PLATINUM-GROUP MINERALS AND TELLURIDES FROM THE GEORDIE LAKE INTRUSION, COLDWELL COMPLEX, NORTHWESTERN ONTARIO

THOMAS MULJA* AND ROGER H. MITCHELL

Department of Geology, Lakehead University, Thunder Bay, Ontario P7B 5E1

ABSTRACT

The Geordie Lake Intrusion of the Coldwell alkaline complex in northwestern Ontario hosts a variety of platinum-group minerals (*PGM*) and tellurides. The intrusion consists of alternating zones of unlayered troctolite and ophitic olivine gabbro. The *PGM* found are kotulskite, Bi-rich kotulskite, merenskyite, michenerite, an intermediate phase of the merenskyite–michenerite solid-solution series, sopcheite, paolovite, guanglinite, palladium bismuthotelluride, arsenide and antimonide, and unnamed $Pd_{1.6}NiAs_{1.5}$. Sperrylite is the only platinum mineral present, and Ir-, Os-, and Rh-based *PGM* were not observed. Associated tellurides are hessite, unnamed Ag_3Te_2, melonite (including palladian melonite), and altaite. Most *PGM* and tellurides are contained within disseminated chalcopyrite grains, although some occur in bornite, silicate minerals, massive chalcopyrite and magnetite. The size of the *PGM* ranges from <5 μm to about 15 × 30 μm, and that of the tellurides, up to 30 × 50 μm. Textural evidence suggests that the relatively coarser-grained *PGM* and tellurides (>10 μm), which generally occur at the margins of chalcopyrite bordering silicate minerals, formed contemporaneously with, or slightly after, the host chalcopyrite. Smaller *PGM* grains are enclosed in chalcopyrite and magnetite. Textural relationships between the chalcopyrite and other minerals (magnetite and silicates) suggest that the mineralization was induced by the precipitation of magnetite. The predominance of palladium over platinum minerals is attributed to the relatively evolved nature of the magma. The Geordie Lake deposit is distinct from other *PGM* deposits in that it occurs in unlayered mafic rocks and is poor in Pt-, Ir-, and Rh-based minerals.

Keywords: platinum-group minerals, tellurides, chalcopyrite, troctolite, olivine gabbro, Geordie Lake Intrusion, Coldwell complex, Ontario.

SOMMAIRE

Le massif intrusif de Geordie Lake, qui fait partie du complexe alcalin de Coldwell, dans le Nord-Ouest de l'Ontario, contient une variété de minéraux du groupe du platine (*MGP*) et de tellurures. Le massif contient, en alternance, des bancs de troctolite apparemment massive et de gabbro ophitique à olivine. Nous avons trouvé les minéraux suivants: kotulskite, kotulskite riche en Bi, merenskyite, michenerite, une phase intermédiaire dans la solution solide merenskyite – michenerite, sopchéite, paolovite, guanglinite, bismuthotellurure, arséniure et antimoniure de Pd, et la phase $Pd_{1.6}NiAs_{1.5}$ (sans nom). La sperrylite est le seul minéral de platine dans l'inventaire, et les minéraux riches en Ir, Os et Rh semblent absents. Les tellurures associés comprennent hessite, Ag_3Te_2 (sans nom), mélonite (y inclus mélonite palladifère), et altaïte. La plupart de ces minéraux sont inclus dans la chalcopyrite disséminée, quoique certains se trouvent dans la bornite, les silicates de la gangue, la chalcopyrite massive et la magnétite. Les grains de *MGP* vont de moins de 5 à environ 15 × 30 μm, tandis que les tellurures atteignent 30 × 50 μm. Les textures indiquent que les grains les plus gros, situés en général en bordure des grains de chalcopyrite, près des cristaux de silicates, se sont formés soit en même temps, soit légèrement après, la chalcopyrite hôte. Les petits grains des *MGP* sont occlus dans la chalcopyrite et la magnétite. Les relations texturales entre chalcopyrite et les autres minéraux (magnétite et silicates) semblent indiquer que la minéralisation a résulté de la précipitation de la magnétite. Nous attribuons le fait que les minéraux du palladium prédominent sur ceux du platine au caractère relativement évolué du magma. Le gisement de Geordie Lake se distingue donc des autres gisements des *MGP* par sa pauvreté en minéraux de Pt, Ir et Rh, et par ses roches hôtes, qui sont mafiques et non stratifiées.

(Traduit par la Rédaction)

Mots-clés: minéraux du groupe du platine, tellurures, chalcopyrite, troctolite, gabbro à olivine, massif de Geordie Lake, complexe de Coldwell, Ontario.

INTRODUCTION

The Geordie Lake Intrusion crops out in the north-central part of the Coldwell alkaline complex, in northwestern Ontario (Fig. 1). The presence of platinum-group elements in Cu-sulfide minerals was noted by a group of prospectors from Marathon (Ontario), who, in 1986, rediscovered the 1963 exploratory trench of Ameranium Mines Limited (Patterson *et al.* 1987). In 1987, St. Joe Canada Inc. obtained the prospect from Fleck Resources Ltd. and conducted mapping and core drilling in the mineralized area. This report documents the modes of occurrence of platinum-group minerals (*PGM*) and associated sulfides and tellurides. Sample materials used came from drill cores numbered 1, 2, 3 and 6 in Figure 1.

