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Geology, Petrology, and Controls on PGE Mineralization of the Southern Roby and Twilight Zones, Lac des Iles Mine, Canada

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Abstract

The Lac des Iles Pd mine, with reserves of 88 million metric tons (Mt) containing 1.51 g/t Pd, is hosted by the 2.69 Ga Lac des Iles intrusive complex in the southern Wabigoon subprovince of the Superior province of Canada. The known economic concentration of Pd occurs in the Mine Block intrusion, the central body of the intrusive complex, where gabbroic rocks range from leucogabbro to pyroxenite and show complicated textures, such as breccias, magma mingling, and pods and veins of pegmatite. The ore is characterized by low concentrations of sulfide (typically less than 3 vol %) and exceptionally high Pd contents (Pd/Pt ~10, Pd/Au ~13). Detailed mapping of the southern Roby and Twilight zones shows that early leucocratic rocks are barren and that the bulk of Pd was introduced by late melanocratic magmas. The average concentration of Pd in the melanocratic rocks, excluding the High-Grade zone, is estimated to be ~4 ppm. The concentrations of sulfur correlate positively with those of base metals, platinum group elements (PGE), and Au. Furthermore, sulfide grains commonly show exsolution textures. The evidence suggests a magmatic origin of the PGE mineralization where the PGE were concentrated in an immiscible sulfide melt in the parental magma.

Bulk chemical compositions suggest that all mafic igneous rocks in the mineralized zones, except for late clinopyroxenite, are cogenetic. The hypothetical parental magmas have high MgO and low (~15× chondrite), unfractionated rare earth elements (REE) with $(Ce/Yb)_{chondrite} < 3$, suggesting that the magmas formed through high degrees of partial melting in a moderately depleted mantle. Fractional crystallization of olivine, chromite, and high-temperature platinum group minerals (PGM) resulted in high concentrations of Pt, Pd, and Rh relative to Ir, Os, and Ru in the parental magmas. Extreme enrichment of Pd in the late melanocratic magmas is interpreted to have been attained through the incorporation of earlier formed sulfide melt. This interpretation is supported by high Cu/Pd in early barren leucocratic rocks and low Cu/Pd in fertile melanocratic rocks. Rocks in the volumetrically minor but economically important High-Grade zone (>35% of Pd in the deposit) on the eastern margin of the Roby zone have much higher concentrations of Pd than any other rocks and do not show correlations between sulfur and precious and base metals. Furthermore, the rocks are intensely and pervasively altered to actinolite, talc, anthophyllite, hornblende, chlorite, sericite, calcite, and quartz. These observations suggest subsolidus enrichment of Pd and mobility of S. The lack of apparent fluid pathways within the High-Grade zone and the distribution of the zone are consistent with the enrichment of Pd at high temperatures by fluids that originated from the mafic magmas.

The textures of the Lac des Iles deposit are similar to those of contact-type PGE deposits, but there are fundamental differences between the two. The Lac des Iles deposit is not localized near the contact between the host intrusion and the country rocks and evidence of the assimilation of the host rocks is lacking. Instead, the mineralization at Lac des Iles has many features in common with layered intrusion-hosted deposits, in which pulses of primitive magma introduced the PGE. Unlike the quiescent magma chambers of most layered deposits, the magmas at Lac des Iles were intruded energetically, forming breccias and magma-mingling textures.

Introduction

THE LAC DES ILES MINE is the only primary Pd producer in Canada. The deposit is hosted by the Neoarchean Lac des Iles mafic-ultramafic intrusive complex in the southern Wabigoon subprovince of the Superior province (Fig. 1). In contrast to many platinum group element (PGE) deposits, which are hosted by Ni sulfides at the base of large mafic intrusions (e.g., Sudbury and Noril'sk) or as stratiform layers within large layered intrusions (e.g., Bushveld Intrusion), the Lac des Iles deposit is characterized by low contents of sulfides, common alteration of silicate minerals, and complex igneous textures, such as breccias and pegmatites (Lavigne and Michaud, 2001). The mineralization is extremely enriched in Pd compared to other PGE, with Pd/Pt ratios of ~10 and Pd/Ir ratios of ~10,000. These features are not easily explained by genetic models for other PGE deposits. Previously proposed origins for the deposit include hydrothermal and/or deuteric mineralization based on the occurrence of Bi-bearing platinum group minerals (PGM; Watkinson and Dunning, 1979) and the close association of secondary hydrous silicate minerals with PGM (Talkington and Watkinson, 1984), and a constitutional zone-refining process (Brügmann et al., 1989) based on high Pd contents and coexisting melanocratic and leucocratic rocks in the mineralized zones. The latter process, as originally proposed by McBirney (1987), involves partial melting of gabbro cumulates.

