saturation

The regional scale of the melt fertility indicator mineral trains associated with the Thompson Nickel Belt, Manitoba, Canada, and komattiites in the Timmins area, Ontario, Canada is similar to that of the largest kimberlite indicator mineral trains in the Slave Craton of northern Canada (Armstrong 2003). However a melt fertility anomaly does not necessarily indicate a mineralized intrusion or flow belt because, in addition to being fertile, the melt must become saturated in sulphur at the time of emplacement into the crust (Naldrett 2005; Mungall 2005). This saturation causes sulphide liquid to separate from the silicate melt. The sulphide liquid acts as a collector, scavenging Ni-Cu-PGE from the melt. In addition, being heavier, it settles in pools or layers, further concentrating the scavenged metals by gravity.

Sulphide saturation can occur passively during melt emplacement as S solubility is reduced by both progressive cooling of the melt and fractional crystallization and removal of olivine and pyroxene; however, dynamic saturation concentrates Ni-Cu-PGE more efficiently (Mungall 2005). Dynamic saturation can occur in two ways: (1) by concentrated segregation of cumulus minerals from a large volume of silicate melt flowing through a constriction in the magma chamber as appears to have occurred at the mouth of the feeder conduit of the Reid Brook Intrusion at Voisey's Bay, Labrador, Canada (Li & Naldrett 2000); and (2) through assimilation of felsic crustal rocks by the mafic melt, especially if the assimilated rocks contain sulphur. Each of these sulphide saturation processes tends to produce minerals that can be used as Ni-Cu-PGE indicators.

The indicator minerals produced by concentrated cumulus segregation from the melt are the same as those indicating melt fertility – i.e. enstatite, forsterite, Cr-diopside and chromite – but their dispersal anomalies are generally smaller in extent with higher grain concentrations, reflecting the restriction of the cumulus segregation to a small part of the overall magma chamber or flow. For example, a small low-Cr diopside dispersal train with up to 175 grains per 10 kg till sample (background 0–5 grains) occurs in direct association with the Shebandowan Ni deposit in northwestern Ontario, Canada (Bajc & Crabtree 2001) whereas the regional-scale train from the Thompson Nickel Belt (Fig. 3) is only indirectly linked with the Ni mineralization (McClenaghan *et al.* 2009). Similarly, a chromite anomaly *c.* 4 km long occurs in till down ice (southwest) of the mineralized part of the Mine Block Intrusion at the Lac des Iles Pd deposit, Ontario, Canada (Fig. 5; Barnett & Dyer 2005) whereas the regional-scale Timmins train in till down ice (south) of komatiitic rocks (Fig. 4) appears to reflect the overall fertility of the komatiitic flow belts rather than specific mineralized flows. However, sampling by the Ontario Geological Survey (OGS) in 1991 in the Attawapiskat region west of James Bay, Ontario, Canada (Crabtree 2003) identified a chromite anomaly of the concentrated cumulus type that is of regional scale (Fig. 6). The riverbed gravels contain up to 5000 chromite grains per 10 kg sample. The anomaly extends nearly 400 km down stream (east) and crosses kimberlite pipes of the Attawipiskat field that contain significant chromite. However, the chromite grains in the alluvial gravel have the small average size and sharply angular form of non-kimberlitic chromite. Any larger grains that are present are aggregates of these small grains (Fig. 2h) rather than single crystals; i.e. they consist of the cumulate rock chromitite, indicating that the source is a layered mafic intrusion. Six years after the OGS survey, in 2007–2008, companies exploring for VMS deposits in the Ring of Fire area near the head (west) of the chromite anomaly inadvertently discovered five chromite deposits and two Ni-Cu-PGE deposits. The chromite deposits are of major economic interest as they consist of massive chromitite zones up to 70 m thick. Moreover, the head of the chromite dispersal anomaly appears to be broader than the discovery area, suggesting that additional, undiscovered chromite deposits are present.

The indicator minerals produced by assimilation of felsic country rocks by a mafic melt are hybrid alteration minerals containing both felsic elements from the crust, mainly Al and

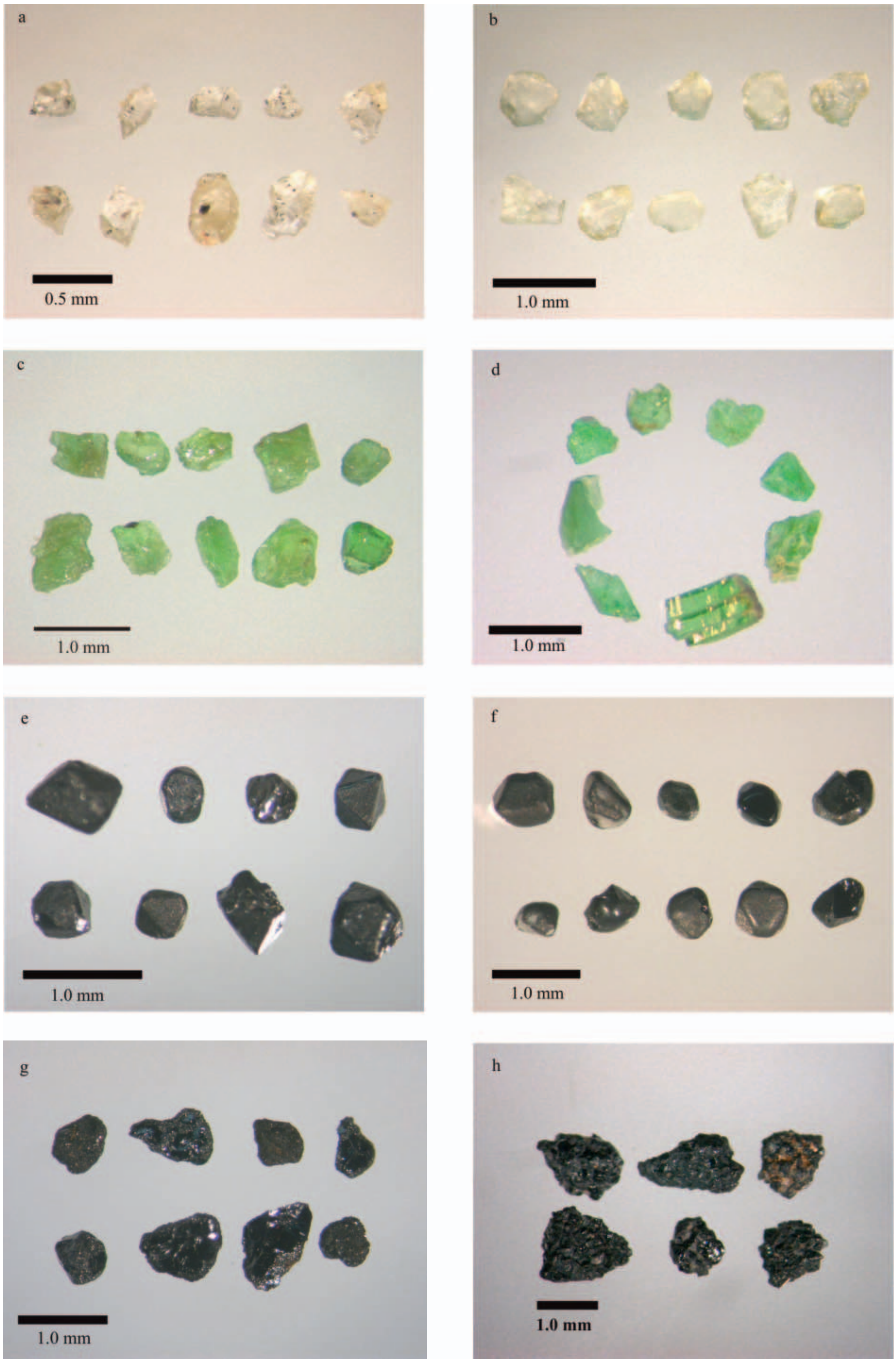
a
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Table 2. *Typical ratios of 0.25–0.5 to 0.5–1.0 mm grains for non-kimberlitic (Project A) and kimberlitic (Project B) forsterite in c. 10 kg till samples. The samples were collected within 10 km of the forsterite sources. Unpublished data from Overburden Drilling Management Ltd*

