Canadian Mineralogist
Vol. 17, pp. 453-462 (1979)

GEOLOGY AND PLATINUM-GROUP MINERALIZATION, LAC-DES-ILES COMPLEX, NORTHWESTERN ONTARIO

D.H. WATKINSON AND G. DUNNING
Department of Geology, Carleton University, Ottawa, Ontario K1S 5B6

ABSTRACT

The Lac-des-Iles complex, 80 km N of Thunder Bay, Ontario, is enclosed by granitic rocks of the Wabigoon belt. Peridotitic, pyroxenitic, and some mafic rocks occur in its northern part and two mafic units in the south; all rocks are crystal cumulates. The eastern gabbro unit is composed of medium-grained gabbroic to noritic rocks and is oxide-rich, sulfide-poor; the western gabbro unit, coarser grained and pegmatitic, consists of gabbroic (70%), noritic (20%) pyroxenitic (10%), and minor anorthositic rocks. The latter are layered, steeply dipping and contain Cu–Ni–Fe sulfides and platinum-group sulfides, arsenides, antimonides and tellurides. The predominant PGM are vysotskite ($Pd_{0.79}Pt_{0.01}Ni_{0.22}S_{0.97}$) and kotulskite ($Pd_{0.96}Pt_{0.01}Te_{0.78}Bi_{0.24}$). The "western gabbro" liquid intruded first, followed by the eastern gabbro and then the ultramafic rocks. Most sulfur, nickel, copper, platinum-group and other similar elements are contained in the first intrusive phase. These elements were concentrated in residual liquid as plagioclase accumulated. When the liquid became sufficiently mafic, pyroxenes became cumulus and sulfides precipitated. In orthopyroxene-rich rocks the sulfides are now dominantly pentlandite–chalcopyrite–pyrite–pyrrhotite assemblages. H_2O also concentrated in the residual liquid giving rise to pegmatite and deuteric alteration, especially in clinopyroxene-rich rocks. Platinum-group and other mineral assemblages are complex in these most highly differentiated and altered rocks. Pd has apparently migrated slightly with Cu and Fe, but is most commonly found with Ni minerals.

SOMMAIRE

Le complexe du lac des Iles, situé à 80 km au nord de Thunder Bay, en Ontario, recoupe les roches granitiques de la ceinture Wabigoon. On trouve des roches péridotitiques, pyroxénitiques et mafiques dans la partie nord et deux unités mafiques dans la partie sud; toutes ces roches sont cumulatives. L'unité gabbroïque orientale se compose de roches à grain moyen, variant du gabbro à la norite, roches enrichies en oxydes et appauvries en sulfures; l'unité gabbroïque occidentale à grain plus grossier et même pegmatitique, comporte: gabbros (70%), norites (20%), pyroxénites (10%) et plus rarement, anorthosites. Ces dernières, stratiformes et à fort pendange, contiennent des sulfures Cu–Ni–Fe et des sulfures, arséniures, antimoniures et tellurures des éléments du groupe du platine. Parmi ces derniers, deux minéraux prédominent: vysotskite $Pd_{0.79}Pt_{0.01}Ni_{0.22}S_{0.97}$ et kotulskite $Pd_{0.96}Pt_{0.01}Te_{0.78}Bi_{0.24}$. Le liquide parental du gabbro de l'ouest a été le premier mis en place, suivi du gabbro de l'est et ensuite des roches ultramafiques. Les éléments du groupe du platine et éléments analogues, ainsi que S, Ni et Cu, furent introduits dès la première intrusion; ils ont été concentrés dans le liquide résiduel à mesure qu'a cristallisé le plagioclase. Quand ce liquide a atteint une composition suffisamment mafique, les pyroxènes sont devenus la phase cumulus, et il y a eu précipitation de sulfures. Dans les roches à orthopyroxène, les assemblages pentlandite–chalcopyrite–pyrite–pyrrhotine sont courants. L'eau aussi se concentra dans le liquide résiduel, d'où formation de pegmatites et altération deutérique, surtout dans les roches à clinopyroxène. Les assemblages de minéraux qui contiennent les éléments du groupe du platine sont compliqués dans ces roches très différenciées et altérées. Le palladium semble avoir migré quelque peu avec Cu et Fe, mais on le trouve surtout associé aux minéraux nickelifères.

(Traduit par la Rédaction)

INTRODUCTION

The Lac-des-Iles complex is located approximately 80 km north-northeast of Thunder Bay, Ontario (Fig. 1); it consists of Archean mafic and ultramafic rocks intruded into granitic and gneissic rocks of the Wabigoon belt (Pye 1968, Goodwin 1977). Nickel–copper sulfides were recognized in the southern, gabbroic part of the complex, and assays revealed significant concentrations of platinum-group elements (Pye 1968). Watkinson (1975) made a preliminary study of the petrology and mineralogy of the complex. Cabri & Laflamme (1976) have studied the mineralogy of some rocks rich in platinum-group elements (PGE). A study of the petrology of the complex is under way, with emphasis on the relationships of platinum-group minerals (PGM) to the presence of Cu–Ni–Fe

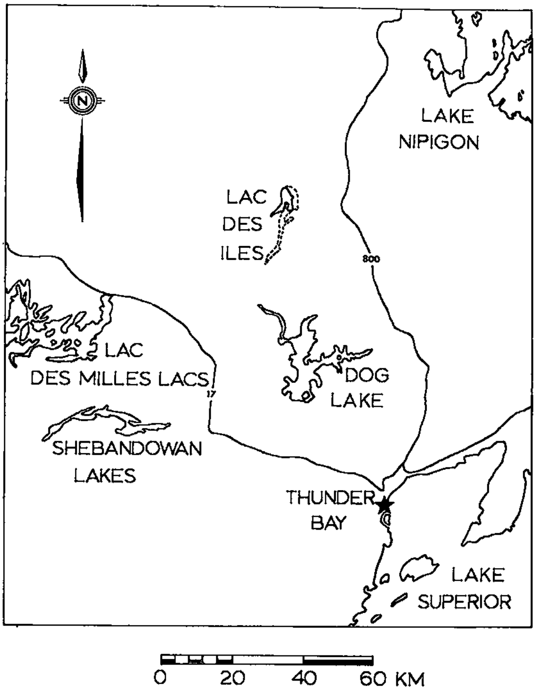

FIG. 1. Location of the Lac-des-Iles complex.

sulfides, layering in the gabbroic rocks and alteration.