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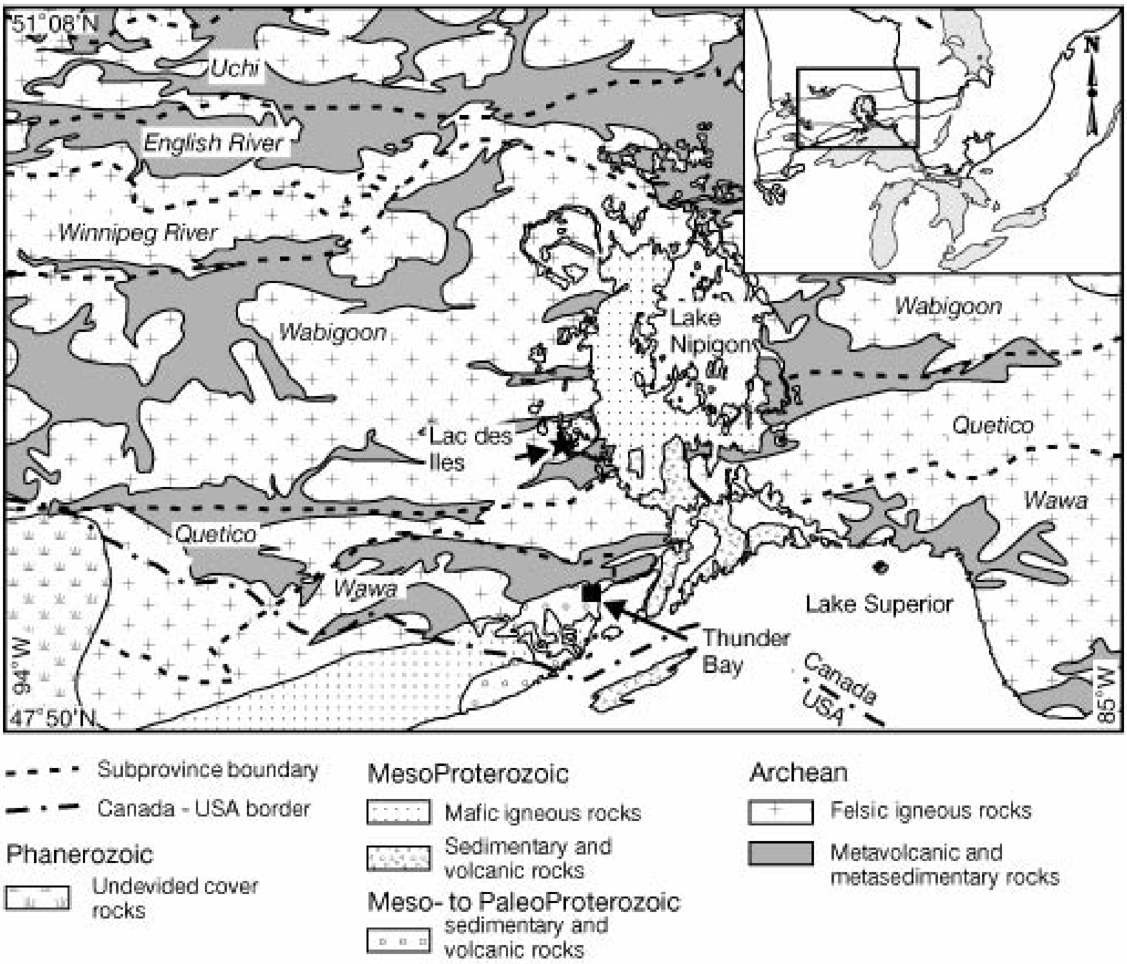

FIG. 1. Regional geology of the western Superior province, illustrating the boundaries of subprovinces, the locations of the Nipigon plate and the Lac des Iles mine (modified from Ontario Geological Survey, 1991). The subprovince names are shown in italics. The Nipigon plate is the northern extension of the igneous province related to the Midcontinental rift. The inset displays a simplified map of the Superior province. The square outlines the area shown in the figure.