Sample no.	*Project A*			Sample no.	*Project B*		
	Number of forsterite grains		Ratio of 0.25–0.5 to 0.5–1.0 mm grains		Number of forsterite grains		Ratio of 0.25–0.5 to 0.5–1.0 mm grains
	0.25–0.5 mm	0.5–1.0 mm			0.25–0.5 mm	0.5–1.0 mm	
3169	~500	1	500	24–01	3	3	1
3170	~300	14	21	24–02	0	0	1
3171	~50	0	>50	24–03	8	4	2
3172	~200	8	25	24–04	26	35	1
3173	~500	19	26	25–01	~100	20	5
3174	~80	7	11	25–02	~150	60	3
3175	~300	3	100	25–03	~200	88	2
3176	~200	2	100	25–04	~200	49	4
3177	~200	15	13	25–05	~40	48	1
3178	~600	10	60	25–06	~60	18	3

Si, and mafic elements from the mantle, mainly Fe, Mg and Cr. Three examples (Table 3) are ruby corundum ($(Al,Cr)_2O_3$), hercynitic spinel ($FeAl_2O_4$) and emerald green Cr-garnet, variably andradite ($Ca_3(Fe,Cr)_2(SiO_4)_3$), grossular ($Ca_3(Al,Cr)_2(SiO_4)_3$) or uvarovite ($Ca_3Cr_2(SiO_4)_3$). Cr-andradite forms a distinctive dispersal train in till down ice (southwest) of Pd deposits at Lac des Iles (Fig. 7; Barnett & Dyer 2005). This train is roughly coincident with the chromite train (Fig. 5) but is 100 times more enriched with up to 20 000 v. 200 grains per 10 kg sample. The Cr-andradite is hydrated and the grains are cryptocrystalline (Fig. 8a) rather than dodecahedral. Their colour varies from emerald green to waxy white with local red patches due to serpentine alteration. Although readily noticed in a till concentrate, the Cr-andratite is otherwise unremarkable and, until the till grains were discovered, was not known to be present in the altered gabbro and pyroxenite that host the Lac des Iles mineralization. These grains appear to be unique to the Lac des Iles dispersal train as no similar occurrences have been identified in till elsewhere in Canada. However, massive Cr-grossular of an identical green to waxy white colour and cryptocrystalline habit (Fig. 8b) occurs in direct association with some of the chromitite bands in the layered Bushveld Complex of South Africa.

Direct indicators of Ni-Cu-PGE mineralization

Ni-Cu-PGE deposits contain a wide variety of metallic minerals but many of these are not resistant to weathering (Table 4) and thus cannot be used routinely as indicator minerals. Pyrrhotite, pentlandite and other Ni sulphides along with all PGE sulphides and tellurides are so unstable that it is rare to find any grains even in slightly weathered till at the C-horizon level. Pyrite is almost as unstable but chalcopyrite can be used as an indicator mineral because a small portion of the dispersed grains normally survive, even under humid tropical weathering conditions. The Pt and Fe arsenide minerals sperrylite and loellingite, along with the Pd antimonide mineral stibiopalladinite, have a high survival rate. However, *c.* 90 % of the grains observed on all till sampling surveys are silt sized (<0.063 mm) or much less than the 0.25 mm minimum for ready identification in a heavy mineral concentrate. Gold grains, isoferroplatinum and other native PGMs are highly stable but also mostly silt sized unless occurring in coarse, silt-depleted gravel rather than unsorted till. Fortunately, all of these fine-grained minerals have a high specific gravity (>8 g) and can be separated from the other heavy minerals by micropaning, easing their identification. Therefore micropanning of the <0.25 mm fraction, along with heavy mineral concentration of the 0.25–2.0 mm fraction, is essential for all Ni-Cu-PGE indicator mineral surveys to detect the key minerals that occur only at fine grain sizes.

The superior stability of chalcopyrite and sperrylite is well illustrated in a rusty specimen (Fig. 8c) from the gossan of the Broken Hammer Cu-(Ni)-PGE occurence near Sudbury, Ontario, Canada where the Geological Survey of Canada has performed detailed indicator mineral sampling (Ames *et al.* 2007; McClenaghan & Cabri 2011). Both minerals remain very fresh whereas pentlandite, pyrrhotite and pyrite have been completely oxidized to rusty brown goethite. Till samples collected proximal to Broken Hammer contain hundreds of sperrylite grains but no PGE sulphides or tellurides even though these are the dominant PGMs in fresh samples of the mineralized zone (Péntek *et al.* 2008).

The chalcopyrite grains that survive in weathered till are not completely fresh. They are weathered to a dull bronze colour and often have deep furrows along their cleavage planes (Fig. 8d). The presence of just 50 to 100 of these grains in a sample having no remaining iron sulphides is a good indication that many more grains of chalcopyrite – and possibly also of Ni or other sulphide minerals – were originally present and the anomaly is important.