Mafic to ultramafic rocks occupy part of the Wabigoon belt near Lac des Iles, Legris Lake, Shelby Lake, Wakinoo Lake and Demars Lake (Fig. 2) and have been described as Archean intrusions by Pye (1968) and Kaye (1969). The complexes intrude approximately east-northeast-striking mafic, intermediate and felsic metavolcanic and associated metasedimentary rocks as well as granitic and other gneisses. All these units have been mildly to moderately deformed and in general metamorphosed to amphibolite- or greenschist-facies assemblages during the Kenoran event (Pye 1968). However, many of the Lac-des-Iles rocks still retain their primary textures and mineralogy. Sills and dykes of Keweenawan-type diabase have intruded all the units described above.

GEOLOGY OF THE LAC-DES-ILES COMPLEX

Introduction

The Lac-des-Iles complex (Fig. 3) consists of a northern ultramafic part (peridotite, clinopyroxenite, websterite and gabbroic rocks) and a southern part composed of western and eastern gabbros. The western gabbro (Dunning 1979) is composed of steeply dipping layers of gabbro, norite, minor clinopyroxenite and anorthosite (Fig. 4) and contains disseminated copper–nickel–iron sulfides and platinum-group minerals. The eastern gabbro (Chassé 1978), composed of norite and gabbro, is oxide-rich and sulfide-poor. Field evidence shows that the order of emplacement is western gabbro, eastern gabbro and ultramafic units (Dunning 1979).

Western gabbro

The western gabbro is the earlier and larger of the two mafic units recognized in the southern part of the complex. It consists of interlayered gabbroic (70%), noritic (20%), pyroxenitic (10%) and minor anorthositic rocks. In the Roby zone (Fig. 3), plagioclase cumulates generally occur to the west, orthopyroxene–plagioclase cumulates in the centre and clinopyroxene cumulates to the east. The layering strikes approximately 160° and is steeply dipping, generally 50° to 85° to the east. Little is known about the more southerly part of this western unit but it may be of more noritic composition (Guarnera 1967). The Roby zone has been thoroughly studied by Dunning (1979) because of its Cu–Ni and PGE concentrations, and most of what follows is generalized from rocks of that zone.

1. *Plagioclase cumulates.* Coarse-grained gabbroic and anorthositic rocks (Fig. 4) contain subequal amounts of plagioclase (An_{80-82}) and augite (Fig. 5). Some pegmatitic pods and mineral-graded layers are present. Plagioclase is essentially unzoned and is variably altered to sericite, epidote and chlorite. Augite is almost always intercumulus even in mafic gabbroic rocks and is generally altered to hornblende, actinolite and chlorite. Sulfides occur as irregularly distributed blebs and fine-grained assemblages interstitial to silicates. They are not abundant but may constitute as much as 3% (vol.) of some size-graded layered rocks. Thin anorthositic layers (Fig. 4) generally contain fresh plagioclase. They contain fine-grained amphibole after clinopyroxene and rare chalcopyrite.

2. *Orthopyroxene–plagioclase cumulates.* These rocks are medium-grained and generally fresh to weakly altered; some are mineral- and size-graded. They contain 30–70% pyroxene (En_{71-79}) but rarely extend to orthopyroxenite. The composition of the plagioclase is An_{79-82}. Occasionally their sulfide content is high enough

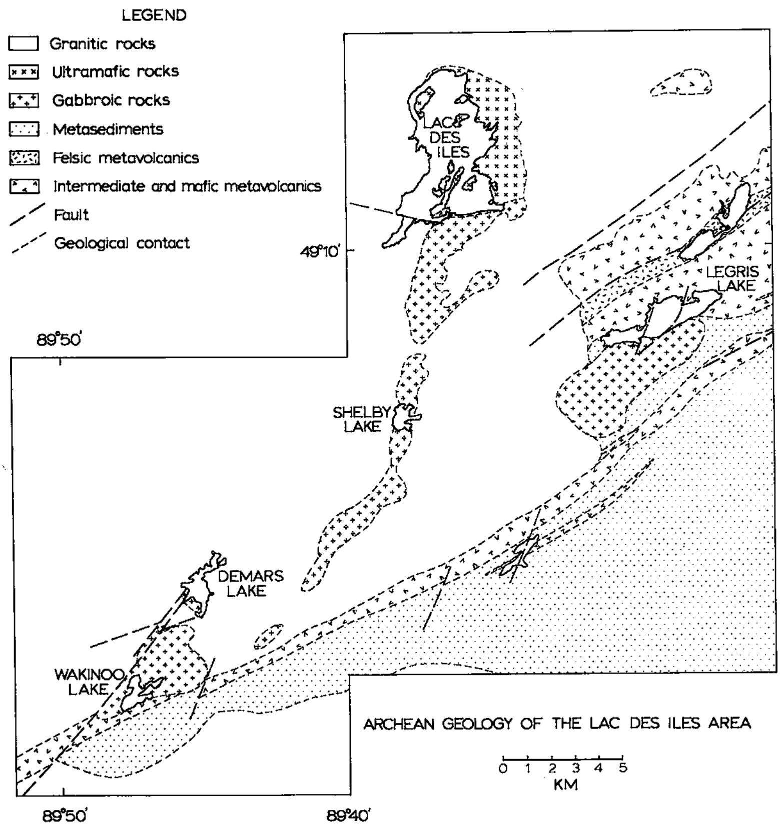

FIG. 2. Archean geology of the Lac-des-Iles area after Pye (1968) and Kaye (1969).

