

Heavy mineral dispersal trains in till in the area of the Lac des Iles PGE deposit, northwestern Ontario, Canada

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ABSTRACT: Till sampling near the Lac des Iles Pd mine north of Thunder Bay, Ontario, Canada has led to the identification of heavy mineral dispersal trains in till as unique as the local Pd deposits. The till at Lac des Iles was deposited by ice actively flowing in a 240° direction. It is commonly thin and ideal for exploration sampling.

Several dispersal trains of chrome-andradite garnet and chromite occur within the area surrounding the Mine Block Intrusion (MBI). Cr-andradite garnet is normally a hybrid, assimilation-type indicator mineral; however, here the Cr-andradite is of a low-temperature, cryptocrystalline form, suggesting that hydrothermal alteration, possibly associated with the Lac des Iles late-stage mineralizing event, may have played a significant role in its formation. A major Cr-andradite + chromite dispersal train occurs over the MBI. It is a narrow, ribbon-shaped, composite train that trends 240°, is *c.* 600 m in width and exceeds 5 km in length. Its farthest up-ice source appears to be located to the NW of the margin of the MBI, in rocks of the Northern Lac des Iles Intrusion (NLDI-I). The distal part of the dispersal train SW of the MBI may contain additional indicator mineral grains from a septa of ultramafic rocks associated with the North Lac des Iles intrusion that lies west of the MBI. The accompanying chromite dispersal trains are shorter and appear to be derived from similar source areas as well as an area in the vicinity of the Baker zone.

The indicator mineral contribution of the main Roby (ore) zone is difficult to assess due to a sampling gap but appears to be minimal, probably because this zone occurs in the interior of the intrusion and is hosted mainly by Cr₂O₃-poor gabbro. The only PGM are rare grains of Pt and Pd arsenides, which are uncommon in the mineralized zones but are stable in near-surface till.

KEYWORDS: *till, heavy mineral concentrate, platinum group mineral, indicator mineral, Cr-andradite, Lac des Iles*

INTRODUCTION

The Lac des Iles Pd mine is located in typical glaciated Canadian Shield terrain *c.* 85 km north of the city of Thunder Bay in northwestern Ontario, Canada (Fig. 1). The open pit mine is accessible by road and is located along the south shore of Lac des Iles at approximately longitude 89°36' W and latitude 49°10' N. Several zones of platinum group element (PGE) mineralization are known at Lac des Iles including the Roby and High Grade zones (mine) and the Powerhouse, Twilight, Moore, Creek and Baker zones (Lavigne & Michaud 2002; Hinchey *et al.* 2005). This paper summarizes investigations into the glacial history of the area, the character of the till and the extent of glacial dispersion of platinum group minerals (PGM) and other associated indicator minerals in the till. Searcy (2001a) previously conducted an orientation survey on the distribution of PGM and PGE in till and soil in the area immediately adjacent to the mine workings. Searcy (2001a)

reported one sperrylite grain in the heavy mineral concentrate of a till sample collected down-ice from the Roby Zone and abundant Cr-andradite garnet in the concentrates of many till samples.

The data presented in this paper were collected as part of the Surficial Geochemical Case Study Project of the Lake Nipigon Region Geoscience Initiative (LNRGI) and was funded by the Northern Ontario Heritage Fund Corporation through the Ontario Prospectors Association. The overall goal of the project was to evaluate various surficial media and sampling methodologies for use in PGE exploration in the glaciated terrain of the Lake Nipigon region (Barnett & Dyer 2005; Dyer & Barnett 2005, 2007; Barnett 2007).

Lac des Iles mineralization

The Lac des Iles mine is owned by North American Palladium Ltd. and is Canada's only primary Pd producer. Economic