Abundance of Ni-Cu-PGE versus kimberlite indicator minerals

While nine minerals that originate in the mantle are used as kimberlite indicators and only four of these minerals – enstatite, forsterite, Cr-diopside and chromite – recrystallize from the mantle melts that produce Ni-Cu-PGE deposits and can be used as indicators of these deposits, Ni-Cu-PGE indicators are

Fig. 2. Examples of Ni-Cu-PGE indicator mineral grains from surficial sediment samples: (**a**) Magmatic non-kimberlitic; and (**b**) xenocrystal kimberlitic forsterite grains from till. Note the colourless character of the non-kimberlitic grains and the presence of microscopic Cr-magnetite inclusions in some of these grains; (**c**) Magmatic non-kimberlitic low-Cr diopside and (**d**) xenocrystal kimberlitic Cr-diopside grains from till. Note the paler emerald green colour of the non-kimberlitic grains, reflecting their lower Cr_2O_3 content; (**e**) Sharp to ragged chromite crystals derived from peridotite; (**f**) Resorbed chromite crystals derived from kimberlite; (**g**) Chromite crystals corroded by lateritic weathering, masking their primary form and paragenesis; (**h**) Chromitite grains from the Attawapiskat River. The grains consist of cumulus chromite crystals in a matrix of serpentine and kammererite (Cr-chlorite). Photos from Overburden Drilling Management Ltd.

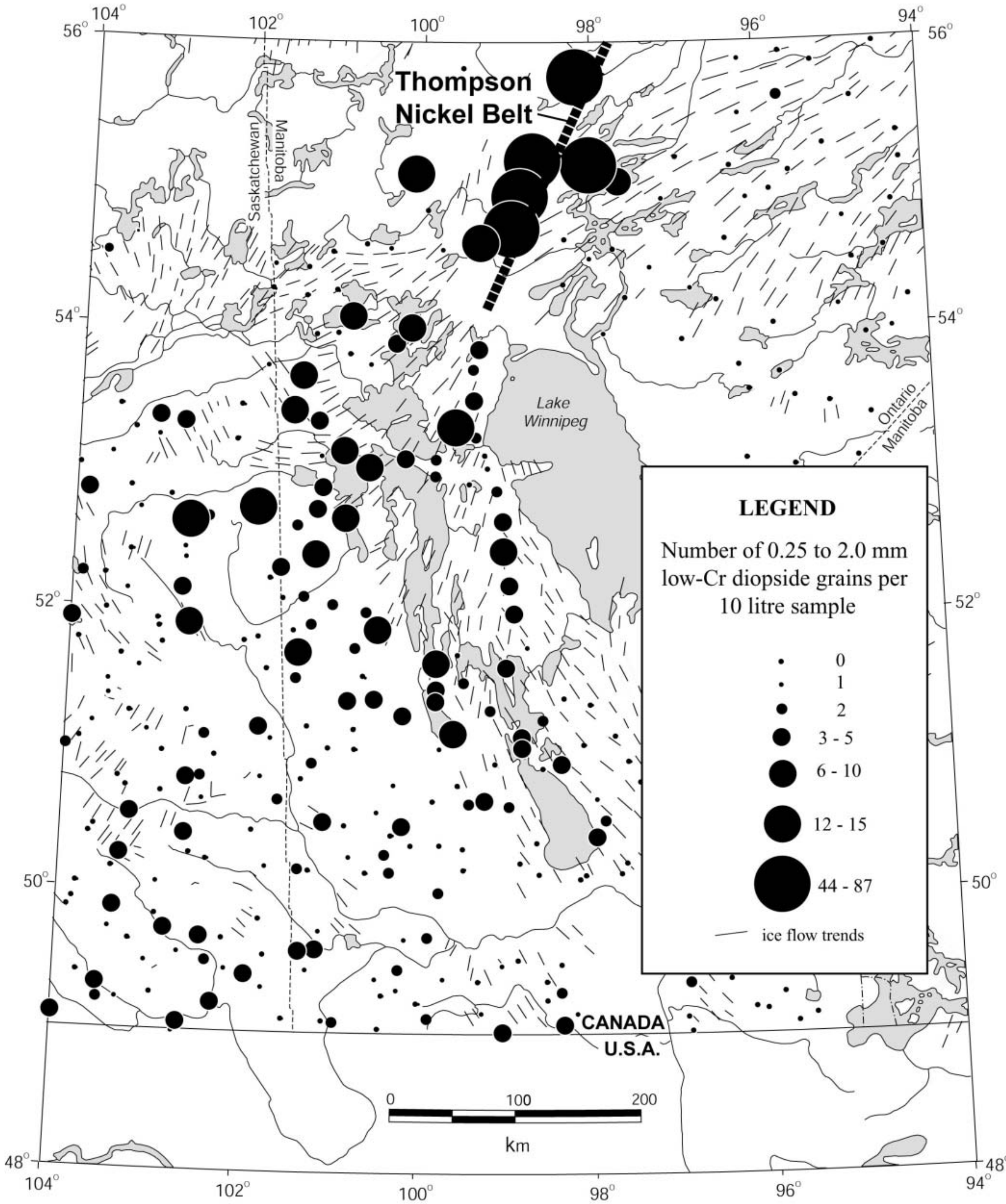

Fig. 3. Regional distribution of low-Cr diopside in till in western Manitoba and eastern Saskatchewan, central Canada. Note the broad dispersal train extending 400 km SW from the Thompson Nickel Belt. Modified from Averill (2001).

not limited to these four minerals. The five hybrid alteration minerals indicating melt contamination and potential sulphide saturation (Table 3) have no counterparts in the kimberlite suite and the approximately ten economic minerals that are sufficiently resistant to oxidation to be used as Ni-Cu-PGE indicators (Table 4) have only one counterpart – diamond – in the kimberlite suite. Diamond is generally too rare to be of practical use. The net result is that there are *c.* 20 useful Ni-Cu-PGE indicator minerals, thus outnumbering kimberlite indicators two to one.