to generate a net texture; the sulfide assemblage is pyrrhotite–pentlandite–chalcopyrite–pyrite.
3. *Clinopyroxene cumulates.* Several layers of pyroxenite occur on the eastern side of the Roby zone (Fig. 4). These consist of fine-grained amphibole aggregates after dominantly cumulus clinopyroxene, enclosed by chlorite, epidote, oxides and sulfides. Sulfides compose less than 5% of clinopyroxenite.

Eastern gabbro

The eastern gabbro (Fig. 3) is composed of oxide-rich, layered gabbroic and noritic rocks. Concentric magnetic anomalies on a ground magnetometer survey map serve to distinguish it from the western gabbro which has a weak magnetic expression and northerly trend of layering. Irregular masses of magnetic and non-magnetic gabbro in some drill core are interpreted to represent inclusions of western gabbro in eastern gabbro (Dunning 1979).

The eastern gabbro is invariably medium-grained, equigranular and commonly less altered than counterparts in the western gabbro. Both plagioclase (An_{52-60}) and some clinopyroxene (Fig. 5) are cumulus; their compositions are distinct from those of the western gabbro. Noritic layers are also medium-grained, fresh and clinopyroxene-bearing. The outer margin of the intrusion contains noritic layers rich in assemblages of magnetite–ilmenite–green spinel (Table 1). Orthopyroxene ($En_{62.5-64.5}$) is more iron-rich than pyroxenes from the remainder of the complex. Sulfides are rare in the eastern unit, apparently being restricted to zones of contact with western gabbro.

Ultramafic and related rocks

The ultramafic part is composed of crystal cumulates of varying proportions of olivine, orthopyroxene, clinopyroxene and plagioclase. There are very minor disseminated spinel-group and sulfide minerals. The primary minerals are variably altered to assemblages with serpentine, talc, sericite, zoisite, magnetite and carbonate.

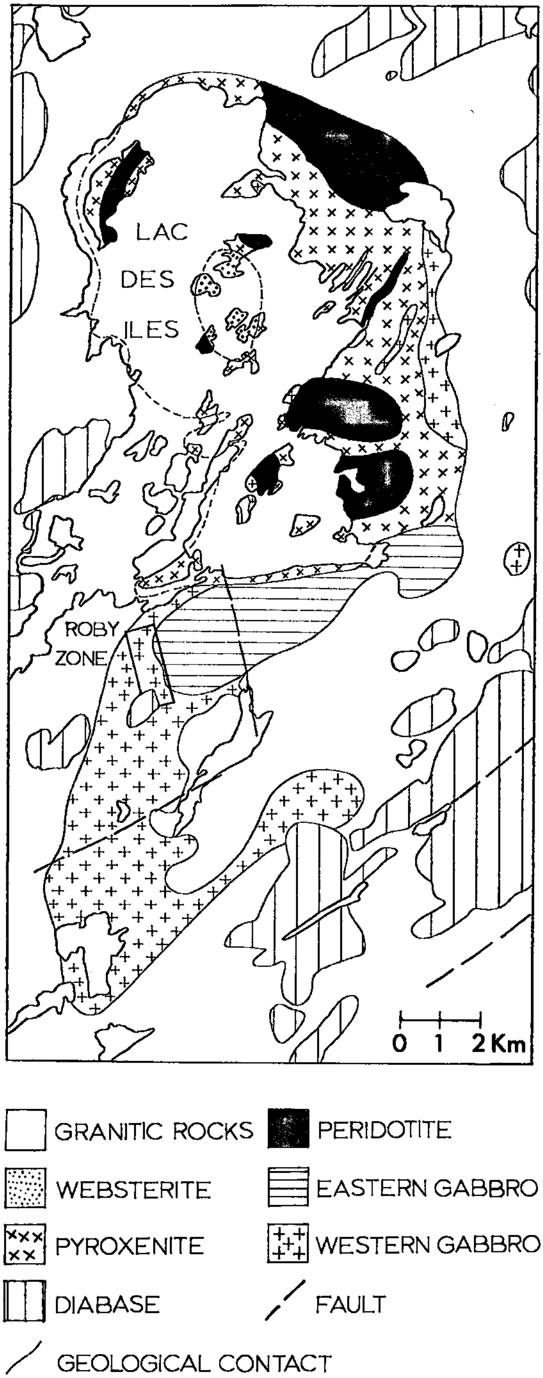

FIG. 3. Geology of the Lac-des-Iles complex modified from Pye (1968) and Texasgulf, Inc. (unpubl.), showing location of Roby zone.

Layering is not well developed. There is some minor mineral grading [olivine and pyroxene, pyroxene and plagioclase (Fig. 4)] and size-graded layering in some clinopyroxenites.