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*Present address: Department of Geological Sciences, McGill University, 3450 University Street, Montreal, Quebec H3A 2A7.
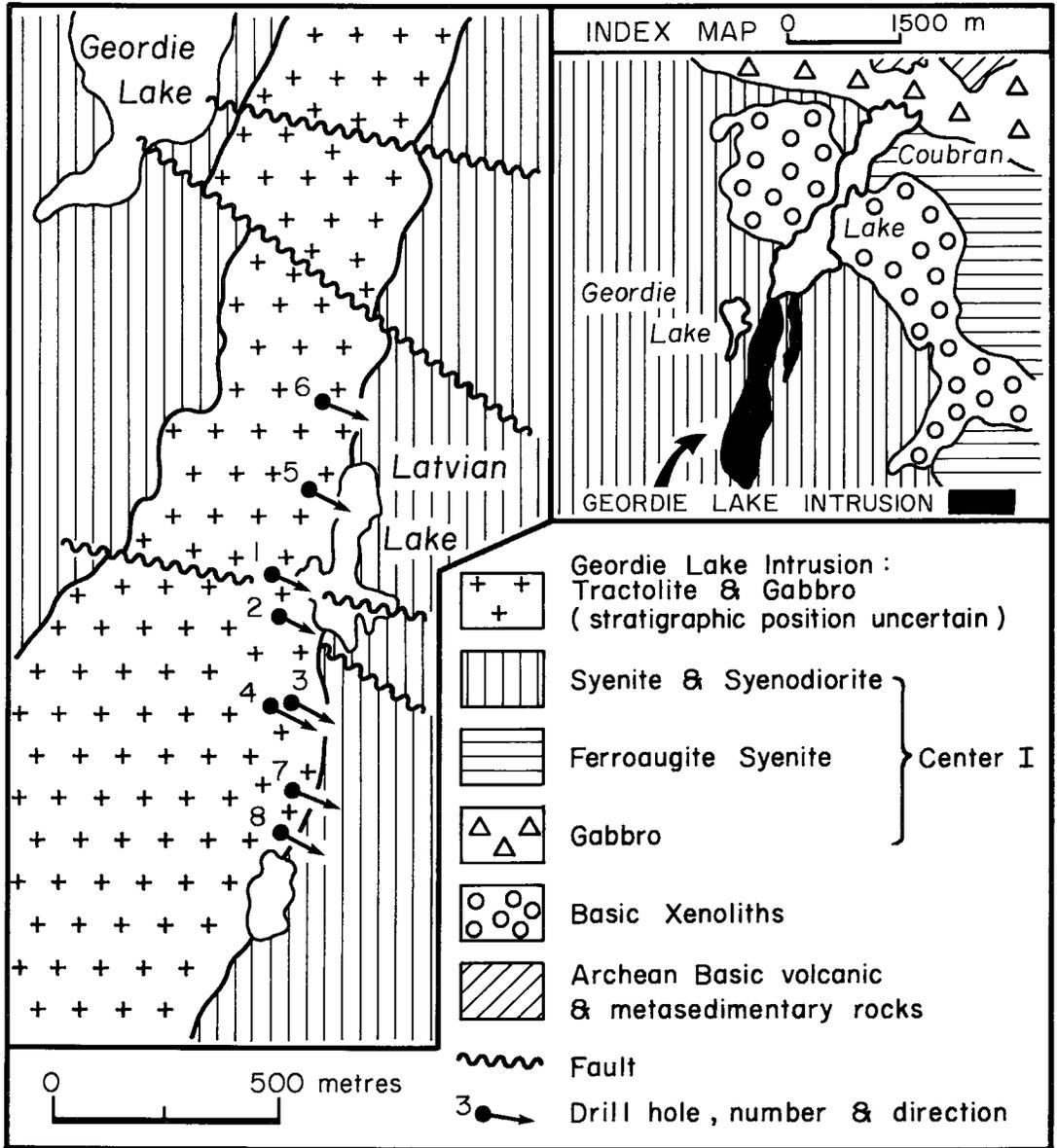
FIG. 1. Geology of the Geordie Lake intrusion.

GEOLOGY AND PETROLOGY

The Geordie Lake intrusion is a part of the Cold-well alkaline complex, which is the largest of its kind in North America (Mitchell & Platt 1978, 1982). The complex was emplaced into the Archean metavol-canic and metasedimentary rocks of the Schreiber – White River greenstone belt during the Proterozoic (Platt & Mitchell 1982). The geology of the complex has been described by Mitchell & Platt (1982, 1978), who interpreted its formation to result from three nested centers of cauldron subsidence. The earliest period of igneous activity at Coldwell, termed center I, consists of border-group gabbro, ferroaugite syenite and other syenitic rocks. Center-II magmatism resulted in the emplacement of nepheline-bearing biotite alkali gabbro and hastingsite-bearing miaskitic nepheline syenite. Magmatism in the Cold-

well complex terminated with the emplacement of quartz and ferro-edenite syenites of center III.

The main body of the Geordie Lake intrusion (GLI) is approximately 500 × 2,000 m in size (Fig. 1). The intrusion is bounded by rocks considered to be Center-I syenites in the east, south, and west (this work). The northern boundary is covered by Coubran Lake. The exact field relationships between the GLI and surrounding syenitic rocks have not yet been established owing to the paucity of outcrop in the Geordie Lake area. The presence of chalcopyrite mineralization extending from the GLI into the syenite, together with recrystallization in regions adjacent to the gabbro, suggest that the GLI intruded the syenite (Mulja 1989).

In contrast, Good & Crocket (1989) have interpreted regions of recrystallization in the syenite as chilled margins, and thus concluded that the syenites intrude the gabbro. This interpretation is improbable given that the syenites adjacent to the GLI are a part of the large center-I syenite body lying to the east of the Redsucker Fault zone (Mitchell & Platt 1982). Intrusion of this body would be more likely to result in contact metamorphism of the GLI rather than the reverse effect, as postulated by Good & Crocket (1989).

A small apophysis of gabbro lies slightly to the east of the main intrusion (Fig. 1). This body is petrologically identical to the main intrusion (Good & Crocket 1989), but was not examined during this study.

In the core samples examined, the GLI is found to consist of alternating zones of unlayered troctolite and olivine gabbro, with gradational contacts between the two rock types. The troctolite is typically coarse grained, and consists of dendritic olivine (Fo_{44-56}) and plagioclase (An_{48-57}). Clinopyroxene ($Di_{36}Hd_{60}Ae_4$–$Di_{30}Hd_{66}Ae_4$) is subordinate and, where present, is anhedral and medium to coarse grained. The olivine gabbro consists of olivine, ophitic clinopyroxene ($Di_{41}Hd_{54}Ae_5$ – $Di_{29}Hd_{66}Ae_5$) and plagioclase (An_{46-54}). Medium- to coarse-grained skeletal magnetite crystals are common in both rock types. Small amounts of allotriomorphic gabbro also are present, especially in core 3. Bands of magnetite-rich troctolite and gabbro are present in the upper parts of the cores. Small amounts of subsolidus amphibole and biotite are present, particularly in the altered and sulfide-mineralized rocks. Euhedral apatite is ubiquitous in all rock types.

The GLI has undergone varying degrees of alteration. In weakly altered rocks, olivine is serpentinized, some plagioclase grains are mantled by albite, alkali feldspar, or sericite, and clinopyroxene is rimmed by actinolite. This alteration is not pervasive and did not produce quartz and carbonate, the typical secondary minerals of postmagmatic hydrothermal processes in basic rocks. Some of the

albite and alkali feldspar mantles are pinkish in color. Fine-grained hornblende and biotite commonly are present in the altered rocks. In the strongly altered rocks, all of the primary minerals have been replaced, and the rocks have a pinkish white hue. Such extensive alteration is uncommon: only three such specimens were encountered in the cores studied. Secondary quartz is present in the strongly altered rocks.