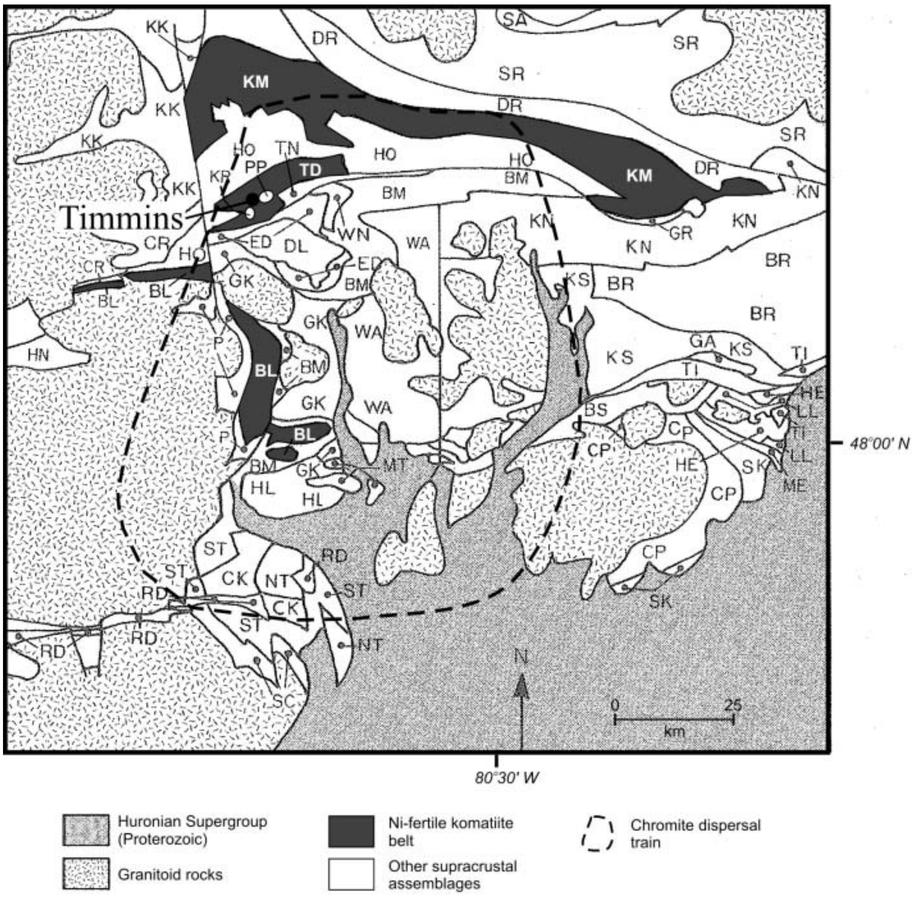

Fig. 4. Distribution of chromite in till down ice (south) of Ni-fertile komatiites of the Tisdale (TD), Kidd-Munro (KM) and Bartlett (BL) supracrustal assemblages in the Timmins area, Ontario, Canada. The chromite anomaly is defined by >10 to >100 grains per 10 kg till sample compared to a regional background of 0–3 grains per sample. Modified from Jackson & Fyon (1991).

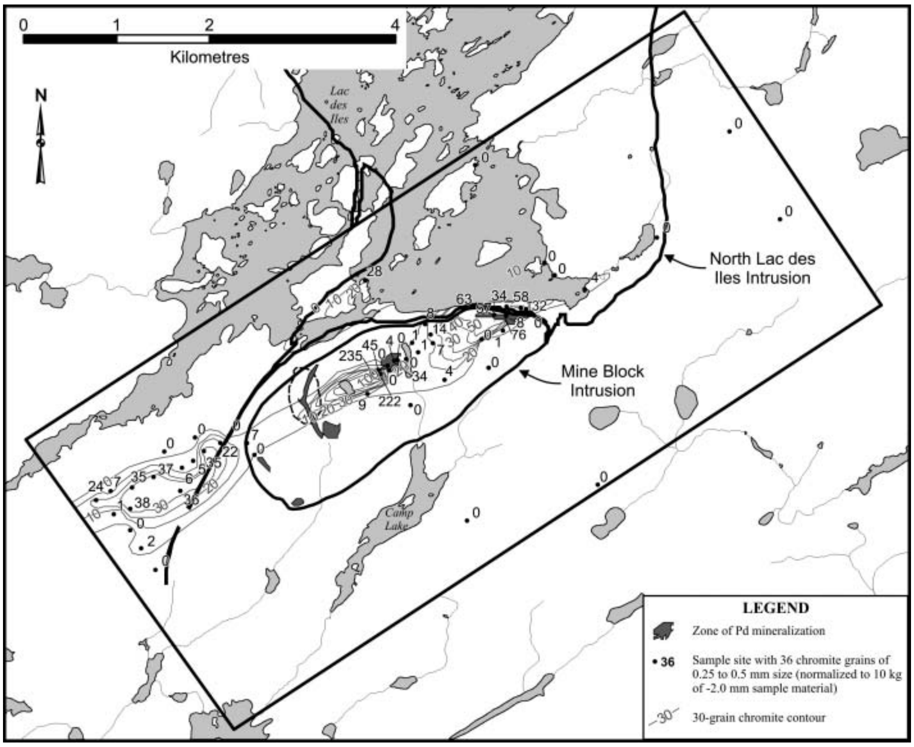

Fig. 5. Distribution of chromite in till near the Lac des Iles Pd deposit, Ontario, Canada. Ice flow direction is SW. Modified from Barnett & Dyer (2005).

Most Ni-Cu-PGE dispersal trains contain only a few of the *c.* 20 possible indicator minerals, especially in the distal portions of the train. This is particularly true for trains associated with the Sudbury Igneous Complex which appears to have been generated by wholesale melting of mostly felsic crust following asteroid impact rather than by partial melting of mantle peridotite (Naldrett 2005). Due to the inherently low Mg and Cr content of felsic rocks, minerals indicating

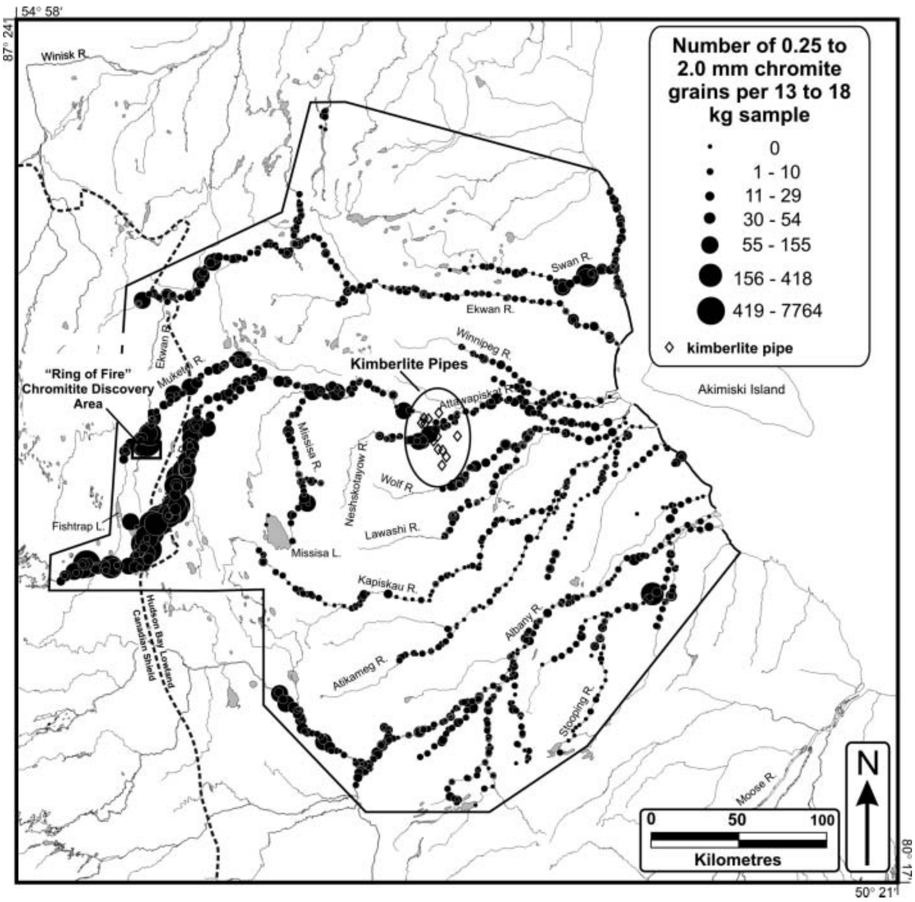

Fig. 6. Regional distribution of chromite in alluvial gravel in the James Bay Lowland, Ontario, Canada. Note the significant concentrations of chromite grains toward the western headwaters of the Attawapiskat River. Modified from Crabtree (2003).