1. *Olivine cumulates.* Peridotitic and small serpentinite bodies occur mainly near the eastern margin of the northern part and occupy about 30% of the area. Olivine (approximately Fo_{77}) is nearly completely altered to serpentine plus

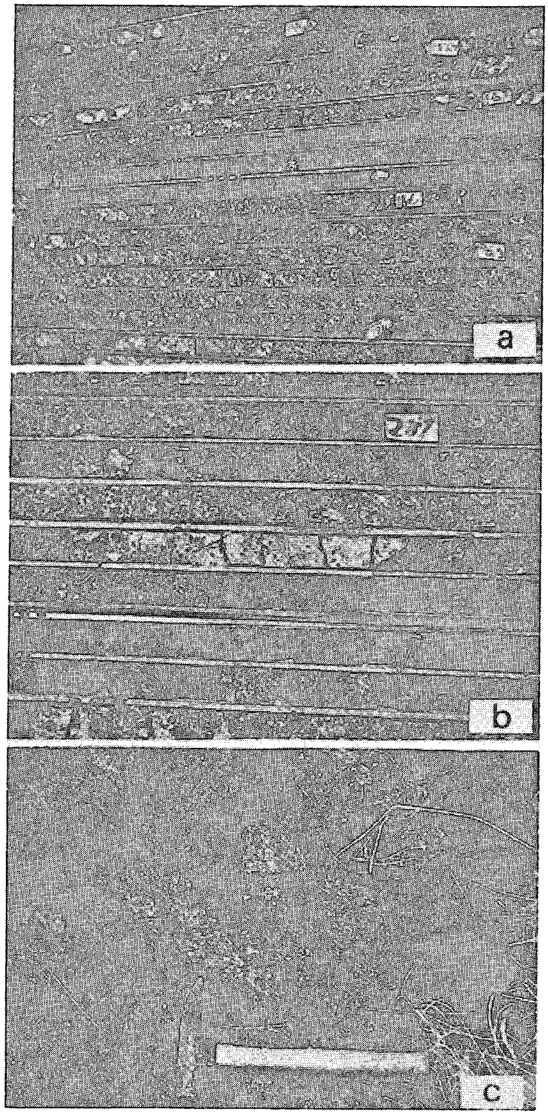

FIG. 4. Layering in the Lac-des-Iles complex. (a) Drill core from P48 (Roby zone) showing uralitized clinopyroxenite band in gabbro and pegmatitic gabbro. (b) Drill core from P48 showing 15 cm anorthositic layer and pegmatitic gabbro. (c) Layered gabbroic inclusion in peridotitic rocks.

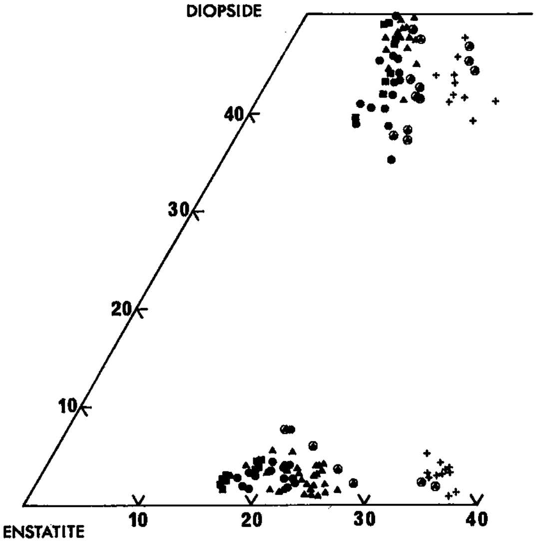

FIG. 5. Projection of chemical compositions of Lac-des-Iles pyroxenes onto part of the pyroxene quadrilateral. Pyroxenes from peridotitic rocks : squares, from pyroxenitic rocks : circles, from the western gabbro : triangles, from the eastern gabbro : crosses, from gabbroic inclusions in peridotite : circled triangles.

TABLE 1. ELECTRON MICROPROBE ANALYSES OF SPINELS FROM THE LAC-DES-ILES COMPLEX

	1.	2.	3.	4.	5.	6.	7.	8.
MgO	4.41(0.53)	2.65	4.63	5.71	2.97	6.34	0.08	14.5
Al_2O_3	16.5 (1.31)	16.4	18.1	19.1	15.3	18.0	0.51	60.8
TiO_2	1.78(0.44)	0.90	1.49	1.26	2.14	1.38	1.28	0.26
Cr_2O_3	31.8 (0.89)	27.1	25.9	27.0	26.0	29.7	0.24	0.02
MnO	0.41(0.03)	0.56	0.46	0.56	0.74	0.34	0.26	0.18
FeO	27.1 (0.97)	28.8	26.2	24.6	28.6	27.1	29.7	19.0
Fe_2O_3	17.6 (0.57)	21.8	21.4	20.2	23.9	14.2	64.6	4.39
NiO		0.38	0.17	0.16	0.12			
ZnO		0.05	0.22	0.33	0.00			
Sum	99.6	98.64	98.57	98.92	99.77	97.1	96.67	99.15

1. Peridotite G-75-13: average composition of 12 analyzed subhedral grains in serpentine, in clinopyroxene and at their contacts. Standard deviation in brackets. 2. Peridotite L1A-75-81, grain enclosed by olivine. 3. Peridotite L1A-75-81, average for 3 grains in orthopyroxene. 4. Websterite L1A-75-80, average for 4 grains in or adjacent to clinopyroxene. 5. Websterite L1A-75-83, average for centres of two grains in cumulus orthopyroxene. 6. Websterite L1A-G-75-46, average for 5 grains. 7. Norite from the eastern gabbro 16-340, magnetite containing ilmenite lamellae and spinel 8. 8. Green spinel in magnetite 7, average of 3 anal.

magnetite. Cumulus ortho- and clinopyroxenes occur in minor amounts; they are slightly altered to talc–magnetite and uralite, respectively. Pyroxene compositions (Watkinson, Dunning & Z. Johan, in prep.; see summary projected on Fig. 5) are variable in Ca but rather restricted in Fe/Mg. Spinel compositions are given in Table 1. Sulfide assemblages are pyrrhotite–pentlandite–chalcopyrite with minor marcasite, pyrite and violarite alteration.