We conducted detailed mapping of the southern Roby and Twilight zones at scales of 1:60 and 1:120, respectively, in the summers of 2002 and 2003. Field observations by Hinchey et al. (2003) show a clear relationship between mineralization and rock types. This paper documents new data on the geochemistry of the different rock types and discusses the origin of the mineralization.

Previous work and exploration history

Geologic investigations in the area began with reconnaissance mapping by Jolliffe (1934), followed by more detailed mapping of the area by Pye (1968). Economic interest in the area was sparked by the discovery of aeromagnetic anomalies in the late 1950s. Significant Pd mineralization was first discovered in the Roby zone in 1963 by prospectors and was subsequently investigated by Gunnex Ltd. and Anaconda Ltd. The Ontario Geological Survey conducted several mapping projects in the area (Sutcliffe and Sweeny, 1986; Macdonald, 1988; Sutcliffe et al., 1989), and M.Sc. thesis projects on the deposit were completed by Dunning (1979), Sweeny (1989), and Michaud (1998).

Madeleine Mines Ltd. commenced mining in 1990 but this lasted only several months. Lac des Iles Mines Ltd. began production in 1993 at a rate of 2,000 t/d. Today the Lac des Iles mine is an open-pit operation conducted by North American Palladium Ltd. Current proven and probable reserves consist of 88 million metric tons (Mt) grading 1.51 g/t Pd, 0.17 g/t Pt, 0.12 g/t Au, 0.06 percent Cu, and 0.05 percent Ni, with additional measured and indicated resources of 65 Mt grading 1.58 g/t Pd, 0.17 g/t Pt, 0.11 g/t Au, 0.05 percent Cu, and 0.05 percent Ni (North American Palladium Ltd. Annual Report, 2002).

Geology

Regional geologic setting

The Lac des Iles intrusive complex is located in the granite-greenstone terrane of the Wabigoon subprovince of the Archean Superior province of the Canadian Shield (Blackburn et al., 1992; Fig. 1). The intrusive complex is one of a suite of Late Archean mafic-ultramafic plutons in the southern Wabigoon subprovince close to the Quetico subprovince

(Pye, 1968; Sutcliffe, 1986). It is part of a 30-km-diameter circular array of mineralized mafic and ultramafic intrusions, including Legris Lake, Tib Lake, and Buck Lake, of which the Lac des Iles intrusive complex is the largest (Gupta and Sutcliffe, 1990; Fig. 2).

Regional metamorphic grades in the area are low, up to greenschist facies (Blackburn et al., 1992; Pettigrew and Hattori, 2002), which contrasts with granulites and migmatites in the adjacent Quetico subprovince (Williams, 1992; Fig. 2). The low grade of regional metamorphism in the study area is supported by the presence of pristine clinopyroxene and orthopyroxene in the northern part of the complex and in the gabbronorite of the Mine Block intrusion.

Geology of the Lac des Iles complex

The Lac des Iles intrusive complex (2692$^{+4}_{-2}$ Ma; Blackburn et al., 1992) is subdivided into three main intrusive bodies (Lavigne and Michaud, 2001; Fig. 3): (1) the North Lac des Iles ultramafic intrusion, centered on the lake, (2) the Mine Block intrusion, consisting of lithologically and texturally complex gabbroic rocks, and (3) the Camp Lake intrusion, which is a homogeneous hornblende gabbro southwest of Camp Lake. The three intrusions are separated by tonalitic country rocks (Lavigne and Michaud, 2001). All rocks in the area have been intruded by diabase dikes and sills, which range from ~2120 to ~1140 Ma (Buchan and Ernst, 2004).

The North Lac des Iles intrusion (Fig. 3) ranges from clinopyroxenite and/or websterite in the northern part to minor gabbro and/or gabbronorite in the southern part. Igneous layering is common and pristine igneous minerals are well preserved. The ultramafic rocks are in direct contact with the tonalitic country rocks but are also locally separated by thin gabbroic layers (Lavigne and Michaud, 2001). The gabbro and/or gabbronoritic rocks of Mine Block intrusion (Figs. 3–4) range from anorthosite to clinopyroxenite. They have complicated textures, including breccias and magma-mingling structures, which vary at scales of less than 5 m.