The compositions of minerals in the troctolite and gabbro are similar, and cryptic layering is absent from the cores examined. Whole-rock compositions of the troctolite and gabbro also are similar, which suggests that the petrographically different units are essentially heteromorphs and thus not related to each

TABLE 1. PLATINUM-GROUP MINERALOGY OF THE GEORDIE LAKE INTRUSION

Kotulskite*	PdTe
Merenskyite**	$PdTe_2$
Michenerite**	PdBiTe
Pd-Bismuthotelluride	~$Pd_8Bi_4Te_3$
Sopcheite	$Pd_3Ag_4Te_4$+
Guanglinite	Pd_3As
Palladium Arsenide	Pd-As
Palladium Antimonide	Pd-Sb
Paolovite	Pd_2Sn
Unnamed PGM	$Pd_{1.6}As_{1.5}Ni$
Sperrylite	$PtAs_2$

* plus Bi-rich kotulskite
** plus an intermediate phase in the merenskykite-michenerite solid solution series
+ Sopcheite is expressed as $Ag_4Pd_3Te_4$ in reports by Cabri & Laflamme (1976) and Dunning et al. (1984).
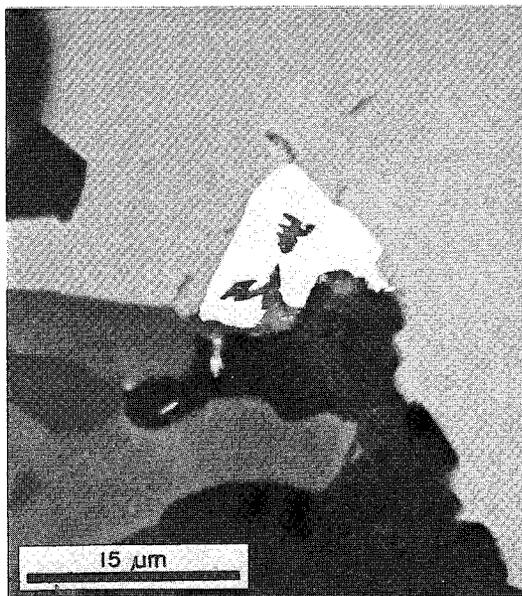

FIG. 2. Kotulskite occurring at the margin of chalcopyrite shows planar grain-boundaries in the chalcopyrite but an irregular boundary on the peripheral silicate grain. This texture is commonly exhibited by most of the coarser-grained *PGM*. Sample G-30.
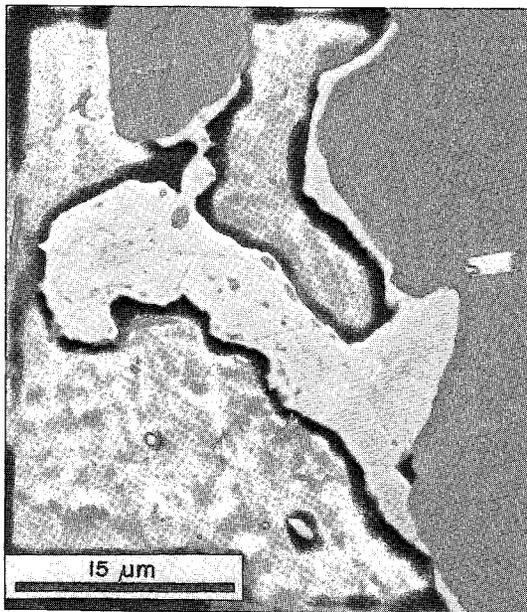
FIG. 3. Kotulskite (right) is intergrown with a sopcheite (left). The kotulskite also rims the host chalcopyrite. The sopcheite is set in a groundmass of altered (?) clinopyroxene and also fringes chalcopyrite. Sample G–24.
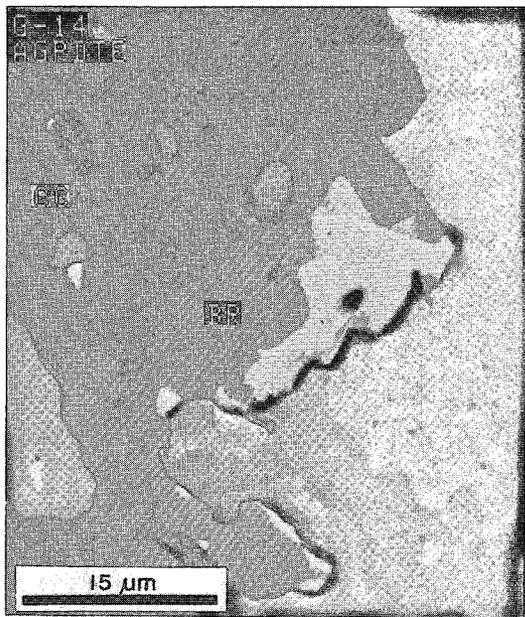

FIG. 5. Coarse- and fine-grained sopcheite (white) occurring at the margin of bornite (BR) that has replaced chalcopyrite. Sample G–14.
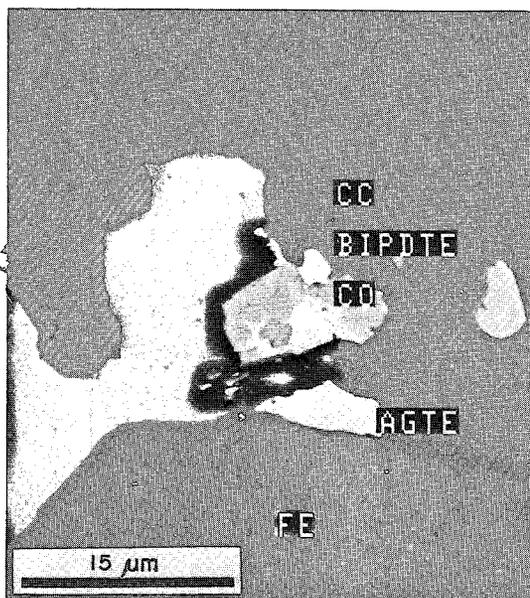