Table 3. *Hybrid alteration minerals used as kimberlite and Ni-Cu-PGE indicators*

Kimberlite	Ni-Cu-PGE Deposits
none	Cr-andradite Cr-grossular uvarovite hercynite ruby corundum

melt fertility or concentrated cumulus segregation from the melt are either absent from the till in the Sudbury area or are less Mg and Cr rich than normal (e.g. orthopyroxene is bronzite rather than enstatite and olivine is fayalitic; Morris *et al.* 1995). Hybrid mafic–felsic alteration minerals are similarly absent; therefore, indicator minerals surveys at Sudbury rely mainly on weathering-resistant ore minerals such as chalcopyrite, sperrylite and gold (e.g. Ames *et al.* 2007; Bajc & Hall 2000).

PORPHYRY CU INDICATOR MINERALS

Porphyry Cu indicator mineralogy (PCIM®)1 has emerged as a significant exploration tool only in the last seven years (Averill 2007). The main focus has been on porphyry deposits in arid regions such as the Atacama Desert in Chile where the climate has stabilized the original hypogene sulphide minerals in the bedrock by converting them to chemically resistant (to ongoing arid weathering following dispersal into surficial sediments) supergene sulphates (e.g., jarosite; Fig. 8e), chlorides (e.g., atacamite; Fig. 8f) and phosphates. In some cases, fresher alluvium containing both hypogene and supergene minerals has been sampled in deep reverse circulation holes that were drilled primarily to sample bedrock, thereby extending the exploration coverage of these holes at minimal added cost. In addition, PCIM® technology has been used to explore for high-sulphidation epithermal Au deposits peripheral to porphyry Cu deposits. A few PCIM® surveys have also been conducted in humid tropical regions.

PCIM® dispersal anomalies tend to be large in the manner of Ni-Cu-PGE indicator mineral anomalies, irrespective of the dispersal mechanism, because porphyry Cu alteration systems are large, e.g. *c.* 10 × 25 km in diameter at Escondida (Richards *et al.* 2001). The anomalies are also strong, in part due to the large size of the source alteration systems but also, in arid regions, due to the conversion of pyrite and chalcopyrite in the upper parts of porphyry deposits to more stable supergene minerals such that the mineralization itself is a major supplier of indicator minerals. Moreover, for those porphyry Cu and other mineral deposits occurring in unglaciated areas, there is no anomaly dilution by heavy minerals derived from distal sources. However, the anomalies are generally limited to a single drainage basin rather than forming linear, basin-crossing trains tens to hundreds of kilometres long as in glaciated areas.

Ten PCIMs® have proven useful to date in arid regions (Table 5). These include five hypogene alteration minerals – diaspore, Mg-tourmaline (dravite), FeCaMn-garnet (primarily andradite but variably grossular or spessartine), primary alunite and barite – plus two supergene alteration minerals – jarosite and secondary alunite – and three 'oxide' Cu minerals, turquoise, atacamite and malachite. Five of these are heavy minerals (SG >3.2) and the other five are mid-density minerals (SG 2.8–3.2). Other minerals that have been observed in surficial sediment samples collected near some of the tested

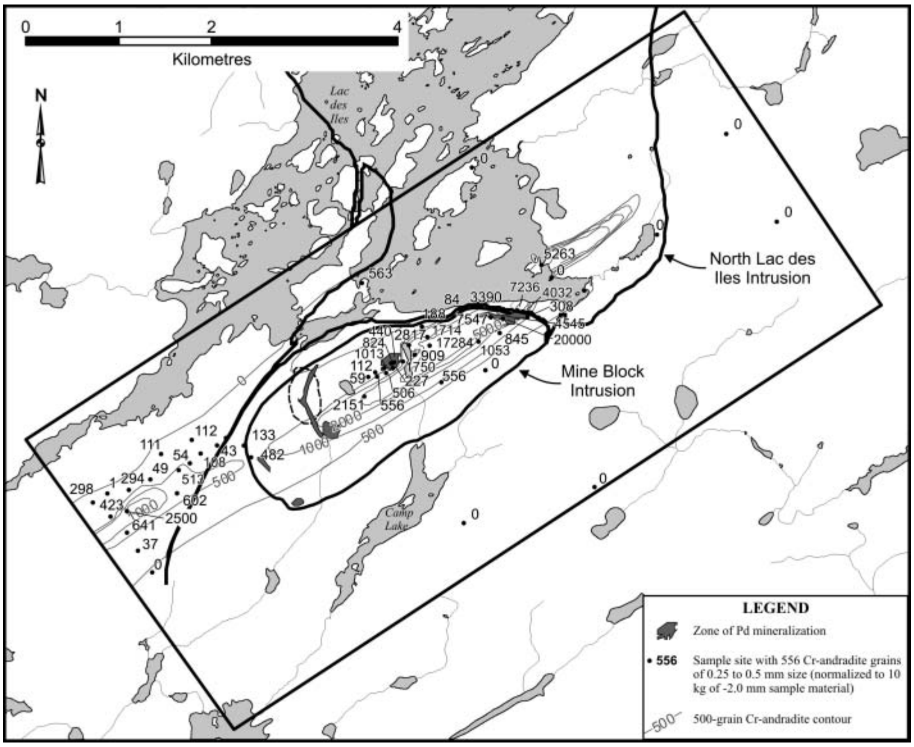

Fig. 7. Distribution of Cr-andradite garnet in till near the Lac des Iles Pd deposit, Ontario, Canada. Ice flow direction is southwest. The regional Cr-andradite background is zero grains per sample. Modified from Barnett & Dyer (2005).

porphyry deposits and may prove useful as indicator minerals are red rutile, apatite, rose zircon, blond titanite, sapphire corundum, epidote and biotite. Studies of apatite and rutile (both the red and more common black colour phases) grains in *bedrock* samples from economic porphyry deposits have shown trace element patterns distinct from those of visually similar grains from barren porphyries and other types of mineral deposits (e.g. Williams & Cesbron 1977; Scott 2005). However, most rutile grains associated with porphyry Cu deposits are much smaller (Scott 2005) than the 0.25 mm cutoff used for indicator mineral grains in surficial sediment samples and both the rutile and apatite grains in these samples are generally derived from diverse bedrock sources such that using mineral chemistry to identify any porphyry-derived grains may not be practical.