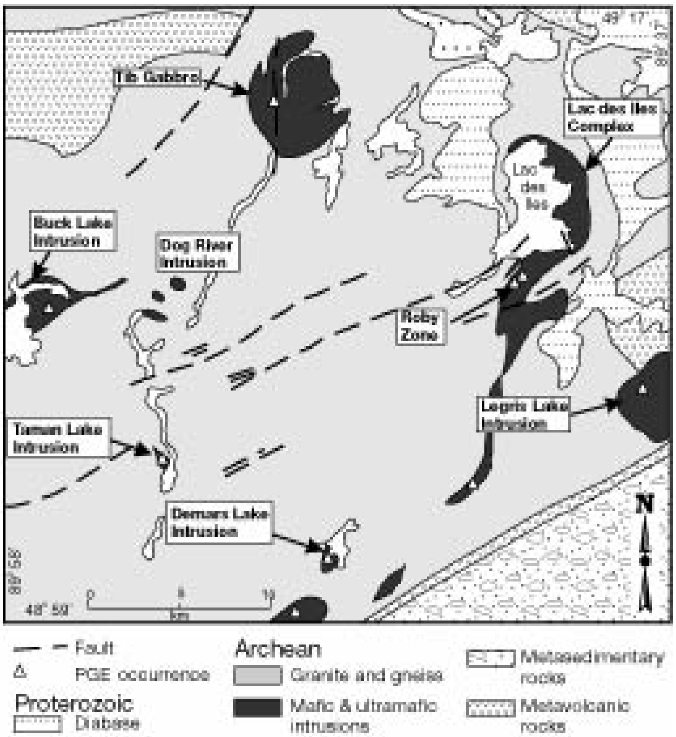

FIG. 2. Simplified regional geologic map of the study area, showing the occurrence of mafic and/or ultramafic intrusions with PGE mineralization (modified after Sutcliffe and Smith, 1988). Note the circular distribution of mafic-ultramafic intrusions. The diabase sills belong to the igneous rocks of the Nipigon plate.