FIG. 4. Bi-rich kotulskite (BIPDTE) crystals are intergrown with cobaltite (CO) and hessite (AGTE) at the boundary of chalcopyrite. The hessite also occurs at the intersection of chalcopyrite, silicate and magnetite (FE). Sample G–30.
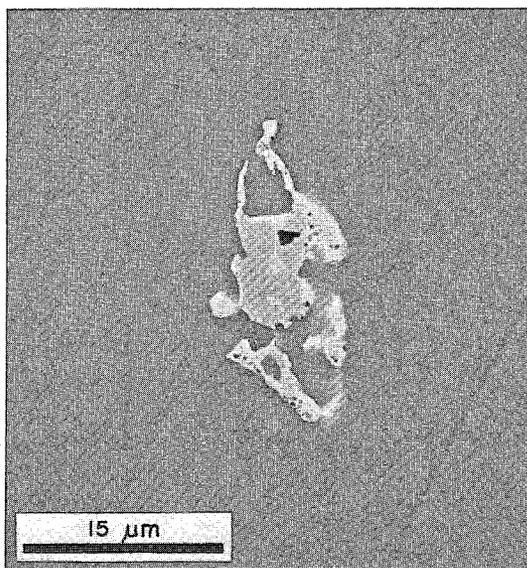
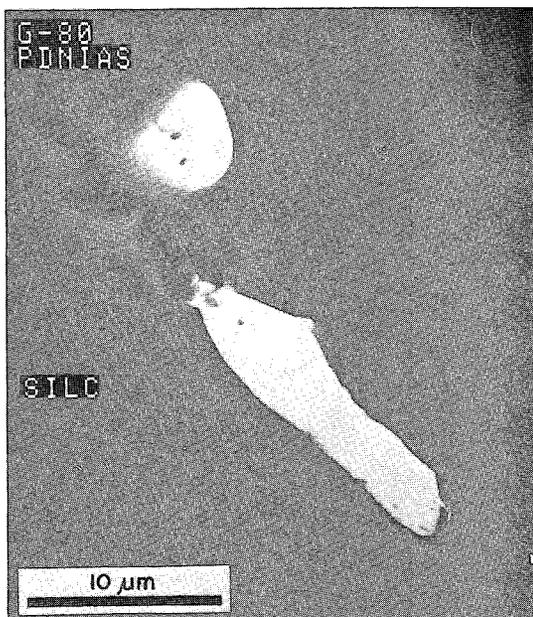FIG. 6. Anhedral paolovite grains hosted by bornite replaced by electrum (white). Sample G–33.

FIG. 7. Unnamed Pd–Ni arsenide minerals set in clinopyroxene. The Pd–Ni–As grains are either intergrown with or being replaced by palladium arsenide (not analyzed owing to small size), which occurs as two white bands in the coarser-grained Pd–Ni–As and as peripheral phases in both grains. Sample G–80.
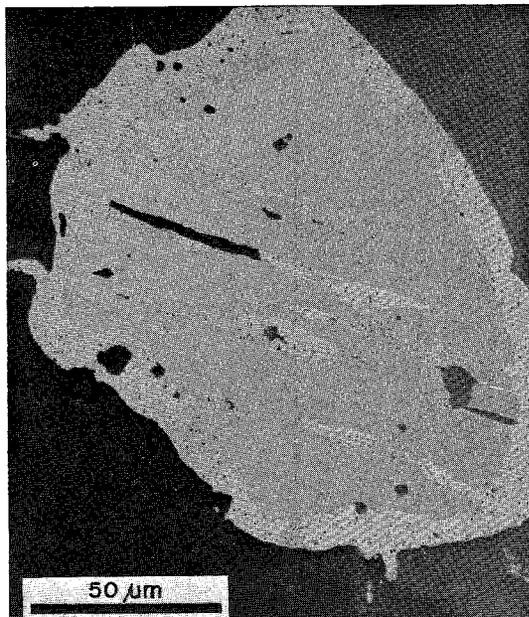

FIG. 9. Coarse-grained melonite (ML) occurring as a subrounded crystal in chalcopyrite. Altaite (AT) replaces the melonite along the periphery and cracks. Hessite (HS) appears to replace the melonite. Sample G–50.
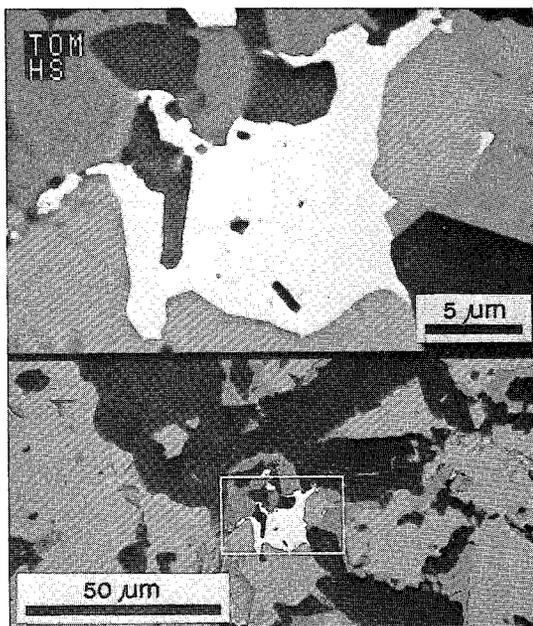

FIG. 8. Relatively coarse-grained hessite occurring at the margin of chalcopyrite. The hessite also fills the interstices between chacopyrite and silicate. Sample G–28.

other by differentiation. The GLI is characterized by low Ni and Cr, and high Sr, Rb, Ba, Th, Ta and light rare-earth-element contents; europium anomalies are absent. The parent magma is interpreted to have been a relatively evolved low-Al tholeiite (Mulja 1989).

Cu-Sulfide Mineralization

Small grains (< 1 mm) of chalcopyrite are commonly visible in all rock types, with the exception of the allotriomorphic gabbro. Disseminated chalcopyrite is the dominant style of Cu-sulfide mineralization. Sulfides typically occur as grains interstitial to the silicate minerals. Biotite, secondary actinolite and hornblende are common in the mineralized rocks. The zone of disseminated chalcopyrite ranges from 5 cm to 1 m in length. The average modal abundance of chalcopyrite grains is about 15%. Chalcopyrite mineralization becomes more pronounced toward the contact between the GLI and the syenite to the east. Rare massive chalcopyrite aggregates approximately 4 cm in length occur in the drill cores. Several chalcopyrite veinlets also are present. Most *PGM* and tellurides are associated with disseminated chalcopyrite and, rarely, with massive chalcopyrite.