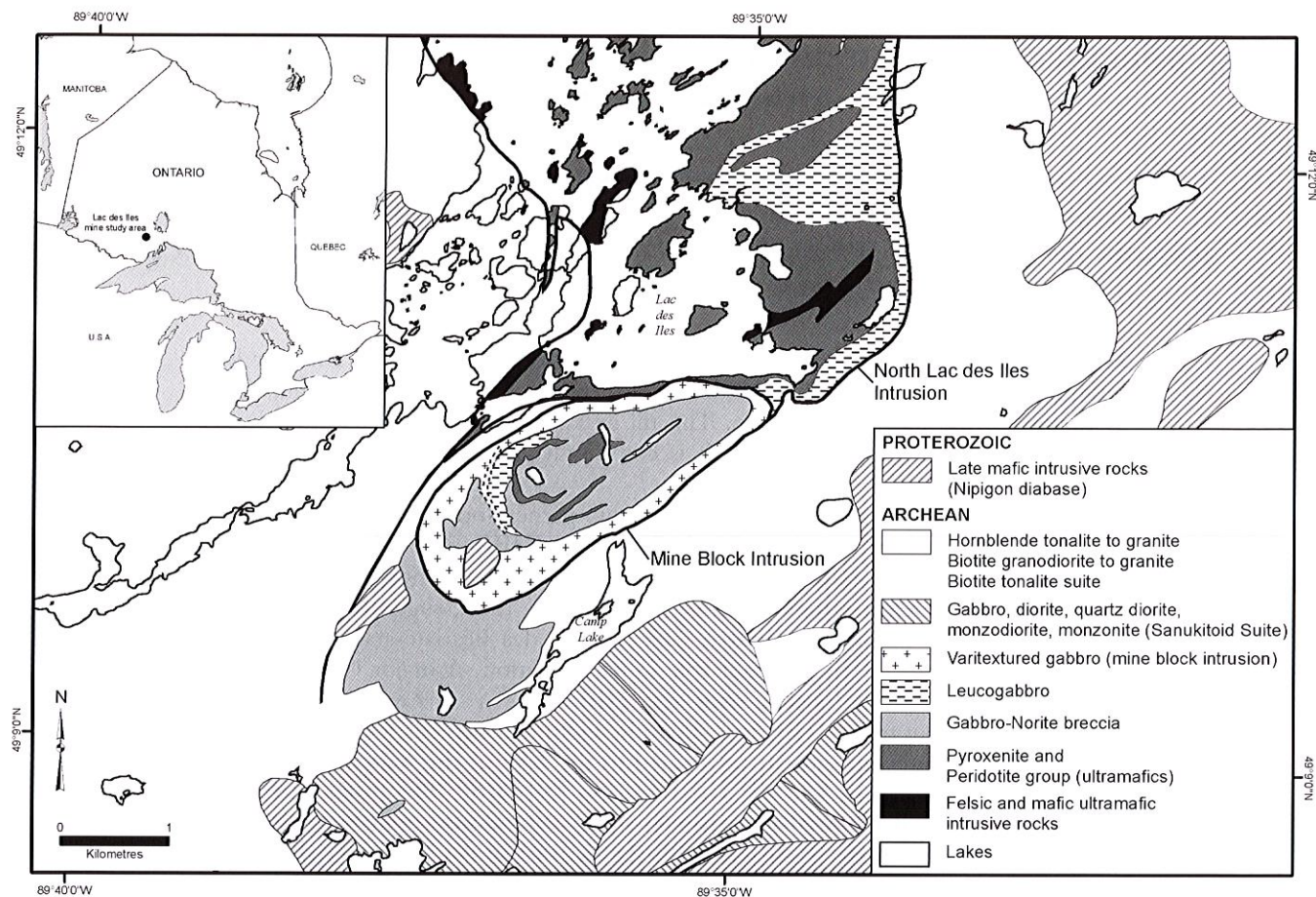


Fig. 1. Location and bedrock geology of the Lac des Iles mine area (modified from Stone *et al.* 2003 and Sutcliffe *et al.* 1989).

concentrations of Pd are hosted by Archean-age rocks of the mafic to ultramafic MBI, the southernmost body of the two-chambered Lac des Iles Intrusive Complex (LDI-IC; Lavigne *et al.* 2005). The LDI-IC is surrounded by tonalite. It is one of a suite of mafic-ultramafic plutons that intruded granite-greenstone terrain of the Wabigoon Subprovince near its southern boundary with the Quetico Subprovince of the Superior Province.

Stone *et al.* (2003) produced the most recent Precambrian geology map of the Lac des Iles area (Fig 1). The exploration history and previous work on the geology and mineralogy of the LDI-IC and proposed processes of mineralization and origin of the ore are reviewed and summarized in several papers (Lavigne & Michaud 2002; Hinchey & Hattori 2005; Hinchey *et al.* 2005; Lavigne *et al.* 2005).

The Pd occurs in gabbroic rocks that contain few sulphides and show complicated textures. Hinchey (Hinchey *et al.* 2005, p. 43) suggests that 'mineralization at Lac des Iles has many features in common with layered intrusion-hosted deposits', however, 'unlike the quiescent magma chambers of most layered deposits, the magmas at Lac des Iles were intruded energetically forming breccias and magma-mingling textures.' The high-grade ore occurs within a discontinuous linear zone (High Grade zone) that is highly fractured and altered with all primary minerals having been replaced by secondary silicate minerals: actinolite, + hornblende, + chlorite, + sericite, ± talc, ± calcite and blue quartz (Hinchey & Hattori 2005; Lavigne *et al.* 2005).

Hinchey & Hattori (2005) suggest a primary magmatic origin of mineralization, based on rock geochemical data, that was followed by further enrichment by hydrothermal transport

of mobile elements. Pyrite, millerite, siegenite, chalcopyrite, pyrite, pentlandite and pyrrhotite are the main sulphide minerals that occur in the mineralized zones of the MBI. Palladium and Pt occur mainly as discrete fine ($c. < 0.2$ mm) grains of the sulphides braggite ((Pt,Pd,Ni)S) and vysotskite ((Pd,Ni)S) or tellurides, merenskyite ((Pd,Pt)(Te,Bi)₂) and kotulskite ((Pd)(Te,Bi)) rather than in stable native minerals or arsenides such as sperrylite (Lavigne *et al.* 2005).

The northern body of the LDI-IC, the North Lac des Iles intrusion (NLDI-I), consists of mafic to ultramafic rocks, primarily pyroxenite. The rocks of the NLDI-I are more even-textured and less altered than the rocks of the MBI and appear to contain only minor mineralization (Fig. 1).

FIELD OBSERVATIONS

Surficial geology

The entire LDI-IC, except for the portion beneath Lac des Iles, is covered by a network of exploration trenches that were employed to expose and sample the bedrock due to the visually innocuous and geophysically unresponsive nature of the mineralization (Lavigne *et al.* 2005). Mineralized areas were further stripped and washed clean. The extensive trenching and stripping provided the opportunity to examine bedrock striae and scour features in detail and to study the surficial strata in section, interpret their origin and identify the various soil horizons developed upon them. A map showing the distribution of the surficial geology of the Lac des Iles area has been previously published (Barnett & Dyer 2005, Map 1).

The region around the Lac des Iles mine was deglaciated $c. 10\,000$ years ago and is a bedrock-dominated terrain with

local relief of up to 45 m. The bedrock surface, where recently exposed, is commonly well polished and striated, with rare large-scale meltwater erosion forms such as transverse troughs and cavets. The dominant direction of ice flow recorded from striae is toward 240° with local variations from 225° to 245°. One exposure sheltered by a large bedrock knob at the northeast end of the Baker Zone has preserved older striae oriented between 180° and 190° (Barnett & Dyer 2005, Map 1).

Till was found only in association with the younger, 240° ice flow direction. It is widespread and typically 0.5 to 3 m thick. It thickens on the flanks of, and down-ice from, bedrock knobs. Several well-developed crag-and-tail features occur near the Creek zone at the northeast corner of the MBI. Their orientations (235° to 242°) are similar to those of the striations on the bedrock surface. Stratified glaciofluvial sand and gravel occur in large and small sinuous ridges (eskers) and in small lee-side cavity fills. Sand of glaciolacustrine origin forms small plains in topographic lows along the southern shore of Lac des Iles.

The till is commonly stony with a massive to fissile, slightly silty, unsorted (very fine to coarse-grained) sand matrix. Grain size analyses of the matrix of 21 samples of C horizon till average *c.* 70% sand, 29% silt and 1% clay. The extensive record of striae, the presence of large-scale meltwater erosion forms and streamlined crag-and-tail features on the bedrock surface and the common occurrence of interbedded stratified sediments and till in lee-side cavity fill suggest the till was deposited by a wet-based glacier, conditions ideal for the application of drift (till) prospecting for mineral exploration.