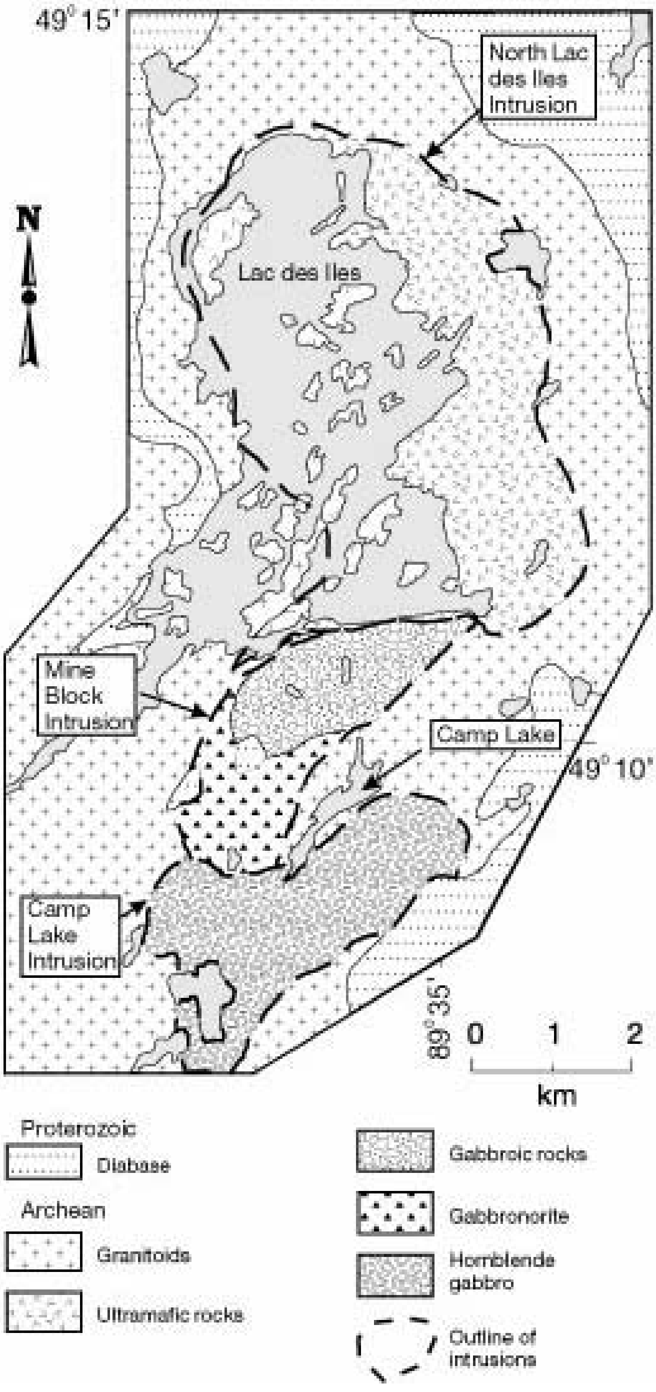

FIG. 3. Simplified geologic map of the Lac des Iles intrusive complex, illustrating the distribution of the North Lac des Iles, Mine Block, and Camp Lake intrusions (modified after Sutcliffe et al., 1989).

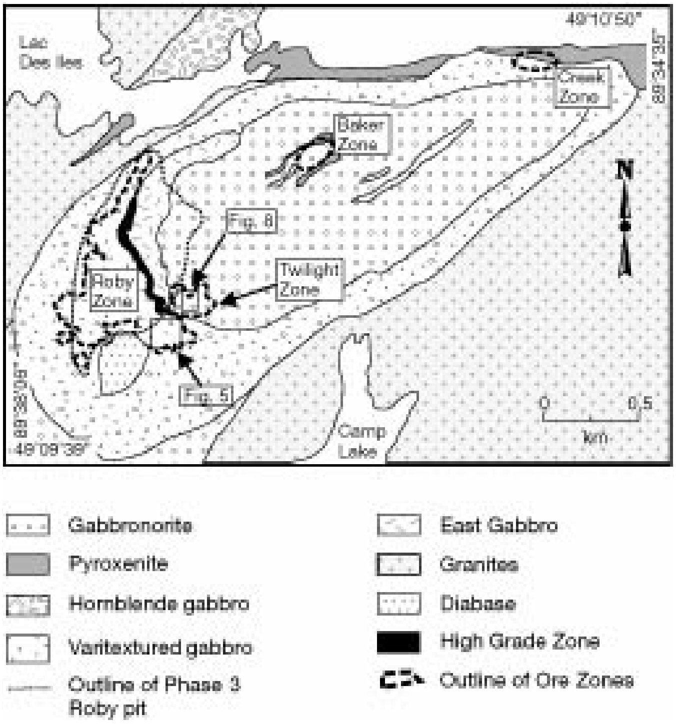

FIG. 4. Simplified geologic map of the Mine Block intrusion of the Lac des Iles intrusive complex (modified after Sutcliffe and Sweeney, 1986), showing the distribution of East Gabbro, the locations of the Roby, Twilight, and High-Grade zones, and the outline of the phase 3 open pit.

Mineralized Zones

Anomalous concentrations of PGE occur locally throughout the Lac des Iles intrusive complex, but known economic mineralization occurs only in the Mine Block intrusion (Fig. 3). The mineralized zones include the Roby, Twilight, and Baker zones (Fig. 4). The Roby zone has dimensions of 950 m north-south, 700 m east-west, and greater than 1,000 m vertically and contains the narrow High-Grade zone on its eastern margin (Fig. 4). The High-Grade zone is 15 to 25 m wide and 400 m long and is bounded by the barren East Gabbro to the east. This ore zone consists of pervasively altered melanocratic rocks and dips nearly vertically to a depth of 250 m, at which depth it shallows out to the east. The High-Grade zone comprises only 7.6 vol percent of the current reserves (Lavigne and Michaud, 2001) but contains approximately 35 percent of the Pd in the Roby zone.

Most of the Roby zone, including the High-Grade zone, is being mined in the phase 3 open pit, but the southwest part of the Roby zone was still exposed on the surface in 2003 and was mapped in detail in this study (approx 65 to 70 m north-south and 35 to 40 m east-west: Fig. 5). The Twilight zone, with a surface exposure of 175 to 200 m north-south and 200 to 225 m east-west, lies southeast of the Roby zone (Fig. 4), with 50 to 70 m of East Gabbro between the two zones. The Baker zone is located approximately 1 km northeast from the Roby and Twilight zones (Fig. 4) and contains rocks and textures similar to those in the Roby and Twilight zones.