TABLE 2. COMPOSITIONS (WT. %) OF Pd-Bi-TELLURIDES

Mineral	Sample	Pd	Ag	Ni	Bi	Te	Total
Geordie Lake							
Kotulskite	1 24	41.67	5.83		6.14	46.7	100.35
Bi-rich PdTe	2 30	34.79	4.12		36.02	26.26	101.19
	3 30	39.48			25.79	34.52	99.79
	4 30	38.99			26.16	34.09	99.24
Merenskyite	5 37	22.16		3.61		72.03	97.8
IMM*	6 59	27.25			28.92	45.32	101.49
Michenerite	7 30	22.23		0.41	49.53	26.92	98.82
Palladium bismuthotelluride							
	8 55B	30.36	4.31		48.51	15.79	98.97
	9 55B	31.93	2.09		52.67	13.75	100.44
	10 55B	35.56	1.97		50.45	11.95	99.93
Palladium bismuthotellurides from Finland (Vuorelainen et al. 1982)							
	1	37.6	0.48	0.6	19.1	43.1	102.83
	2	33.11		0.08	43.5	20.41	99.45
	3	33.65		0.03	5.04	14.12	99.6

* Intermediate phase in the merenskyite-michenerite solid-solution series. Host minerals are disseminated chalcopyrite, with the exception of sample 30, which is a massive chalcopyrite.

Bornite is the second most abundant Cu-sulfide mineral. It occurs as an exsolved phase in, and as a replacement of, chalcopyrite. Other sulfide minerals present in small amounts are siegenite with exsolved pentlandite, pyrite, millerite, galena, sphalerite and supergene chalcocite. With the exception of bornite, none of these minerals was observed to host *PGM*.

ANALYTICAL METHODS

The *PGM* and tellurides were identified by back-scattered electron imagery and energy-dispersion X-ray spectrometry (EDS) using a Hitachi 750 scanning electron microscope (SEM) at Lakehead University. This method is far more effective for the recognition of these fine-grained minerals than optical microscopy. The operating conditions were: acceleration voltage, 20 kV; beam current, 0.38 nA; spot size, $\pm$ 0.2 μm; counting time, 60–240 seconds. Various pure elements were used as standards. X-ray spectra were processed using the Tracor Northern computer program MICROQ with a full ZAF correction procedure. The accuracy (*i.e.*, deviation from ideal stoichiometric composition) and precision (2 standard deviations) are, for Pd: $\pm$ 0.24 and $\pm$ 0.91, Pt: $\pm$ 0.28 and $\pm$ 1.19, As: $\pm$ 0.21 and $\pm$ 0.62, and Ni: $\pm$ 0.09 and $\pm$ 1.0. The accuracy of the tellurium analyses is $\pm$ 0.68. Sample numbers referred to in the text are fully documented in Mulja (1989).

PLATINUM-GROUP MINERALS

Table 1 lists the eleven *PGM* identified, and demonstrates that the *PGM* are dominantly palladium-based minerals. Sperrylite is the only platinum mineral present, and Ir-, Os-, and Rh-based *PGM* are absent. Many palladium minerals could not

be accurately identified because of their small size. The modes of occurrence of the *PGM* range from very small inclusions (<5 μm) in, to comparatively coarse grains (15×35 μm) at, the margins of Cu-sulfide blebs (Figs. 2–9). The *PGM* are hosted principally by disseminated chalcopyrite, less commonly by bornite and silicates, and rarely by magnetite. *PGM* and associated minerals occur in both the troctolite and ophitic olivine gabbro, and have not yet been found in the allotriomorphic gabbro.

Pd–Bi–Te minerals

Compositions of Pd–Bi–Te minerals (Table 2) plot in the ternary system Pd–Bi–Te (Fig. 10) and show that the end-member compositions of kotulskite, merenskyite, and michenerite are present in the GLI. Three grains of Bi-rich kotulskite were identified in sample 30. This variety of kotulskite previously had been found in the Sudbury area (Cabri & Laflamme 1976). Sample 59 is an intermediate composition in the michenerite–merenskyite solid-solution series. Pd–Bi–Te minerals from sample 55 are tentatively regarded as palladium bismuthotellurides, as their compositions (Table 2) are quite similar to those reported by Vuorelainen *et al.* (1982). There might be a complete solid-solution series between kotulskite (PdTe) and polarite (PdBi) (Fig. 10). The kotulskite occurs as discrete grains on the margin between chalcopyrite and altered clinopyroxene (Fig. 2), as an intergrowth with sopcheite (Fig. 3), as oval inclusions in chalcopyrite, and as an intergrowth with hessite and cobaltite (Fig. 4).

Sopcheite $Pd_3Ag_4Te_4$

Three sopcheite grains found in the GLI represent the third reported Canadian occurrence. The mineral had been previously described from Levack West (Sudbury) and Lac-des-Iles, Ontario (Dunning *et al.* 1984). An anhedral sopcheite grain (10×20 μm) occurs between the grain boundary of silicate and bornite replacement of the host chalcopyrite (Fig.5) in a sheared gabbro. The sopcheite and sulfide are, however, undeformed, indicating that mineralization occurred subsequently to the shearing event. The second grain (25×45 μm) is intergrown with kotulskite and enclosed by silicates but not chalcopyrite (Fig. 3) in a troctolite–gabbro transitional rock. The third grain occurs as a subhedral grain (7×10 μm) enclosed in a chalcopyrite bleb. The composition of the sopcheite (Table 3) is close to the ideal formula, $Pd_3Ag_4Te_4$, with a small amount of substitution of Pd by Co. The compositions of sopcheite from Lac-des-Iles, Ontario, and Monchegorsk, USSR (Dunning *et al.* 1984) are similar to those of the GLI, although the sopcheite from the USSR differs in containing Fe, Cu and Ni.
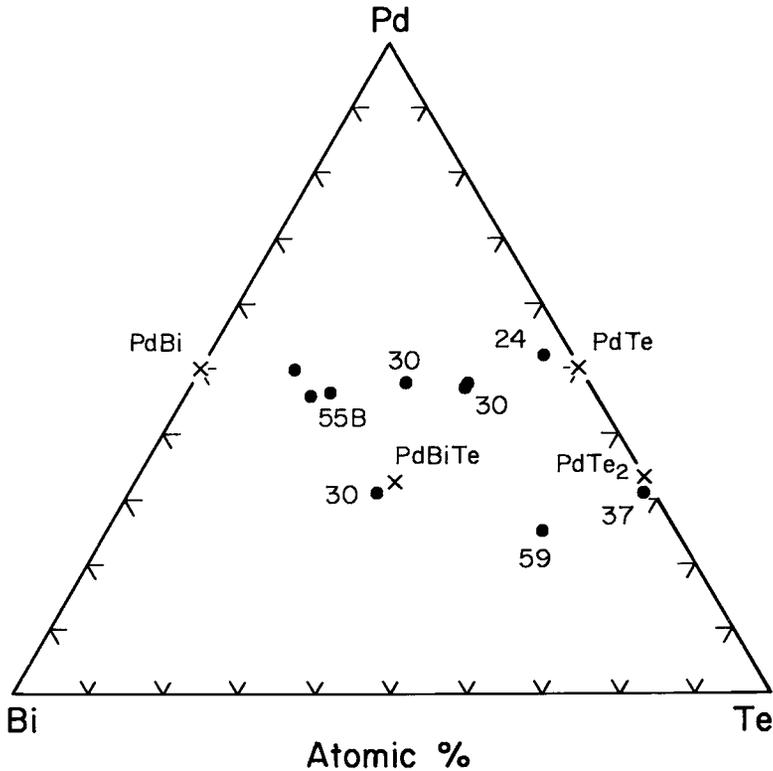
FIG. 10. Compositions of the Pd–Bi–Te minerals.