Soil development

Soils developed on till at Lac des Iles generally consist of a very thin humus layer commonly containing charcoal, a thin to nonexistent zone of eluviation (Ae), usually <1 cm thick, and a B horizon 30 to 50 cm thick. The B horizon consists of a 10-cm thick, dark orange-brown Bf horizon that is enriched in Fe and a 20- to 40-cm thick, yellow-brown to brown Bm and/or BC horizon. Fresher, underlying C horizon till tends to be grey in colour and this material was exclusively sampled for this study. Samples collected by Searcy (00-CAS-series) appear to have been taken from both the C horizon and the BC horizon.

METHODS

Sample collection

In the current survey, 28 bulk samples (03-PJB-series and 04-PJB-series) of screened (<7 mm) C horizon till weighing between 10 and 15 kg were collected in an area extending from the Roby zone 6 km up-ice across and beyond the LDI-IC (Fig. 2). Complete indicator mineral results were released along with till and soil geochemistry data in MRD-154 (Dyer & Barnett 2005). Data for previously collected till samples (00-CAS-series) down-ice from the Roby/Powerhouse zones and in the vicinity of the Baker zone were reported by Searcy (2001*a*). Indicator mineral data from both surveys were used in the present study to better define dispersal patterns (Fig. 2). However, a critical 1.2-km gap with no till samples exists around the largest deposit, the Roby/High Grade zones, due to the large size of the mine pit, waste dumps, tailings ponds and related infrastructure. Thus, the results of this study cannot be used to evaluate the dispersion of indicator minerals from these zones; however, till samples were collected immediately down-ice of mineralized bedrock at the Creek and Baker zones.

Heavy mineral processing procedures

All till samples were processed by Overburden Drilling Management Limited (ODM), Nepean, Ontario. The <2 mm

fraction was processed by gravity tabling followed by heavy liquid refining at specific gravity 3.20, a magnetic separation to remove magnetite from the concentrate, sieving of the nonferromagnetic heavies into 0.25–0.5 mm (medium sand), 0.5–1.0 mm (coarse sand) and 1.0–2.0 mm (very coarse sand) sizes and further electromagnetic sorting of the 0.25–0.5 mm minerals. The major (>15%) paramagnetic and nonparamagnetic minerals (i.e. the background mineral assemblage) in the 0.25–0.5 mm fraction of each sample were systematically observed and recorded in order of decreasing abundance using a binocular microscope, and the indicator minerals occurring in each size fraction were identified and put into vials. Energy dispersive x-ray spectrometry (EDS) analysis with a scanning electron microscope (SEM) was used to confirm visual mineral identification when required. Any finer (< 0.25 mm) PGM and gold grains were micropanned from the table concentrates, measured and classified as to degree of wear during glacial transport. The processing methodology is described in greater detail in several other publications (Morris & Kaszycki 1997; Averill 2001; McMartin & McClenaghan 2001). The data reported by ODM include a complete suite of magmatic/metamorphosed massive sulphide indicator minerals (MMSIM[®]), of which Ni–Cu–PGE indicators are just one type, along with kimberlite indicator minerals (KIM). Mineral grain counts on six till sub-samples were processed and studied independently by the Ministry of Northern Development and Mines Geo Labs. Microprobe analysis using a Cameca SX-50 EPMA of >700 selected mineral grains believed to be Cr-andradite garnets from 28 sample sites was also undertaken by the Ontario Ministry of Northern Development and Mines Geo Labs (Searcy 2001*b*).

RESULTS

Background heavy minerals

ODM identified several mineral assemblages within the Lac des Iles till samples. All are dominated by paramagnetic pigeonite derived from Nipigon diabase 3.5 km to the NE (up-ice). The diabase contains up to 50% pigeonite (Larson & Mooers 2005). Consequently, the 0.25–2.0 mm till concentrates tend to be greatly oversized, often exceeding 100 g. The excessive pigeonite overwhelms and effectively masks the signature of any contained indicator minerals if the concentrates are analysed geochemically (Bajc 1999, 2000; Averill 2001; Larson & Mooers 2005) but the actual number of indicator mineral grains recovered for visual observation is unaffected. However, it is impractical to thoroughly examine concentrates >100 g for indicators. Therefore some (*c.* one-third) of the table concentrates were split; only 25 or 50% was refined and examined and the total number of indicators present was determined by extrapolation. In addition, the intensity of the electromagnetic separation was increased to cleanly separate the much smaller nonparamagnetic mineral fraction from the major paramagnetic pigeonite. The main nonparamagnetic minerals present are diopside and epidote. Heavy mineral grain counts on six till sub-samples processed and studied independently by the Ministry of Northern Development and Mines' Geo Labs revealed that they contain on average 71% clinopyroxene (mainly pigeonite), 9% calcic amphibole, 7% orthopyroxene and minor amounts (<2%) of almandine, ilmenite, fayalite and epidote.

Heavy mineral indicators of mineralization

Very few mineral grains were found that could be directly related to mineralization. Searcy (2001*a*) obtained one sperrylite (PtAs₂) grain *c.* 1.2 km from the Roby/Powerhouse zones