2. *Clinopyroxene cumulates.* About 50% of the exposed area of the northern part consists of clinopyroxenite. It is coarse-grained, contains greater than 90% (vol.) augite, largely as cumulus grains with minor amounts of olivine, orthopyroxene and plagioclase. Strongly developed alteration to fine-grained aggregates of amphibole with minor chlorite and sericite is typical. Pyroxene compositions are slightly less magnesian than those in peridotite and are also highly variable in Ca (Fig. 5).

3. *Orthopyroxene–clinopyroxene cumulates.* A core of websterite in the northern part was recognized by Pye (1968). It is composed of fresh, medium-grained assemblages of two pyroxenes as cumulus minerals with some intercumulus clinopyroxene.

4. *Gabbroic rocks.* Plagioclase cumulates occur in narrow zones along the eastern margin of the northern part and as pods and inclusions in ultramafic rocks (Fig. 4c). They are coarse-grained and generally highly altered. Noritic and anorthositic rocks also occur in the northeastern part and in the websterite. These mafic units may be remnants of either "western" or "eastern" gabbros, or related to the ultramafic rocks. Their pyroxene compositions are consistent with the first possibility (Fig. 5).

Ni–Cu–Fe Sulfides and Platinum-Group Minerals

Introduction

Economic interest in the Lac-des-Iles area began in the late 1950s with the discovery of magnetite and Cu–Ni sulfides. Concentrations of PGE as high as 11 g Pd and 1 g Pt per tonne associated with eight Cu–Ni sulfide-rich zones outlined by Gunnex Ltd. were reported by Pye (1968). More recent work by Boston Bay Mines Ltd. and Texasgulf Inc. has revealed a major body of 35,000 tonnes per vertical metre grading 5.75 g PGE, 0.62 g Au, and 0.2% Cu–Ni (Anon. 1976).

Very few data are available on Pt/(Pt + Pd) or Cu/(Cu + Ni) in the body, but from Pye's report and microprobe analyses of an assay bead (Watkinson 1975) it seems that these ratios are approximately 0.07 and 0.5 respectively. The latter is compatible with Naldrett's & Cabri's (1976) generalized trend for this ratio in gabbroic liquid, but the apparent Pt/(Pt + Pd) value is lower than that expected for tholeiitic complexes.

Vysotskite (Pd, Ni)S was the first PGM

TABLE 2. ELECTRON MICROPROBE ANALYSES OF VYSOTSKITE AND ASSOCIATED SULFIDES

	1.	2.	3.	4.
Pd	63.0	0.03	0.00	0.00
Co	-	0.57	1.45	0.01
Ni	13.2	62.4	0.42	0.15
Fe	0.57	2.30	45.5	1.51
Cu	-	0.58	0.48	0.61
Pb	-	0.00	0.00	0.00
Zn	-	0.04	0.03	65.8
S	24.1	35.6	53.5	32.9
	100.87	101.52	101.38	100.98

1. Vysotskite in millerite, with chalcopyrite + sphalerite + galena + pyrite in uralitized gabbro P 22-380. Average of four analyses. 2. Millerite intergrown with chalcopyrite. 3. Pyrite; average of three analyses. 4. Sphalerite.

identified in the complex (Watkinson 1975); its composition and that of some associated minerals in the assemblage pyrite–millerite–chalcopyrite–sphalerite–galena–magnetite from altered gabbro are given in Table 2. Cabri & Laflamme (1976) reported the presence of eight PGM (vysotskite, kotulskite, merenskyite, sperrylite, mancheite, isomertieite, stillwaterite and unnamed Pd_5As_2) and found that Pd occurs in solid solution in melonite, gold and pentlandite. They reported the presence of twenty other sulfides, arsenides and oxides in their study of concentrates.

In the study of Roby-zone polished sections and concentrates (Dunning 1979) six PGM were identified as well as some as yet unidentified very small grains.

Cu–Ni–Fe sulfide assemblages in the Roby zone

Sulfide assemblages occur in peridotitic rocks of the ultramafic body and to a much greater extent in all rock types of the western gabbro. Although stringers and veinlets of pyrite–chalcopyrite are common in altered and sheared rocks, most sulfides occur as intercumulus blebs. Net-textured sulfide occurs rarely in noritic and anorthositic rocks. The following assemblages (all with chalcopyrite) occur in the western gabbro: 1. pyrrhotite–pentlandite–pyrite, 2. pyrrhotite–pyrite, 3. pentlandite–pyrite, 4. pentlandite–millerite–violarite, 5. pentlandite–millerite, 6. pyrite–millerite. There is some development of millerite and violarite from pentlandite in deuterically altered rocks. Assemblages 3 and 1 are the most common in noritic rocks, and are interpreted to be slightly metamorphosed equivalents of primary exsolution from monosulfide solid solution. Most net-textured sulfide is composed of assemblage 1. Assemblage 4–6, from strongly altered gabbroic rocks, are interpreted to be metamorphosed assemblages of altered (oxidized) equivalents of 1–3.