Petrology of the Southern Roby Zone

The detailed mapping by Hinchey et al. (2003) classified rocks into three groups; (1) early leucocratic rocks, (2) sulfide-bearing melanocratic gabbroic rocks, and (3) late, sulfide-free melanocratic gabbroic rocks. The area also contains young felsic dikes and diabase dikes that cut all rocks of the Lac des Iles intrusive complex (Fig. 5).

Most rocks of the southern Roby zone show cumulate textures, consisting of subhedral to euhedral cumulus crystals of clinopyroxene, plagioclase, and minor orthopyroxene with intercumulus material consisting of the same assemblage plus minor biotite, magnetite, ilmenite, and sulfides. Breccias are common and are named on the basis of matrix composition. For example, a breccia with melanogabbro matrix is referred to as a melanogabbro breccia (Fig. 6A). Gabbroic rocks with varying grain size from fine to coarse and local pods and veins of pegmatite are termed "varitextured" gabbro.

Early leucocratic rocks (group 1)

The early leucocratic rocks consist of (1a) medium-grained anorthosite and/or leucogabbro; (1b) medium-grained gabbro, which is commonly varitextured close to pegmatite; (1c) medium-grained, light-gray gabbro with local layering that strikes N 64-68° E, defined by alternating layers of plagioclase and clinopyroxene; and (1d) medium-grained, locally foliated gabbro. The relationships between these rocks are not certain due to the lack of exposed contacts. All leucocratic rocks have similar mineral abundances, with 45 to 65 vol percent plagioclase, 35 to 55 vol percent clinopyroxene, and less than 10 vol percent of combined orthopyroxene, biotite, and epidote. They contain less than 1 vol percent of finely disseminated pyrite, chalcopyrite, and oxides. The plagioclase in the rocks commonly displays cumulus texture, with crystals 1 to 7 mm in length. Intercumulus material is dominated by clinopyroxene (grain sizes of 1–3 mm), with lesser amounts of orthopyroxene, biotite, sulfides, and oxides. The rocks are unaltered to moderately altered, with variably sericitized plagioclase. Clinopyroxene is commonly replaced by actinolite, hornblende, epidote, and chlorite.

Mineralized melanocratic rocks (group 2)

The mineralized melanocratic rocks range from gabbro to clinopyroxenite, contain sulfide, and have irregularly shaped pods and veins of pegmatite. Brecciation and magma-mingling structures with the earlier leucocratic rocks of group 1 are common. From north to south, the melanocratic rocks are (2a) medium-grained meso- to melanogabbro breccia, (2b) medium- to relatively coarse-grained clinopyroxenite, and (2c) medium-grained, dark gabbro (Fig. 5). Pegmatite (2d) is common within and in contact with these melanocratic rocks. Most rocks are altered with very rare relict pyroxenes and plagioclase. Clinopyroxene is commonly replaced by a mixture of hornblende, actinolite, and chlorite, whereas interstitial clinopyroxene is replaced by chlorite. Plagioclase is mostly sericitized.

Medium-grained mesogabbro to melanogabbro breccia (2a): This breccia contains fragments of leucocratic rocks of group 1 (Fig. 6A). The matrix of the breccia is dominated by subhedral, equigranular clinopyroxene (1–6 mm, 50–80 vol