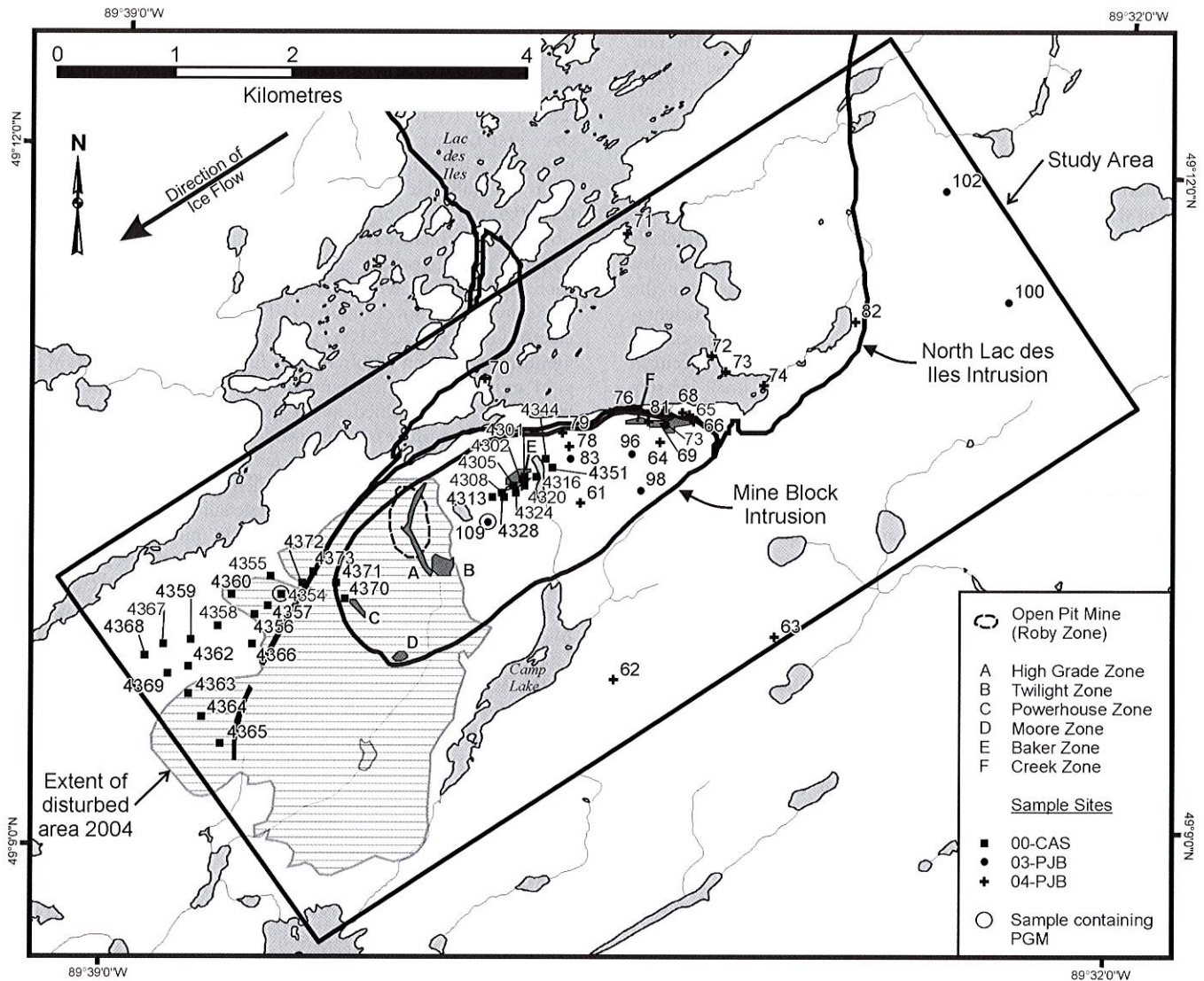


Fig. 2. Sample locations in relation to mineralized zones and the area of mine workings (infrastructure, waste rock and tailings) at the Lac des Iles Mine. The two samples that contain PGM grains in the heavy mineral concentrate from till are highlighted (open circles). The study area (box) is oriented with its long sides parallel to the ice flow direction ($\approx 240^\circ$).

(Fig. 2). In the current study, two stillwaterite (Pd_8As_3) grains were recovered from a sample collected ≈ 300 m from the Baker Zone (Fig. 2). Based on the location of the sample sites and the direction of ice flow, neither the Roby/Powerhouse zones nor the Baker zone are the likely source areas of the PGM.

Pyrite grains were found at $\approx 20\%$ of the sample sites but only $\approx 5\%$ or 3 sites had greater than one grain. One site at the western end of the Baker zone contained 100 grains of pyrite. Only two till samples contained grains of chalcopyrite with only one grain found in each sample. Gold grains in till range from 0 to 29 grains per 10 kg of sample. The highest grain counts (> 5 grains) occur ≈ 700 m down-ice of the main area of mineralization (Roby/High Grade zone).

Other indicator minerals

Several other heavy minerals have interesting distributions in the Lac des Iles area and shed light on dispersal train dimensions. Their spatial relationships with the MBI may provide clues to the possible processes involved or related to mineralization. Well developed dispersal trains in till exist for two heavy minerals, Cr-andradite garnet and chromite.

Cr-andradite abundance in the till at Lac des Iles ranges from 0 to ≈ 900 grains per 10 kg till sample in the 0.5 to 1.0-mm fraction (Fig. 3) and from 0 to ≈ 20000 grains in the 0.25 to 0.5-mm fraction (Fig. 4). The grains are a pale green to white colour and have a drusy cryptocrystalline habit. Some of the Cr-andradite grains tend to be spotted red with serpentine, suggesting that their source is in ultramafic rocks. In the most anomalous sample some of the coarsest (1.0–2.0 mm) Cr-andradite grains appear to have originated from veins. The pale green to white colour of the grains (Fig. 5) indicates that they have a variable and comparatively low Cr_2O_3 content (Table 1).

The geochemistry of 719 Cr-andradite grains from 28 sites is summarized in Table 1 (Searcy 2001b). Of the garnets probed, 45% had a wt% Cr_2O_3 of greater than 0.5 and 27% had a wt% Cr_2O_3 of 1 or greater and could be called Cr-andradite. All 28 sites with probed garnets contained Cr-bearing garnets with >0.3 wt% Cr_2O_3 and 86% of the sites contained Cr andradite garnets (>1 wt% Cr_2O_3).