Platinum-group mineralogy of the Roby zone

Vysotskite (approximately $Pd_{0.79}Pt_{0.01}Ni_{0.22}S_{0.97}$) is the most abundant PGM in the Roby zone (Dunning 1979). It occurs most commonly with nickel minerals, especially in pentlandite as discrete anhedra or in lamellar intergrowth with pentlandite. It also occurs in chalcopyrite as subhedral rods with intergrown pentlandite. Most grains are relatively homogeneous chemically; for example, eight grains associated with pentlandite and chalcopyrite in specimen P96–227.4 gave the following average compositions (range in parentheses) Pd 66.2, (65.3–67.2), Pt 1.36 (0.63–1.99), Fe 0.72 (0.15–2.08), Ni 10.3 (9.4–11.3), S 24.1 (23.1–24.4), sum 102.68 wt. %. The high total is due to high Fe and Ni in one grain; this may be attributed to the electron beam overlapping pentlandite during one determination of these elements. One large grain with pentlandite had variable Pt/(Pt + Pd) such that it ranged to braggite according to the redefinition of Cabri *et al.* (1978). Very fine grains of vysotskite occur with finely disseminated chalcopyrite and pyrite in strongly altered gabbroic rocks.

Kotulskite, $Pd_{0.96}Pt_{0.01}Te_{0.78}Bi_{0.24}$, occurs as homogeneous anhedra in chalcopyrite and pentlandite, and in complex intergrowth with merenskyite and $Ag_4Pd_3Te_4$ (unnamed). Stibiopalladinite occurs with kotulskite, pentlandite, violarite and pyrite and some of it has many fine kotulskite inclusions. Native gold was found with pyrite in sheared, altered gabbroic rocks and in a concentrate from noritic rocks.

Relationship of platinum-group elements and lithology in the Roby zone

The relationship between PGE mineralization and lithology in the Roby zone was studied by Dunning (1979) using drill logs, core and assay data, especially from diamond drill hole P–57 (Fig. 6). The PGE assays are total platinum-group values. P–57 was collared in the eastern gabbro and drilled at -45° at an azimuth of 251°, penetrating approximately 30 m of eastern gabbro before entering the mineralized Roby zone of the western gabbro. Layering in this part of the Roby zone dips east at approximately 65°.

The basal layers of the mineralized zone (approximately 105–130 m) are plagioclase cumulates, some of anorthositic composition. Higher in the sequence orthopyroxene–plagioclase cumulates are interlayered with these (approximately 45–105 m). Mineral-graded layers are present and net-textured sulfide is occasionally developed in orthopyroxene-rich layers. Noritic layers are discontinuous; they pinch out both along strike and down dip. Clinopyroxenite, interlayered with gabbro, occurs near the stratigraphic top of the mineralized zone. Clinopyroxene is the cumulus phase in clinopyroxenite and plagioclase is the cumulus phase in gabbro. Both rock types are strongly altered to secondary assemblages.

Ni values range from 100 to 600 ppm with peaks in a noritic layer and a pyroxenitic layer. An increase in Ni content is observed in several noritic layers. PGE values attain 16.6 ppm in P–57. In the basal gabbroic layers PGE values vary up to 0.6 ppm. These layers extend west past the bottom of P–57 but contain only sporadic high PGE values. The noritic layers contain the highest concentrations of PGE in P–57 but the highest values recorded from the Roby zone pertain to sheared, altered clinopyroxenite. One clinopyroxenite in P–57 contains 3.8 ppm PGE, the other only 0.8 ppm. The strongest concentration of PGE in P–57 corresponds to only a slight increase in Ni content, but in general, peaks in Ni concentration correspond to those for PGE. This is compatible with the general relationship in all types of Roby-zone mineralization: coincidence of PGM and nickel minerals, as noted above. The correlation of PGE and Ni concentrations with pyroxene cumulates is very apparent in Figure 6 and suggests that the precipitation of abundant mafic minerals and that of PGM and sulfides are related processes. The effects of alteration and metamorphism on mobilization of the economically significant elements are not extensive enough to mask this apparent relationship.

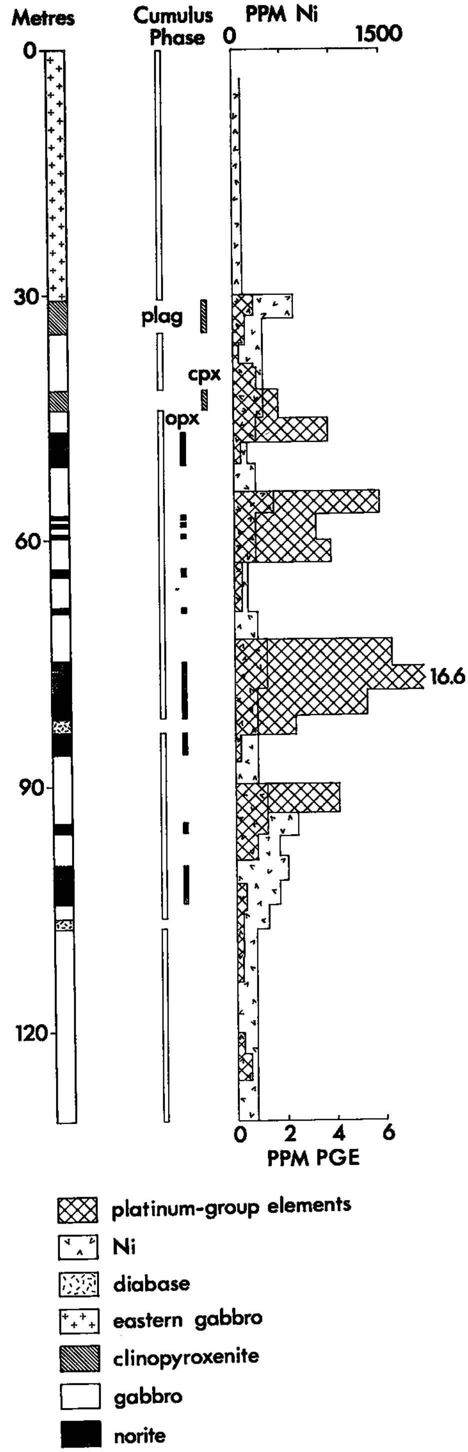

FIG. 6. Relationships of rock types, cumulus phases, nickel and platinum-group-element concentrations in diamond-drill hole P57 (Roby zone).