Paolovite Pd2Sn

Two anhedral grains (maximum 6 × 10 μm) of paolovite, rimmed by electrum, occur in a bornite bleb (Fig. 6). In addition, five anhedral paolovite grains (1 to 3 μm across) were found in chalcopyrite occurring in a moderately altered gabbro. The composition of the paolovite found in sample 33 (Table 4) does not deviate significantly from ideal Pd_2Sn. The paolovite in sample 55C (Table 4) contains a considerable amount of As. This grain is enriched in Sn at the rim, and may be a pseudomorph of a Pd–As mineral.

Pd–As (± Ni, Sb) mineral

Grains of a Pd–As (± Ni, Sb) mineral occur as very small spherical inclusions (<2 μm across) in late magnetite grains that lack ilmenite exsolution lamellae, as a discrete grain (3 × 7 μm) intergrown with a subhedral niccolite in the silicate groundmass, and as a comparatively coarse (0.15 × 0.55 mm) interstitial palladium arsenide exhibiting a planar grain-boundary against the chalcopyrite and an irregular boundary against the silicate mineral. The latter tex-

TABLE 3. COMPOSITIONS (WT. %) OF SOPCHEITE

Sample	Pd	Ag	Te	Co	Bi	Fe	Cu	Ni	Total
Geordie Lake									
14	25.34	32.39	41.06	0.26					99.05
24	26.5	32.4	41.48						100.39
Lac-de-Iles, Ontario*									
	26.1	34.4	39.4		1.0				100.9
	25.8	34.	39.1		0.36				99.26
	25.5	34.6	40.6						100.7
Levak, Sudbury*									
	25.2	32.62	41.32						98.9
Monchegorsk, USSR*									
1	25.26	32.62	41.32		0.17	0.8	0.09	0.03	100.29
2	23.92	33.56	42.13			2.13			101.74

* after Dunning *et al.* (1984)

ture is characteristic of the *PGM* in the GLI. Although eleven Pd–As grains have been recognized in five samples, only the coarsest was large enough for microanalysis (Table 4). The composition of this mineral $(Ni,Pd)_2(Sb,As)$ is close to the ideal formula of palladoarsenide (Pd_2As). Substitution of As by Sb in palladoarsenide previously had been reported by Hudson (1986). Analyses of palladoarsenide from various localities compiled by Cabri &

copyrite; two to four grains per section are typical. Sperrylite is not found intergrown with other *PGM*.

Unnamed Pd–Ni–As mineral

Two grains (15 × 50 μm and 1.5 μm across) of an unnamed palladium mineral with the formula $Pd_{1.6}As_{1.5}Ni$ are hosted by clinopyroxene (Fig. 7) in an altered and weakly sulfide-mineralized troctolite. This *PGM* is intergrown with or is replaced by two bands of palladium arsenides (1.5 μm in width). Table 6 indicates that this phase has a similar composition to that of Pd–Ni arsenides from the Two Duck Lake prospect in the eastern border gabbro of the Coldwell complex and from the Sudbury complex. This Pd–Ni arsenide differs significantly in composition from majakite, whose formula is PdNiAs.

Four crystals of Pd–Ni–As minerals also were identified in sample 27. Two (<3 μm) occur at the margin of an anhedral grain of chalcopyrite, which also hosts two very small sperrylite inclusions (<3 μm). One occurs as a discrete grain (4 μm) in mica, and the other crystal is interstitial to chalcopyrite and ilmenite. The small size of these crystals precludes full quantitative analysis; however, their X-ray spectra resemble those of the analyzed Pd–Ni–As phase.

TELLURIDES

Hessite AgTe₂

Hessite is ubiquitous. For example, more than thirty discrete grains of hessite were found in samples 26 and 27. It generally occurs as fine-grained (5–10 μm) crystals in disseminated and massive chalcopyrite, silicate and bornite. The coarsest hessite (17 × 17 μm) exhibits an octahedral habit and coexists with chalcopyrite and silicate minerals (Fig. 8). This hessite also penetrates the interstices between the sulfide and silicate. Hessite is intergrown with palladium antimonide and is replaced by galena. Numerous small crystals of hessite are present in sulfide veinlets. The composition of the hessite is essentially pure AgTe₂ (Table 7), with minor substitution of Ag by Ni and Co, and of Te by As and Sb.

Unnamed Ag₃Te₂

An unnamed silver telluride was found in samples 46 and 62, as discrete grains (4 × 2 μm) in chalcopyrite. The mineral has the composition Ag₃Te₂ (Table 8). This phase previously had been reported only by Chizhikov & Shchastlivyi (1970), who ascribed its formation to a peritectic reaction in the system Te–Ag.

TABLE 9.   REPRESENTATIVE COMPOSITIONS (WT. %) OF MELONITE NiTe₂

Sample	Ni	Te	Pd	Co	Ag	Bi	Total
1 18	18.86	78.35	2.85				100.86
2 36	12.49	80.55	0.61	5.32	0.54		99.5
3 37	13.6	79.0	6.81	0.6			100.01
4 38	12.15	78.01	6.69	0.72			100.57
5 48	12.14	76.11	8.3	0.82		2.23	99.6
6 48	11.59	74.57	10.05			2.57	98.77
7 50	18.42	81.79					100.21
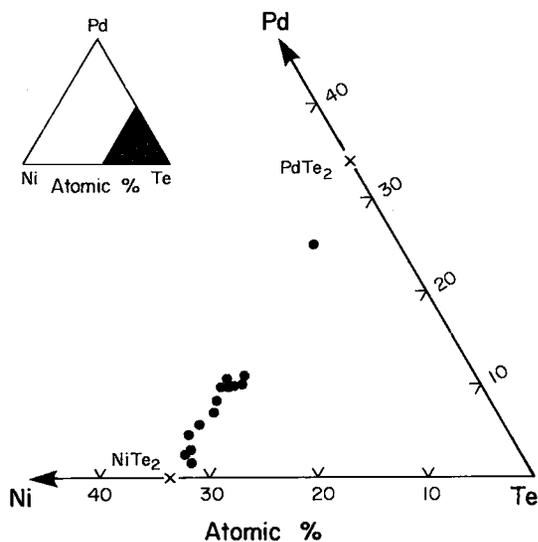
FIG. 11. Compositions of palladian melonite plotted in the system Pd–Ni–Te.