Several sources are indicated by the distribution of Cr-andradite garnets in samples from the Lac des Iles area (Figs 3 and 4); however, to date no Cr-andradite garnets have been identified in rock samples. Two independent trains are directly

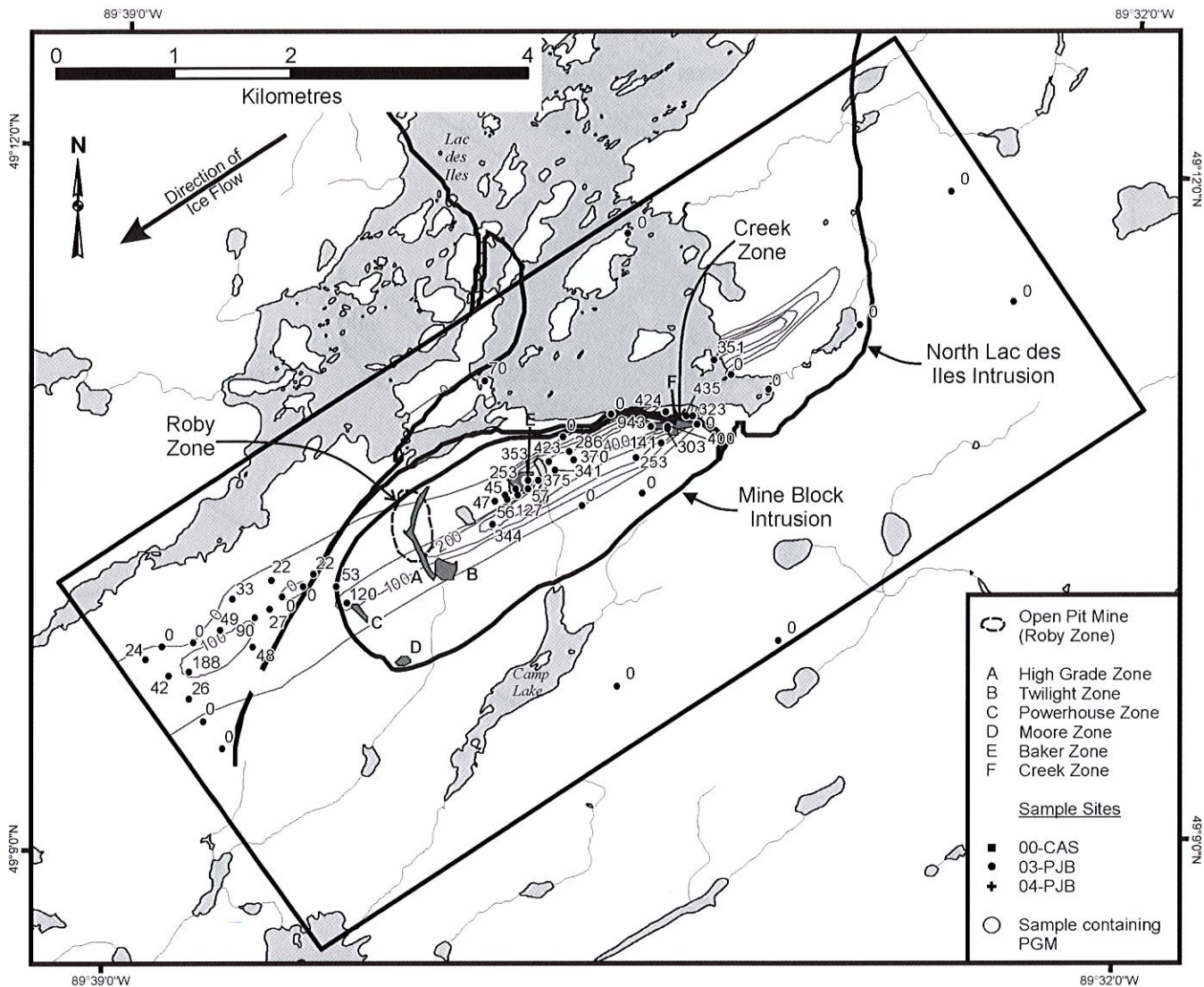


Fig. 3. Distribution of chrome andradite garnet grains in the 0.5–1 mm fraction of the heavy mineral concentrate from till, Lac des Iles mine area. The number of counted or estimated grains per 10-kg sample is displayed beside a black dot indicating its location. The 0, 100, 200, 300 and 400 grain contour lines are shown. The study area (box) is oriented with its long sides parallel to the ice flow direction ($\approx 240^\circ$).

down ice-flow direction of narrow belts of rocks mapped as mafic suite hornblende gabbro, pyroxene-hornblende gabbro by Stone *et al.* (2003). The largest or main train appears to head in rocks mapped as ultramafic pyroxene group (Stone *et al.* 2003) including olivine websterite, websterite, orthopyroxenite, clinopyroxenite beyond the eastern margin of the MBI. This train may be composed of two, possibly three, overlapping trains including one that might originate west of the western margin of the MBI. In total the composite train measures ≈ 7 to 8 km long and varies between 400 and 600 m wide. The individual trains are more likely 1.5 to 4 km in length.

Chromite grains were found in several of the heavy mineral concentrates from till samples collected in the Lac Des Iles area. Concentrations range from 0 to estimates of 200 grains per 10 kg till sample (Fig. 6). As with Cr-andradite, many grains are spotted red with serpentine, suggesting that their source is in ultramafic rocks. Four areas of elevated chromite grains in till samples occur. Three correspond to, or are coincident with, Cr-andradite trains and possibly indicate similar source areas. The other occurs within the major Cr-andradite train but its bedrock source appears to be in the vicinity of the Baker zone. The chromite grains appear to be derived from ultramafic rocks

beyond the north and NE margins of the MBI (NLDI-I) and possibly 'subvertical pyroxenite dikes ... that cross cut the other units in the outcrop' at the Baker zone (Lavigne *et al.* 2005, p. 387). Dispersal trains are not as well defined as the Cr-andradite garnet trains; however, they are in the order of 500 m to 2 km long depending on the concentration of chromite grains (the higher number of grains the longer the dispersal train).