Together the above minerals fingerprint the overall porphyry Cu system. However, porphyry systems are distinctly zoned (Lowell & Guilbert 1970) and some of the indicator minerals are derived from specific alteration zones. For example, the presence of diaspore, tourmaline or primary alunite in a surficial sediment sample normally indicates proximity to the advanced argillic or potassic alteration zones, FeCaMn-garnet indicates propylitic alteration (or possibly skarn) and barite suggests a transition from porphyry Cu to epithermal Au mineralization (Table 5). This indicator mineral zoning was clearly demonstrated in one of the earliest PCIM surveys, performed in 2003 by Aur Resources Inc. at the company's Quebrada Blanca mine in Chile. The terrain at Quebrada Blanca is steeply sloping and the thickness of the alluvial cover ranges from <1 to *c.* 20 m. Aur Resources Inc. collected 38 samples at *c.* 1 km intervals (Fig. 9) and, to ensure that the survey was unbiased, did not divulge either the sample locations or geological setting to ODM until Aur Resources Inc. had received the indicator mineral results and plotted them in relation to the known alteration zones (Fig. 10). The indicator mineral patterns clearly outline the outer propylitic (andradite garnet; red dots in Fig. 10) and more central advanced argillic/potassic (jarosite + alunite + turquoise; blue dots in Fig. 10) alteration zones and, at higher elevations, suggest a transition to epithermal (barite; pale yellow dots in Fig. 10) alteration.

Anomalous concentrations of andradite garnet, in some cases accompanied by grossular and spessartine, have been encountered in surficial sediments not only at Quebrada Blanca but also at every other porphyry Cu deposits tested to date. Andradite is a characteristic skarn mineral and the lower temperature regime of propylitic alteration does not favour garnet production. However, grossular produced by destruction of plagioclase has been reported from the propylitic zone at Escondida (Padilla Garza *et al.* 2001), and most if not all of the andradite grains observed in surficial sediments at the porphyry deposits tested to date appear to reflect propylitic alteration rather than skarns because: (1) skarns are associated with carbonate rocks and the tested porphyries were emplaced into andesitic to basaltic volcanics, not carbonate-bearing sedimentary sequences; (2) in skarns, andradite is generally associated with and subordinate to diopside, a mineral that is absent from the andradite-bearing surficial sediments; (3) the andradite anomalies outlined in the surficial sediments are generally extensive, indicating a large source area, and the propylitic alteration zone, being the outermost and least intense alteration zone, is generally much larger than the other zones (e.g. 25 v. 5 km at Escondida; Richards *et al.* 2001); and (4) in areas of thin to moderate cover and thus limited andradite dispersal such as Quebrada Blanca (Fig. 10), the andradite anomalies generally correlate more closely with the outermost part of the alteration system than with the contact of the porphyry intrusion where skarns, if present, would be localized. Although not directly diagnostic of mineralization, andradite appears to be the most useful indicator of porphyry Cu systems identified to date because the propylitic zone is a much larger exploration target than the other alteration zones and, being the outermost zone and also the uppermost, if not pierced and overprinted by later sericitic and advanced argillic mineral assemblages (Sillitoe 2010), may be the only exposed target for deposits that have not been completely unroofed by erosion.

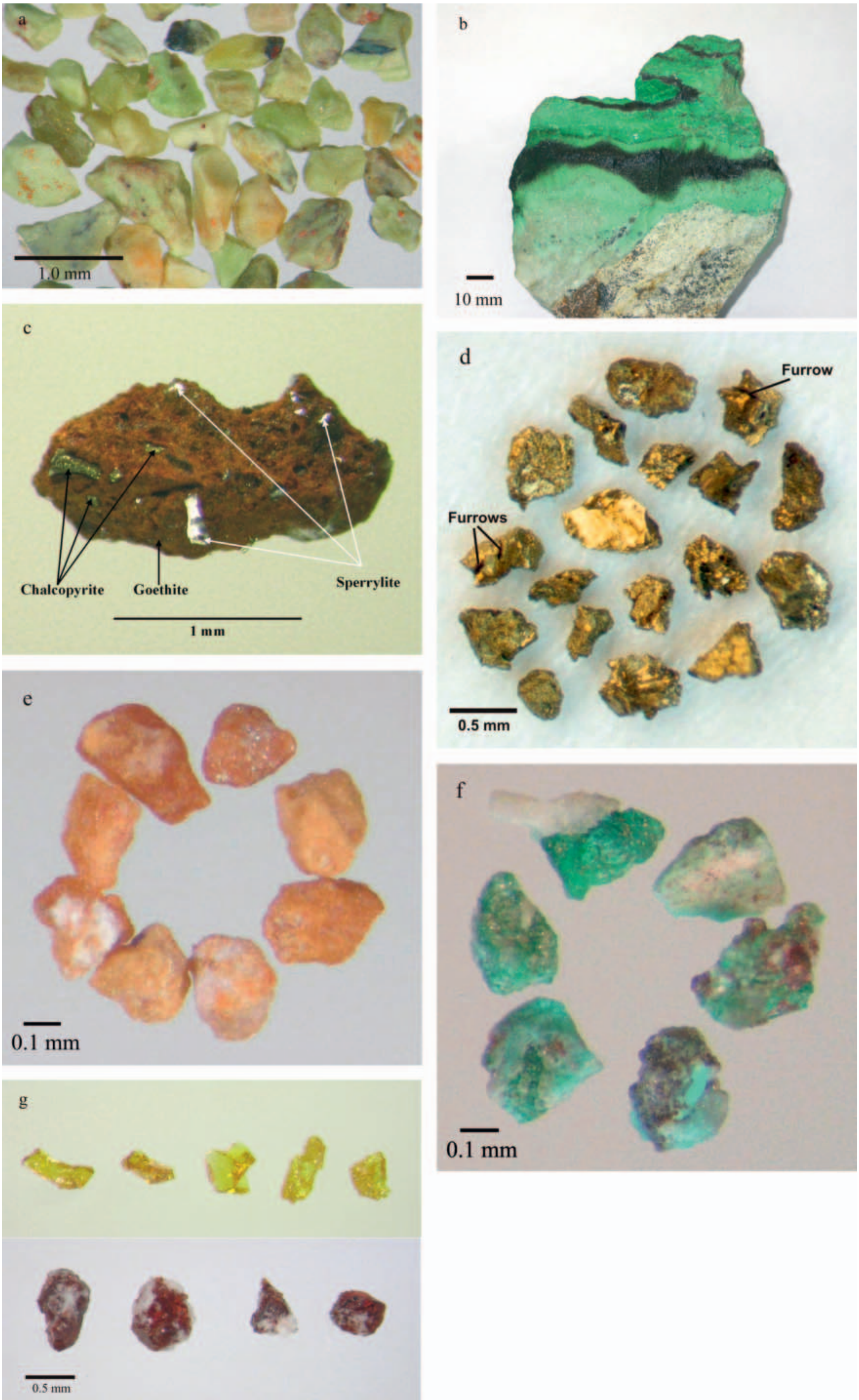
a
1.0 mm
b
10 mm
c
Chalcopyrite
Goethite
Sperrylite
1 mm
d
Furrow
Furrows
0.5 mm
e
0.1 mm
f
0.1 mm
g
0.5 mm