Melonite NiTe₂

Melonite is the second most abundant telluride; it occurs as discrete grains in pyroxene, altered olivine, chalcopyrite, and bornite. In the silicate minerals, melonite ranges in size from small equant (5–10 μm) to prismatic (4 × 15 μm) grains. Some grains of melonite are intergrown with chalcopyrite grains. In the disseminated sulfides, coarse-grained melonite (75 × 100 μm) occurs as subhedral to euhedral crystals forming sharp grain-boundaries with chalcopyrite blebs and silicate minerals. This melonite also infills the narrow interstices between chalcopyrite and silicate in a texture similar to that exhibited by hessite. Other coarse-grained melonite crystals are replaced by hessite and altaite, or by galena (Fig. 9).

Compositions of melonite (Table 9) show that pure NiTe₂ is found only in a few grains and that substitution of Ni by Pd, and Co, and of Te by Bi to varying extents is common in most samples. Ana-

TABLE 10. COMPOSITIONS (WT. %) OF ALTAITE

Sample	Pb	Te	Ag	Total
1 18	60.13	38.64	0.6	99.54
2 18	63.03	37.63		100.69
3 36	63.74	37.11		100.84
4 37	62.78	37.81		100.59
5 50	63.27	36.58		99.85

lyzed grains of melonite contain up to 10 wt.% Pd. Palladian melonite is common in other *PGE* deposits, having been reported from the Kambalda nickel deposit, Australia (Hudson 1986) and the Ivrea–Verbano ultrabasic complex, Italy (Garuti & Rinaldi 1986). Melonite and merenskyite are considered to form a complete solid-solution (Vermaak & Hendriks 1976). The compositions of the palladian melonite from the GLI plot on the melonite-merenskyite join in the Pd–Ni–Te system (Fig. 11).

Altaite PbTe

Altaite is present in all rock types. It occurs as discrete crystals (<6 μm) in silicate and chalcopyrite, and as a replacement mineral. Altaite typically

replaces melonite and, rarely, hessite. The compositions of altaite (Table 10) show that it is essentially pure PbTe, with minor substitution by Ag in one of the grains in sample 18. In contrast, altaite found in the Ivrea–Verbano complex contains up to 9 atomic % Ag (Garuti & Rinaldi 1986). The low Ag-content of the GLI altaite is attributed to its late crystallization, most of the Ag having previously combined with Te to form hessite.

DISCUSSION

Paragenesis

The paragenetic sequence of the sulfides, tellurides, and *PGM* is shown in Figure 12. Palladium antimonide, sperrylite, and the unnamed Pd–Ni–As mineral, which are hosted by silicate minerals instead of chalcopyrite, may have been the earliest members of the *PGM* and telluride suite to have formed. Palladium antimonide and sperrylite, however, continued to precipitate even after the onset of the deposition of hessite and melonite, because palladium antimonide is found intergrown with hessite, and is either intergrown with, or forms a replacement of, palladium arsenide, which is hosted by chalcopyrite.
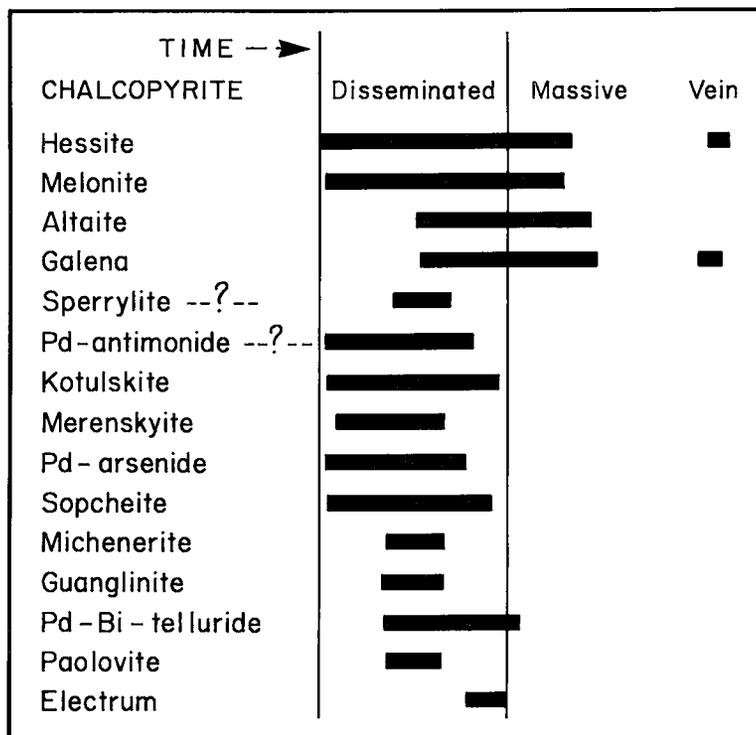

FIG. 12. Paragenetic sequence of the mineralization at Geordie Lake.

Small inclusions of sperrylite also occur in disseminated chalcopyrite.

Mostert *et al.* (1982) stated that the *PGM* of the Impala mine, South Africa, crystallized after chalcopyrite, as they occur mostly at the margin of the Cu-sulfide grains. Vermaak & Hendriks (1976) proposed that minerals that are euhedral in chalcopyrite but irregular against the silicate matrix crystallized after the solidification of the silicate, while the sulfide was still in a molten state. This textural relationship is observed in the GLI, where coarse-grained melonite, hessite, kotulskite, palladium arsenide, sopcheite, and merenskyite occur as euhedral to anhedral crystals between chalcopyrite and silicate. Some tellurides and *PGM* also rim the Cu-sulfide and fill in the interstices between the chalcopyrite and silicate, which suggests deposition later than the Cu-sulfide. It appears that 1) the initial deposition of the coarse-grained tellurides and *PGM* was contemporaneous with, or slightly earlier than, that of the disseminated chalcopyrite, and 2) the tellurides and *PGM* continued to precipitate after the crystallization of the Cu-sulfide. Precipitation of these *PGM* ceased before the crystallization of the massive chalcopyrite and the formation of chalcopyrite veinlets, since they are absent in the Cu-sulfide aggregates.

Michenerite, paolovite, palladium bismuthotelluride, and guanglinite, which occur as oval and anhedral inclusions in chalcopyrite, or in late magnetite in the case of fine-grained palladium arsenide, are interpreted to have exsolved from their host. Altaite replaces melonite, and galena replaces hessite and melonite, thus demonstrating that the two lead minerals formed later than melonite and hessite. Electrum, which rims paolovite, represents the latest stage of precious metal mineralization in the disseminated chalcopyrite.