Part of the distal segment of the Cr-andradite + chromite dispersal train, SW of the sampling gap at the Roby zone, is coincident with and may be derived from a septum of ultramafic rock mapped by Sutcliffe & Sweeny (1986). This septum is 50 m wide, strikes NE oblique to both the dispersal train and the western contact of the MBI, and occurs within tonalite 300 m from the contact (Fig. 1). It has been linked to another exposure (Sutcliffe *et al.* 1989) that occurs 2 km to the NE on the southern shore of Lac des Iles that is part of the NLDI-I. The Cr-andradite + chromite anomaly in the till supports their interpretation that the ultramafic rocks extend under the drift-covered area between the two exposures (Sutcliffe *et al.* 1989). The septum consists of olivine gabbro and peridotite and has hornblende diorite margins, which could indicate

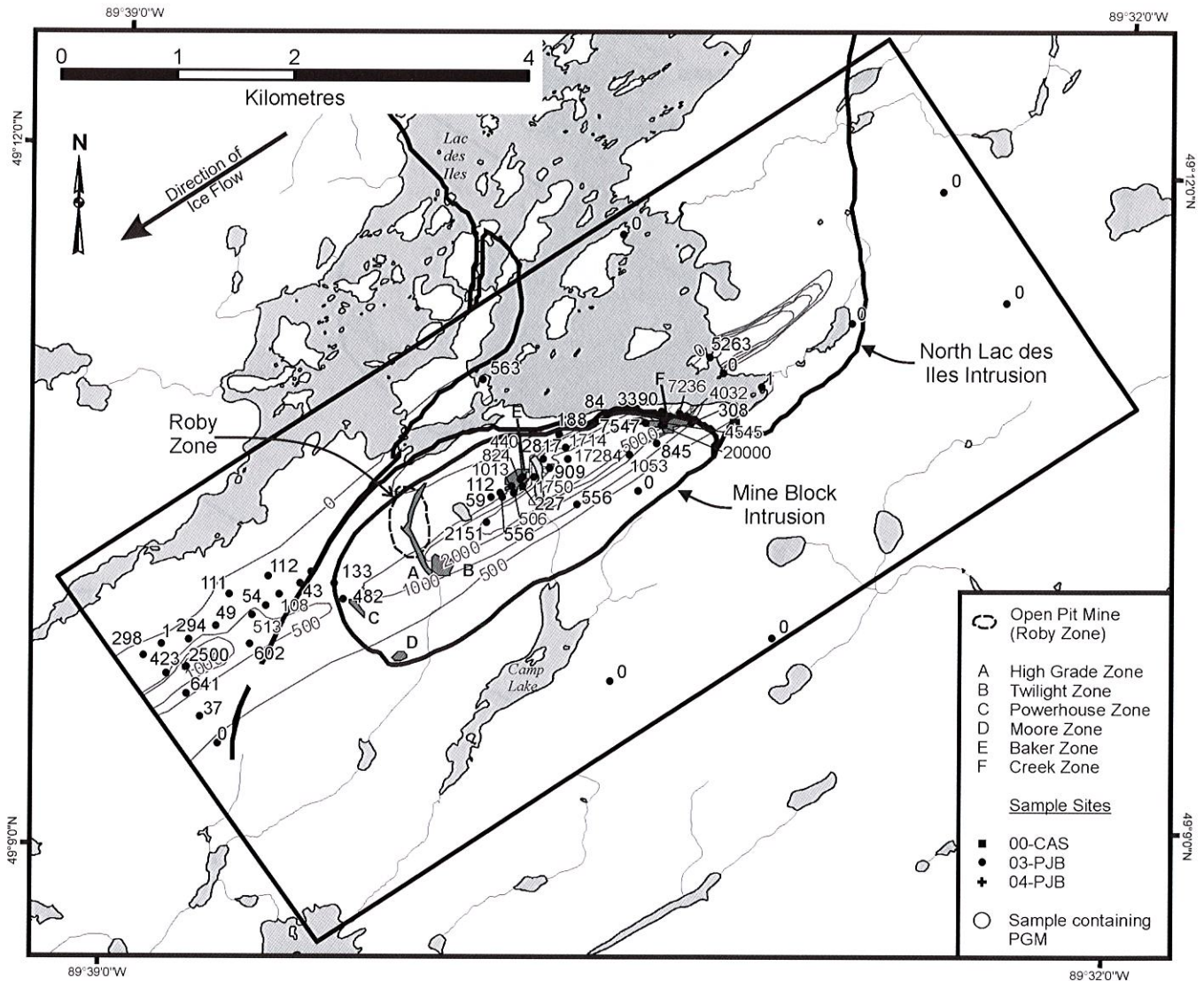


Fig. 4. Glacial dispersal of chromite andradite garnet grains in the 0.25–0.5 mm fraction of the heavy mineral concentrate from till, Lac des Iles mine area. The number of counted or estimated grains per 10-kg sample is displayed beside a black dot indicating its location. The 0, 500, 1000, 2000, 5000 and 10 000 grain contour lines are shown. The study area (box) is oriented with its long sides parallel to the ice flow direction ($\approx 240^\circ$).

significant assimilation of the adjoining tonalite. It was interpreted by Sutcliffe *et al.* (1989) as a possible feeder dyke of the NLDI-I.

Two isolated till samples, one on an island in Lac des Iles and another on the eastern shore, also yielded strong Cr-andradite anomalies (Figs. 3 and 4). The island anomaly has associated chromite grains (Fig. 6). Both anomalies overlie rocks of the NLDI-I.

Till samples collected west of the MBI contain up to 50 grains of low-Cr diopside overlying an area mapped as biotite tonalite suite (Stone *et al.* 2003). Up to 20 grains of manganese-bearing epidote occur in till samples collected over the eastern part of MBI.

DISCUSSION AND CONCLUSION

Till is a useful sample medium for mineral exploration and for mapping bedrock geochemistry in covered areas between bedrock exposures (outcrops and trenches). The till in the area is for the most part thin (commonly <3 m) and deposited directly from the base of an active glacier and, hence, reflects the

composition of bedrock and other materials immediately up-ice flow direction from the sample site. With proper sampling density, dispersal trains within till can be defined, such as in the Lac des Iles area (Barnett & Dyer 2005).

The heavy mineral fraction of the till at Lac des Iles is unusually large due to the presence of pigeonite derived from a large area of pigeonite-rich Nipigon diabase 5 km up-ice to the northeast. This large size makes the processing of the heavy mineral concentrate and identification of indicator mineral grains more laborious but does not reduce the number of indicator mineral grains.

The till at Lac des Iles appears to contain very few PGM, probably because the more stable PGM are native minerals and arsenides and most PGM in the mineralized zones at Lac des Iles are sulphides and tellurides. Searcy (2001*a, b*) tested several other PGE occurrences in northwestern Ontario and obtained two native Pt grains at Legris Lake and two sperrylite grains at Nym Lake. Tardif (2000) obtained 16 sperrylite grains and one stibiopalladinite (Pd_5Sb_2) grain from nine till sample sites collected down-ice from the Dana Lake and Azen Creek zones in the River Valley intrusion NE of Sudbury, Ontario. In



Fig. 5. Representative chrome andradite garnet grains picked from the 0.5–1 mm fraction of till at the Lac des Iles mine area.