Table 4. *Relative stabilities of Fe-sulphides and Ni-Cu-PGE ore minerals in surficial sediments weathered under temperate to humid tropical climatic conditions*

Mineral	Stability
pentlandite	very unstable
millerite	very unstable
PGE-sulphides	very unstable
PGE-tellurides	very unstable
pyrrhotite	very unstable
pyrite	unstable
chalcopyrite	marginally stable
FeNi and PGE-arsenides	stable
PGE-antimonides	stable
native Au and PGE	very stable

The andradite grains found in the surficial sediments (Fig. 8g) are crystalline, typically yellow or red-orange in colour and may have adhering silica (quartz) alteration; they are not cryptocrystalline and Cr-green with red serpentine alteration like the andradite grains that are used as a Ni-Cu-PGE indicator (Fig. 8a) because the andradite is not hydrated and contains no Cr. The Ca + Fe-rich composition of andradite ($Ca_3Fe_2(SiO_4)_3$) is compatible with that of the calcite, epidote and pyrite that characterize propylitic alteration. Andradite grains are easily identified in surficial sediment samples collected near porphyry Cu deposits because these deposits typically occur in unmetamorphosed terrains lacking almandine and other types of garnet. However, the same andradite grains would be much less noticeable in altered rock samples because they are small (mostly <0.5 mm), intergrown with quartz and closely resemble titanite, a common mineral in porphyry intrusions. Moreover, andradite is probably a relatively minor constituent of the overall alteration assemblage because its concentration in anomalous surficial sediments is generally <50 grains/kg. In the same manner that Cr-andradite grains were recognized in the till at the Lac des Iles Pd deposit before the alteration zones associated with the Ni-Cu-PGE mineralization were known to contain Cr-andradite, the recognition of andradite grains in surficial sediments around porphyry Cu deposits may lead to greater recognition of this mineral in the propylitic alteration zones associated with these deposits.

The supergene minerals jarosite ($KFe_3(SO_4)_2(OH)_6$) and alunite ($KAl_3(SO_4)_2(OH)_6$) are end member minerals of a solid solution series in which considerable substitution of both Na for K and Fe for Al occurs. They are particularly useful indicators because they combine the sulphur and iron from hypogene pyrite with potassic, sodic and aluminous alteration all in one mineral. That is, they are hybrid indicator minerals like the green Cr-andradite (Fig. 8a) that is used as a Ni-Cu-PGE indicator.

CONCLUSIONS AND RECOMMENDATIONS

Indicator mineralogy for Ni-Cu-PGE and porphyry Cu exploration is relatively new but has proven to be as effective as that used in kimberlite exploration because: (1) the dispersal anomalies are just as large as those for kimberlite; (2) a greater number of useful indicator minerals are available; and (3) some of these minerals, such as the unique Cr-andradite grains in the till at Lac des Iles (Figs 7, 8a), the sperrylite grains in till at Broken Hammer (Ames *et al.* 2007) and elsewhere (e.g. Sudbury (Bajc & Hall 2000)), Lac des Iles (Searcy 2001) and Thompson Nickel Belt (McClenaghan *et al.* 2009)) and the turquoise grains occurring directly over the core alteration zones at Quebrada Blanca (Fig. 10), are just as diagnostic of potentially economic mineralization as G10 Cr-pyrope garnet is of diamond potential. The large size of the dispersal anomalies reflects the large scale of the magmatic–hydrothermal systems that are associated with Ni-Cu-PGE and porphyry Cu deposits, and this basic fertility can be detected from regional-scale sampling. The large variety of available indicator minerals reflects the regular zoning of both systems, and indicator minerals derived from specific zones can be used effectively to focus in on the best-mineralized sectors of these systems.

The success of a Ni-Cu-PGE or porphyry Cu indicator mineral survey is highly dependent on the ability of the sample processing laboratory to recover and identify all of the useful indicator minerals. The requisite skill level is higher than for kimberlite indicator mineral processing because many more mineral species are involved. For a Ni-Cu-PGE survey, the laboratory must be able to recover and identify very fine-grained PGMs and gold grains in addition to the many coarse-grained indicator minerals and also visually distinguish the four crossover minerals – enstatite, forsterite, Cr-diopside and chromite – from their counterparts in the kimberlite indicator mineral suite. For a porphyry Cu survey, mid-density concentrates of SG 2.8–3.2 are required in addition to the usual SG >3.2 heavy mineral concentrates to capture all of the indicator minerals.

Ni-Cu-PGE indicator mineralogy has been applied mainly in glaciated terrains where the overall dispersal train defined by melt fertility indicator minerals such as chromite or Cr-diopside may be tens to hundreds of kilometres long and cross divides between major post-glacial drainage basins. A 10–20 km sample spacing – similar to that used on initial, regional-scale kimberlite exploration programs – is sufficient to detect such trains but a closer, *c.* 1 km spacing may be needed to locate indicators of sulphide saturation and Ni-Cu-PGE mineralization. A 1 km spacing is also required for porphyry Cu exploration in unglaciated terrains where the indicator mineral dispersion is confined to a single drainage basin. If the alluvial cover is not excessive, sampling at this density will normally outline the individual alteration zones. On broad alluvial plains where the cover exceeds 20 m, a blended anomaly may be obtained from the overall alteration system but the individual zones can be resolved by drilling reverse circulation holes to obtain samples closer to bedrock.

Although Ni-Cu-PGE indicator mineralogy is now well proven for exploring glaciated areas, more testing is required to

Fig. 8. Examples of Ni-Cu-PGE and porphyry Cu indicator minerals from surficial sediment and rock samples: (**a**) Cr-andradite garnet grains from till near the Lac des Iles Pd deposit, Ontario, Canada; (**b**) Cr-grossular garnet associated with chromitite bands in the Bushveld Complex, South Africa. Note the cryptocrystalline (hydrated) form of the garnet at both localities and the variation in colour from white to green with increasing Cr_2O_3 content and with decreasing distance from the chromitite bands; (**c**) Small gossan fragment from Broken Hammer Cu-(Ni)-PGE occurrence, Sudbury, Ontario, Canada, illustrating variable resistance to weathering of sulphide and arsenide minerals. Pentlandite, pyrrhotite and pyrite have been completely oxidized to goethite but chalcopyrite and sperrylite remain fresh; (**d**) Typical chalcopyrite grains from weathered till. The original bright metallic surfaces have been oxidized to a dull bronze colour and deep furrows have formed along some cleavage planes; (**e**) Transported jarosite grains from sheet wash gravel, Chile. Jarsoite was produced by supergene weathering of hypogene pyrite in the porphyry Cu source rock; (**f**) Transported atacamite grains from sheet wash gravel, Chile. Atacamite was produced by supergene weathering of hypogene chalcopyrite in the porphyry Cu source rock; (**g**) Andradite garnet grains from weathered alluvium near a porphyry Cu deposit. Grain colour may vary from yellow–orange (upper row) to red-orange (lower row; garnet is intergrown with fine-grained quartz alteration) or orange–brown. Photos from Overburden Drilling Management Ltd.