Melonite, hessite and fine-grained palladium tellurides and antimonides also occur in the massive chalcopyrite. However, in this paragenesis these minerals are much finer grained and not as abundant as they are in the disseminated chalcopyrite.

In summary, there appears to have been at least three major periods of deposition of the *PGM* and associated Cu-sulfide mineralization. The initial minerals deposited, fine-grained chalcopyrite together with sperrylite and palladium antimonide, were followed (in no particular order) by disseminated chalcopyrite blebs, coarse-grained melonite, hessite and *PGM*, and later by massive chalcopyrite, fine-grained *PGM* and tellurides, altaite, galena, and electrum.

Speculation on the mineralization processes

Spherical inclusions of sulfide (chalcopyrite in the GLI) in feldspar grains represent early-trapped sulfide droplets in the silicate melt (Ramdohr 1980).

Chalcopyrite encloses euhedral magnetite grains without corroding them, suggesting that this sulfide was magmatic (Loucks 1987). Von Gruenewaldt (1976) stated that crystallization of Fe-rich olivine and clinopyroxene together with magnetite would reduce the solubility of sulfur in the crystallized portion of the magma, thereby causing the formation of the sulfide droplets. These observations point to the segregation of sulfide droplets during the crystallization of the GLI. During segregation, the sulfide melt also collected palladium, copper and other chalcophile elements. The importance of sulfide as a Pd-carrier has been stressed by Crocket *et al.* (1976), who have demonstrated that Pd is more chalcophile than Pt; it thus tends to partition more strongly into the sulfide melt. The association of most tellurides and *PGM* with chalcopyrite in the GLI agrees with this hypothesis.

Precipitation of the primary silicate minerals and skeletal magnetite grains during the crystallization of the GLI promoted subsequent segregation of molten sulfide. Experimental studies by Haughton *et al.* (1974) have indicated that sulfur is complexed with Fe^{2+} in mafic magmas; thus the decrease in the Fe^{2+} content of the silicate liquid lowers sulfur solubility and results in the precipitation of sulfide minerals. This stage is represented by the disseminated chalcopyrite and *PGM* deposition in the GLI. Subsequent to the formation of the disseminated sulfide, changes in the composition of the magma led to the re-establishment of sulfur undersaturation and precipitation of a second generation of magnetite. This magnetite lacks exsolved ilmenite, and the euhedral to subhedral crystals are set in a groundmass of massive chalcopyrite. This relationship is interpreted to indicate that the massive chalcopyrite precipitated after the deposition of the second generation of magnetite. The melt from which this chalcopyrite crystallized was already depleted in the platinum-group elements, as the *PGM* had been precipitated in the earlier phase of sulfide deposition. This explains why only a few *PGM* and tellurides are hosted by massive chalcopyrite.

The disseminated chalcopyrite, which occupies silicate interstices, did not replace the silicate minerals along grain boundaries. Its abundance can also be positively correlated with the amount of subsolidus actinolite, amphibole, and biotite. The *PGM*-bearing host rocks did not undergo pervasive alteration and contain no secondary minerals such as quartz and carbonates, which are typical of hydrothermal deposits; plagioclase and clinopyroxene have remained relatively unaltered. These characteristics indicate that the sulfide melt and the residual silicate fluid may have coexisted. The mineralization found in the GLI thus appears to have occurred during the later stage of solidification of the magma and was induced by the precipitation of magnetite. Cyclic

deposition of magnetite and chalcopyrite in response to changing sulfur solubility and oxygen fugacity appears to have occurred. The alteration of the mineralized rocks is tentatively interpreted to result from the circulation of residual magmatic fluids.

Comparative studies

The palladium-dominated mineralization of the GLI occurrence is unusual as compared to that of other *PGM* deposits in terms of host rocks and mineralogy. The *PGM* deposit in the Two Duck Lake intrusion of the eastern Coldwell complex is hosted by various types of rocks ranging from magnetite-rich banded gabbro, which consists of several subunits of fine- to medium-grained subophitic gabbros, to pegmatitic gabbro–monzonite (Wilkinson 1983, Watkinson *et al.* 1983). The palladium mineral assemblage from the Two Duck Lake *PGM* deposit (Watkinson & Dahl 1988) has similarities to that of the GLI; however, hollingworthite (RhAsS) is present only in the former. In contrast, sperrylite and pyrrhotite are common in the Two Duck Lake deposit. The Lac-des-Iles *PGM* deposit is hosted by layered gabbro, norite and clinopyroxenite (Watkinson & Dunning 1979). Pyrite, pentlandite, pyrrhotite are common sulfides. The *PGM* assemblage at Lac des Iles includes vysotskite (braggite series), moncheite, stillwaterite, and Pt-Fe(-Au) alloys (Sweeny & Edgar 1988), all of which are absent from the GLI. Well-known *PGM* deposits, such as the Bushveld and Stillwater complexes, are associated with less evolved host-rocks, and Pt-, Ir-, and Rh-based *PGM* are common (Todd *et al.* 1982, McLaren & De Villiers 1982). Palladium minerals constitute only a small fraction of the total assemblage (Kingston & El-Dosuky 1982). Even though the Konttijarvi Intrusion, northern Finland, hosts abundant palladium minerals, sperrylite is the predominant *PGM*, and the host rocks are layered mafic–ultramafic rocks (Vuorelainen *et al.* 1982). The *PGE* deposit of the Mullen Creek Intrusion, Wyoming (Loucks 1987) is mineralogically similar to that of the GLI in that it is also dominated by palladium minerals; however, the Mullen Creek Intrusion consists of layered mafic and ultramafic rocks.

Mineralogical and geochemical studies indicate that the magma that formed the GLI was relatively evolved (Mulja 1989). Pentlandite and pyrrhotite, which are intimately associated with the *PGM* in other deposits, are not observed in the GLI, and pentlandite is present only as an exsolved phase in rare siegenite.

The predominance of palladium over platinum minerals in the GLI may be explained by the hypothesis of Naldrett & Cabri (1976), that the ratio Pt/(Pt + Pd) decreases with increasing differentiation of the host rocks, and that Pt is incorporated preferentially with respect to Pd in early-forming silicates and oxides (chromite). Early-formed *PGM* assemblages are thus dominated by Pt- and Ir-based minerals. If this hypothesis is correct, the less evolved portion of the magma, from which the GLI was derived, might contain the missing Pt and Ir elements. However, the existence of such rocks, which would be comagmatic with the GLI, cannot be proved at present.

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