Table 1. Chemical composition (wt %) of chrome-bearing andradite garnet grains

	SiO ₂	Al ₂ O ₃	Cr ₂ O ₃	CaO	Fe ₂ O ₃	MgO
Mean	33.54	0.70	0.68	32.91	28.93	0.57
Median	33.57	0.54	0.40	33.13	29.13	0.27
Mode	33.33	0.27	0.33	33.21	29.88	0.24
Standard Deviation	0.63	0.59	0.62	0.86	1.19	0.82
Range	4.69	5.41	3.56	12.08	12.87	9.95
Minimum	31.10	0.11	0.01	22.08	21.38	0.04
Maximum	35.79	5.52	3.56	34.16	34.25	9.99
Count	719	719	719	719	719	719

addition, Bajc & Hall (2000) obtained a native Pt grain from a till sample collected from Leveck Township, NW of Sudbury. Ames *et al.* (2006) report 714 sperrylite grains in a sample of till collected at the Broken Hammer vein-style mineralization site, NW of Sudbury. They (Ames *et al.* 2006) suggest that sperrylite grain dispersion in till does not extend 150 m down-ice flow of mineralization at Broken Hammer. It is noteworthy that none of the above grains are of unstable PGE sulphides or tellurides. Although the number of recovered PGM grains is very low, their occurrence is considered important because it indicates very close proximity to mineralization.

A few grains of chalcopyrite and pyrite were found in the heavy mineral concentrates of till samples collected at Lac des Iles. Their low numbers may be the result of sampling near surface where sulphide grains are unstable (Averill 2001) or because most of the bedrock mineralization contains little chalcopyrite except at the main Roby/High Grade zones where no samples were collected due to mine development. Searcy (2001*a*, *b*), Barnett & Dyer (2005) and Barnett (2007) found that Cu and Pd dispersal trains in C horizon till (< 74 µm) are weak and poorly defined but are commonly associated with the mineralized zones of the MBI. They are often masked by high concentrations of Ni, Cr and Mg that form well-defined trains that extend for several kms down-ice from the MBI (Barnett & Dyer 2005; Barnett 2007). The trains for these elements, however, are probably related to dispersion of ultramafic rocks of the NLDI-I rather than mineralization within the MBI (Barnett 2007).

Two other heavy indicator minerals, Cr-andradite garnet (Ca₃(Cr, Fe)₂(SiO₄)₃) and chromite, are much more abundant in till at Lac des Iles and best reflect the direction and distance of glacial dispersal in the till. Their spatial distribution to the MBI and some of its known mineralized zones also has certain implications concerning the potential processes that produced the mineralization. Indeed, Cr-andradite appears to be unique to the LDI-IC when compared to other mafic intrusions in Canada; it is not present at other mafic intrusions in northwestern Ontario tested by Searcy (2001*a*) and Barnett & Dyer (2005) and no other occurrences are known elsewhere in Canada. Commonly, Cr-free andradite (Ca₃Fe₂SiO₄) occurs as a late-stage mineral in some altered mafic intrusions such as the East Bull Lake complex, Ontario (Kamineni 1986) and the Loch Borrallan complex, Scotland (Styles *et al.* 2004). Such andradite is of a plain yellow-brown to black colour and is not a Ni–Cu–PGE indicator mineral because it is not indicative of a mineralizing event. However, ODM has established that similar-coloured andradite is one of the most diagnostic indicators of the outer, Ca + Fe metasomatized (propylitic) alteration zones of porphyry Cu deposits. To be a Ni–Cu–PGE indicator, andradite must contain significant Cr₂O₃. Conveniently, this transforms the colour to a distinctive emerald green.

The principal indicator mineral present in the till is green to white Cr-andradite garnet. Cr-andradite is normally a hybrid felsic–mafic mineral formed by assimilation of siliceous country rocks by Cr-bearing ultramafic magma (Averill 2007). The