CHEMISTRY OF OXIDE AND SILICATE MINERALS

Spinel-group minerals

Because of the relationship between spinels, especially chromite, and platinum-group minerals (*e.g.*, Vermaak 1976), Lac-des-Iles spinels were specifically sought and studied using the electron microprobe. Analyses of spinels are given in Table 1; ferric and ferrous iron were calculated from total iron assuming that the number of atoms of Fe^{2+} + Mg + Ni + Zn equals half the sum of Al + Cr + Fe^{3+} + Ti. Details of the microprobe technique and discussion of spinel chemistry are given by Watkinson *et al.* (in prep).

Spinels are not common at Lac des Iles, except for ilmenomagnetite and green spinels in the eastern gabbro (Table 1). Disseminated chrome spinels occur in ultramafic rocks of the northern part, but no concentrations of these are known. Their Mg/(Fe + Mg) ratio is restricted to the range 0.15 to 0.32; Fe/(Fe + Mg) and Al/(Al + Cr) are higher than those reported for Merensky Reef chromites (Vermaak & Hendriks 1976). There are no concentrations of spinels associated with PGM of the western gabbro; in fact, disseminated spinels are notably absent but minor disseminated assemblages of ilmenite + rutile are present (Table 3).

Pyroxenes

Pyroxenes have been analyzed from all three parts of the Lac-des-Iles complex (Watkinson *et al.*, in prep.). A résumé of the data is presented in Figure 5. Cumulus and postcumulus pyroxene compositions are virtually identical. Most orthopyroxenes have the composition of bronzite. Inverted pigeonite is common in ultramafic rocks of the northern part. The most Mg-rich orthopyroxenes occur in peridotite of the ultramafic body (En_{80-83}); those in pyroxenite of the ultramafic body are slightly more Fe-rich ($En_{76.5-82}$).

Orthopyroxene of the western gabbro has a compositional range of $En_{72-82.5}$, overlapping the range of pyroxene compositions from the pyroxenites, whereas that of the eastern gabbro is significantly more Fe-rich: En_{62-65}. Clinopyroxenes of the peridotite, pyroxenite and western gabbro have similar compositional ranges and are highly variable in Ca because of orthopyroxene exsolution.

Pyroxene equilibration temperatures

Pyroxene equilibration temperatures were determined by using analyses of coexisting orthopyroxenes and clinopyroxenes from each of the parts of the Lac-des-Iles complex and a computer program prepared by P. Mainwaring for the model of Wells (1977). Temperatures are about 1100° for pyroxene pairs from the peridotite and 1030°C for the pyroxenite. Temperatures obtained for the western gabbro range from 1066°C to 726°C, whereas those for the eastern gabbro are consistently around 950°C. The ranges of values obtained are narrow for all rock types except the western gabbro. This may be a reflection of the presence of fluid extending the temperature range of crystallization of the western gabbroic liquid. Little fluid was present in other parts of the complex, and the crystallization range was small. The consistently higher temperatures obtained for eastern gabbro in spite of the higher Fe/(Fe + Mg) values in its pyroxenes suggest that this body results from a separate magma injected after the emplacement of the western gabbro.

TABLE 3. ELECTRON MICROPROBE ANALYSES OF TITANIFEROUS OXIDES, ROBY ZONE, LAC-DES-ILES COMPLEX

	1.	2.	3.	4.
SiO_2	0.00	0.02	0.00	0.05
FeO	0.05	40.8	47.0	42.9
MgO	0.00	0.14	0.08	0.10
Al_2O_3	0.00	0.05	0.00	0.11
Cr_2O_3	0.26	0.00	0.00	0.06
CaO	0.00	0.00	0.04	0.08
NiO	0.00	0.02	0.13	0.00
TiO_2	99.6	52.2	50.5	51.1
ZnO	0.07	0.00	0.00	0.15
MnO	0.00	3.85	2.29	3.78
Sum	99.98	97.08	100.04	98.33

1. Norite P57-190.5. Rutile associated with ilmenite, amphibole and partly altered orthopyroxene. 2. Ilmenite adjacent to 1. 3. Norite P57-162.4. Ilmenite. 4. Norite P57-270.2. Ilmenite at contact of orthopyroxenes.

Discussion

In our preferred model for the development of the PGE and Cu–Ni mineralized zone we infer that magma for the western gabbro formed first, incorporating most of the available S, PGE, Cu and Ni from a mantle source. Magma for the ultramafic rocks, if from the same source region, formed later and contained less of these elements. Alternately, the ultramafic rocks may have formed from magma generated by partial fusion of the mantle residuum after generation of gabbroic liquid.

Crystallization of the western gabbro began with the formation of plagioclase cumulates followed later by orthopyroxene–plagioclase cumulates and clinopyroxene cumulates. When magma was sufficiently enriched in "mafic" constituents, pyroxenes and sulfide coprecipitated. The absence of olivine or other early mafic cumulates resulted in the sulfide being moderately nickeliferous (Cu/Ni ratio is approximately 1).

The PGE were dissolved in sulfide liquid which, on cooling, precipitated monosulfide solid solution (MSS), possibly with a small amount of intermediate solid solution and PGM as well. On further cooling, pyrrhotite, pentlandite and chalcopyrite exsolved from MSS to form the primary sulfide assemblage. Vysotskite may have exsolved from the MSS; however, intergrowths of vysotskite and pentlandite suggest that there may have been a high-temperature precursor to the exsolved products. Some pyrite is apparently an exsolution product of MSS, but some formed on alteration and metamorphism of primary assemblages.