Table 5. *Porphyry Cu indicator minerals regularly observed by ODM in oxidized surficial sediments in arid regions of Chile, Peru and western USA*

		Principal provenance (alteration zone)				
Mineral	Composition	Potassic	Argillic	Phyllic	Propylitic	Epithermal Au
Hypogene suite:						
Diaspore	AlO(OH)		—			
Alunite	$KAl_3(SO4)_2(OH)_6$	—	—			
Dravite	$NaMg_3Al_6(BO_3)3(Si_6O_{18})(OH)_4$		—			
Andradite	$Ca_3Fe_2(SiO4)_3$				—	
Barite	$BaSO_4$					—
Supergene suite:						
Alunite	$KAl_3(SO_4)_2(OH)_6$	—	—			
Jarosite	$KFe_3(SO_4)_2(OH)_6$	—	—			
Atacamite	$Cu_2Cl(OH)_3$	—	—	—		
Turquoise	$CuAl_6(PO_4)_4(OH)_{8.5}H_2O$		—			
Malachite	$Cu_2CO_3(OH)_2$			—	—	

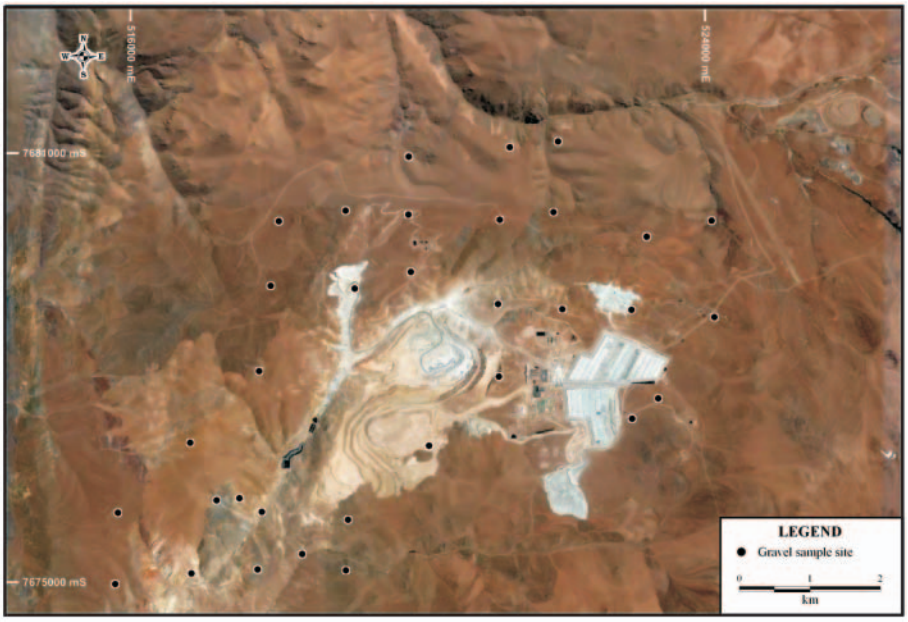

Fig. 9. Sample sites for Aur Resources Inc.'s Quebrada Blanca indicator mineral survey, Chile. Satellite image source: Google Earth.

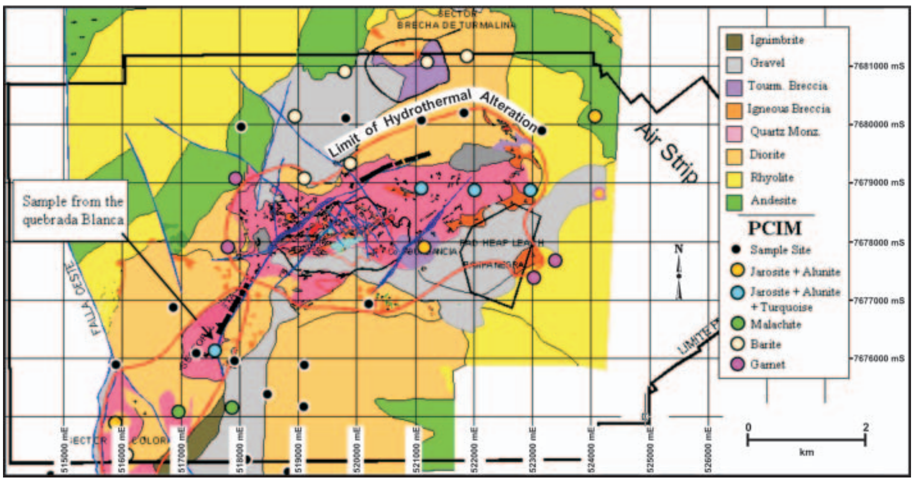

Fig. 10. Distribution of porphyry Cu indicator minerals in weathered alluvium near the Quebrada Blanca deposit, Chile. Unpublished data from Aur Resources Inc. and Teck Cominco Limited.

determine whether it is effective for lateritic Ni deposits where the Ni is concentrated from peridotite by secondary weathering of olivine rather than triggered by sulphide saturation during emplacement of the peridotite melt. Initial results suggest that the only indicator mineral that survives in this environment is chromite and that the morphology of the chromite grains is considerably modified by the intense weathering (Fig. 2g). This limitation may be partly offset by the very high concentrations of chromite that can occur in the residual *canga* blanketing lateritic deposits.

For porphyry Cu, additional indicator mineral test surveys are needed to validate the initial indications that minerals such as red rutile, sapphire corundum and rose zircon may be useful indicators. Laboratory testing should also be performed to determine the extent to which physically dispersed grains of turquoise, atacamite and other Cu minerals in the surficial sediments near porphyry deposits are responsible for the very weak Cu anomalies that have been reported from selective extraction geochemical surveys and ascribed to aqueous, gaseous or electrochemical migration of Cu through thick alluvium (e.g. Cameron *et al.* 2002). It would also be instructive to investigate the indicator mineral responses of other types of deposits that are related to large-scale magmatic-hydrothermal systems such as porphyry Cu-Au, porphyry Mo and iron oxide-Cu-Au.

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