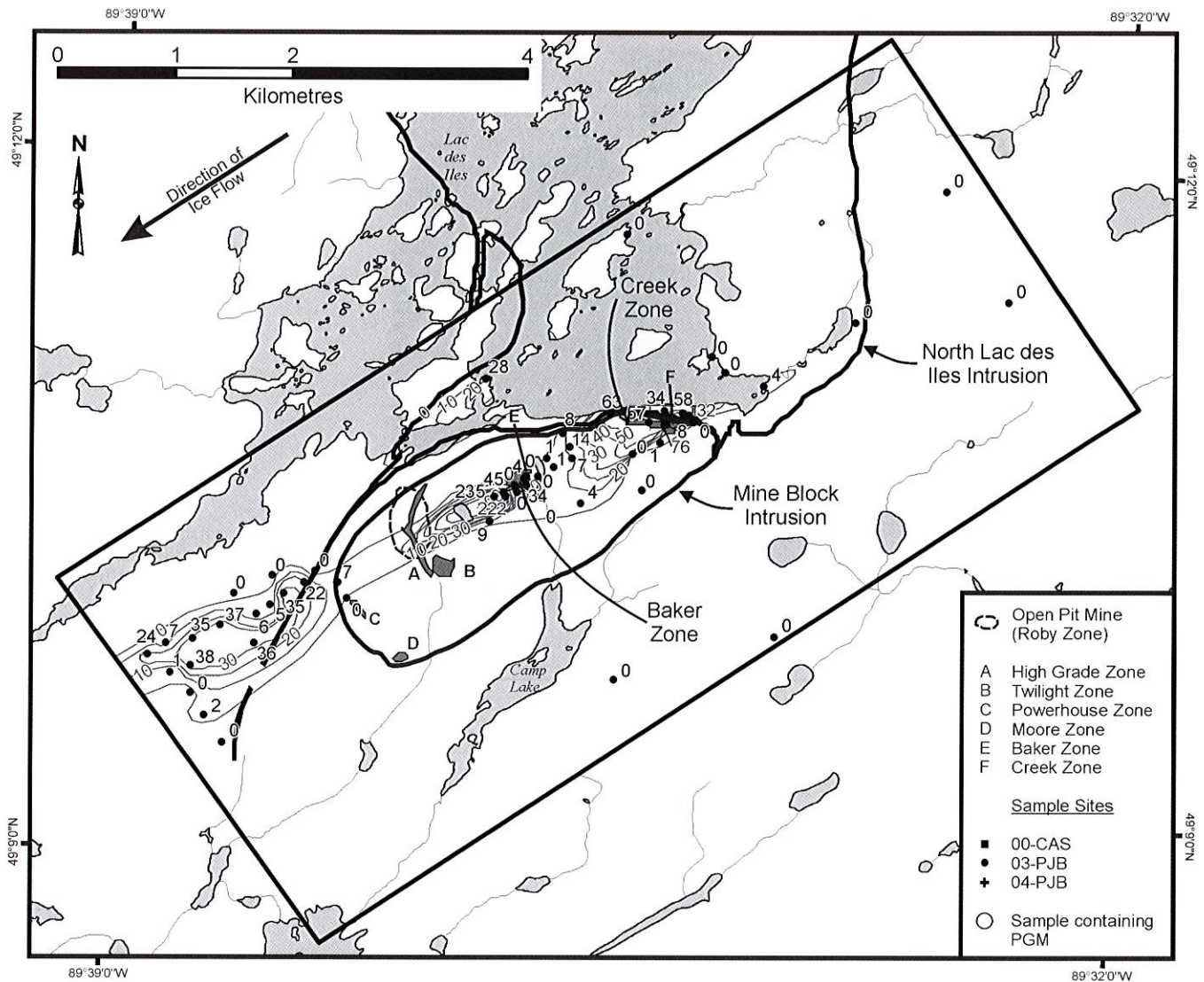


Fig. 6. Glacial dispersal of chromite grains in the 0.25–0.5 mm fraction of the heavy mineral concentrate from till, Lac des Iles mine area. The number of counted or estimated grains per 10-kg sample is displayed. The 0, 10, 20, 30, 40, 50, 100 and 200 grain contour lines are shown. The study area (box) is oriented with its long sides parallel to the ice flow direction ($\approx 240^\circ$).

Cr-andradite at Lac des Iles does not have the usual garnet crystal form; it is of an unusual hydrated, cryptocrystalline variety (hydroandradite) that is not known elsewhere in Canada but similar garnet occurs in direct association with PGE-bearing chromitite layers in the Bushveld Complex in South Africa (Averill 2007). The crystal form of the Cr-andradite at Lac des Iles suggests that their formation involved a low-temperature fluid, probably that responsible for the hydration of primary pyroxene and remobilization of PGE mineralization in the High Grade zone of the MBI.

Hydrogrossular garnet (hibschite) with a very similar colour range and texture to the Cr-andradite at Lac des Iles occurs in association with chromitite in the Bushveld Complex (Averill 2007); the amount of green Cr pigment decreases with distance from the chromitite bands. At Lac des Iles, some of the Cr-andradite grains are spotted red with serpentine, suggesting that they are derived from hydrated olivine-bearing rocks. Such rocks would also have a higher Cr_2O_3 content than the more ubiquitous gabbro. In the most anomalous sample some of the coarsest (1.0 to 2.0 mm) grains have a flattened, vein-like form, further supporting a late-stage hydrothermal origin. Several varieties of pyroxenite including olivine websterite have been

mapped in both the MBI and NLDI-I in the prime source area near the Creek zone (Stone *et al.* 2003) but Cr-andradite has not yet been identified *in situ*, possibly because much of the fertile area lies under the surficial cover to the NE of the MBI or under Lac des Iles (Fig. 4).

The main Cr-andradite dispersal train is >5 km long, 400 to 600 m wide and trends parallel to final 240° ice flow. It is probably a composite train having more than one bedrock source. The train is interrupted by a large sampling gap over the main Roby zone but little, if any, of the Cr-andradite appears to be derived from this zone, probably because Roby mineralization is hosted by Cr-poor mafic rocks. The principal source is probably in more Cr-rich, olivine-bearing pyroxenite near the northern contact of the MBI and NLDI-I and may underlie Lac des Iles. Some of the Cr-andradite in the distal part of the train may be derived from the olivine-rich septum located west of the MBI that is possibly related to the NLDI-I. The Cr-andradite was possibly produced by assimilation of siliceous tonalite by the pyroxenitic magma associated with the emplacement of the NLDI-I or within a metasomatic or hydrothermal alteration halo formed during the emplacement of the MBI or the subsequent silicification event associated with PGE

enrichment within the High Grade ore zone. The cryptocrystalline texture of the grains and their local vein-like habit may support the latter method of formation and the association with serpentine may suggest that the fluid temperature had diminished significantly before the Cr-andradite formed.

Till also contains significant amounts of chromite. The principal chromite dispersal trains are 500 m to 2 km long, roughly coincident with the main Cr-andradite train. The chromite appears to be derived from the NLDI-I north and NE of the MBI, the septum of ultramafic rock west of the MBI and from the vicinity of the Baker zone within the MBI.

In summary, the main PGM occurring in the mineralized zones are sulphides and tellurides. These minerals are unstable in near-surface environments and the only recovered PGM are rare grains of the more stable Pt and Pd arsenide minerals sperrylite and stillwaterite. Sulphide minerals associated with mineralization are also absent or in low concentrations due to their instability. Chalcopyrite is not significantly anomalous because it is a relatively minor constituent of the mineralized zones, is only marginally stable in till and no samples were collected close to the main Roby zone.

The indicator mineral response in the till at Lac des Iles is as unique as the local Pd deposits. The occurrence of abundant Cr-andradite garnet may indicate the presence of an alteration halo around the MBI that may have formed during the emplacement of the intrusion or possibly during the silicification event that is thought to have enriched the tenor of the ore (Hinchey & Hattori 2005). Cr-andradite possibly formed only where the addition of silica to the country rock chemistry was favorable. The Cr-andradite \pm chromite anomalies in till on the islands and southern shore of Lac des Iles could therefore be significant even though they are located within rocks of the NLDI-I rather than MBI. Any similar indicator mineral responses encountered in exploration programs elsewhere should be considered prime Ni–Cu–PGE exploration targets.

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