Alteration, which is especially intense in clinopyroxene-rich rocks, is apparently deuteric but may also be the result of fluids mobilized during the intrusion of the eastern gabbro or, less likely, the surrounding granitic rocks. At the time of alteration, migration up to a few cm of Pd, Cu, Fe and S occurred; fine-grained disseminations of vysotskite, chalcopyrite and pyrite were formed in fractures adjacent to primary sulfide blebs. Finally, metamorphism to greenschist-facies conditions resulted in recrystallization of some of these altered assemblages.

The apparent restriction of significant amounts of PGE, Cu and Ni to the western gabbroic rocks is interpreted to be the result of relatively high initial concentrations of these elements plus S and H_2O in the first liquid generated in the mantle and their further concentration in residual silicate and, subsequently, sulfide liquids. This is compatible with the variable grain size, occurrence of pegmatitic patches and pronounced deuteric alteration that are common in the western gabbro and the wide range of pyroxene equilibration temperatures.

Conclusions

The order of intrusion of the major units of the Lac-des-Iles complex is (1) western gabbro, (2) eastern gabbro, and (3) ultramafic rocks. Only the western gabbro is known to contain significant Cu–Ni and PGE mineralization. In the mineralized Roby zone of the western gabbro, primary magmatic crystallization produced plagioclase, orthopyroxene and clinopyroxene cumulates. This was followed by widespread alteration of variable intensity. Subsequently, some recrystallization occurred in a metamorphic episode that reached greenschist-facies conditions.

Assemblages of Cu–Ni–Fe sulfides are present in the mineralized zone of the western gabbro and may be classified as primary, secondary and metamorphic. The primary assemblages occur in fresh noritic layers and in large sulfide blebs in altered gabbroic rocks. Secondary assemblages occur with fine-grained chlorite and amphibole assemblages in gabbroic rocks and to a lesser extent in other altered lithologies. Metamorphic sulfide assemblages also occur in altered gabbroic rocks often in the same layer in which secondary assemblages are found. PGE mineralization is found in all major rock types of the western gabbro and is associated with primary, secondary and metamorphic sulfide assemblages; however, a correlation between high PGE values and pyroxene cumulates is evident in some drillholes. The predominant platinum-group mineral is vysotskite, which usually occurs with pentlandite in primary and metamorphic sulfide assemblages.

Acknowledgments

This study was initiated and supported by Texasgulf, Inc. We thank G. Mannard and his staff for encouragement and J.P. Sheridan for his permission to continue this work. Discussions with L. Cabri, Z. Johan, G. MacVeigh and P. Mainwaring have been particularly helpful. L. Whitmore drafted some of the diagrams. Financial assistance through NRC grant A7874 and GR-5 grant of Carleton University to Watkinson are greatly appreciated as is the generosity of Bureau de Recherches Géologiques et Minières (France) in the use of their facilities.

References

ANONYMOUS (1976): Deep hole for Boston Bay at Lac des Iles palladium. *Northern Miner* **62**, 11.

CABRI, L.J. & LAFLAMME, J.H.G. (1976): Ore microscopy of some samples from Lac des Iles, Ontario. *Geol. Assoc. Can., Mineral. Assoc. Can. Program Abstr.* **1**, 56.

———, ———, STEWART, J.M., TURNER, K. & SKINNER, B.J. (1978): Mineralogy and phase relations: cooperite, braggite and vysotskite. *Geol. Assoc. Can. / Mineral. Assoc. Can. Program Abstr.* **3**, 376.

CHASSÉ, J.L. (1978): *The Petrology of the Eastern Part of the Lac des Iles Complex, Northwestern Ontario.* B.Sc. thesis, Carleton Univ., Ottawa.

DUNNING, G. (1979): *Geology and Platinum-Group Mineralization, Lac des Iles Complex, Northwestern Ontario.* M.Sc. thesis, Carleton Univ., Ottawa.

GOODWIN, A.M. (1977): Archean volcanism in Superior province, Canadian Shield. *In* Volcanic Regimes in Canada (W.R.A. Baragar, L.C. Coleman and J.M. Hall, eds.), *Geol. Assoc. Can. Spec. Pap.* **16**, 205-241.

GUARNERA, B.J. (1967): *Geology of the McKernan Lake Phase of the Lac des Iles Intrusive, Thunder Bay District, Ontario.* M.Sc. thesis, Michigan Tech. Univ., Houghton, Mich.

KAYE, L. (1969): Geology of the Eayrs Lake–Starnes Lake area. *Ont. Dep. Mines Geol. Rep.* 77.

NALDRETT, A.J. & CABRI, L.J. (1976): Ultramafic and related mafic rocks: their classification and genesis with special reference to the concentration of nickel sulfides and platinum-group elements. *Econ. Geol.* 71, 1131-1158.

PYE, E.G. (1968): Geology of Lac des Iles area. *Ont. Dep. Mines Geol. Rep.* 64.

VERMAAK, C.F. (1976): The Merensky Reef – thoughts on its environment and genesis. *Econ. Geol.* 71, 1270-1298.

——— & HENDRIKS, L.P. (1976): A review of the mineralogy of the Merensky Reef, with specific reference to new data on the precious metal mineralogy. *Econ. Geol.* 71, 1244-1269.

WATKINSON, D.H. (1975): Report on the petrology and mineralogy, Lac des Iles complex, northwestern Ontario. *Internal Rep., Texasgulf Inc.*

WELLS, P.R.A. (1977): Pyroxene thermometry in simple and complex systems. *Contr. Mineral. Petrology* 62, 129-139.

Received September 1978, revised manuscript accepted December 1978.