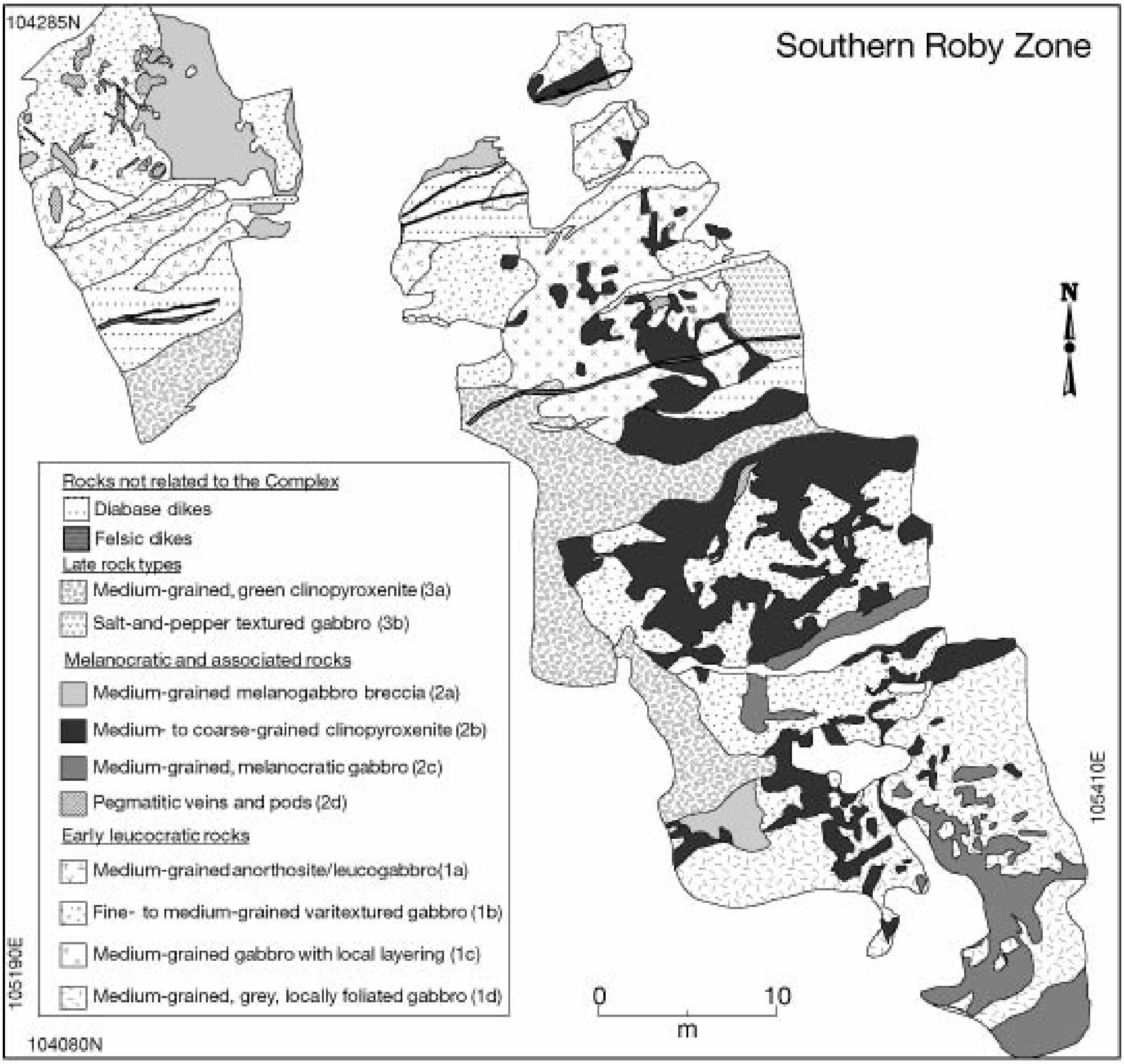

FIG. 5. Illustration of the complicated distribution of various rock types in the southern Roby zone in the Mine Block intrusion after 1:60 scale mapping by Hinchey et al. (2003). Rocks are divided into early leucocratic, mineralized melanocratic, and late barren melanocratic rocks. The mineralized melanocratic rocks are commonly accompanied by pegmatitic veins and pods of various sizes from several centimeters to 50 cm. Only large pegmatites are shown in the map. Felsic and diabase dikes cut all rock types of the Lac des Iles intrusive complex. Numbers on the sides correspond to the mine grid.

%) that commonly forms aggregates, with lesser amounts of plagioclase (1–4 mm, 30–50 vol %) and minor (<5 vol %) orthopyroxene and biotite. Interstitial minerals are plagioclase (1–4 mm with minor aggregates of small ~0.5-mm crystals), minor clinopyroxene and biotite, and sulfide and oxide minerals. A mixture of sulfide and oxide minerals occur as blebs (1–6 mm diam) and fine-grained disseminations (1–3 vol % of the matrix). The sulfide minerals are mostly pyrrhotite with exsolved chalcopyrite and pentlandite. Minor pyrite and magnetite are present, and minor amounts of calcite occur in the blebs of sulfide minerals. Chalcopyrite also commonly occurs along cleavage planes of actinolite.

Medium- to coarse-grained clinopyroxenite (2b): These rocks range from massive, medium-grained clinopyroxene-rich melanogabbro to clinopyroxenite and consist of equigranular clinopyroxene (1–7 mm, 85–100 vol %) with interstitial clinopyroxene, plagioclase, orthopyroxene, biotite, sulfides and oxides, and rare gahnite. The rocks have an orthocumulate texture, with a minor adcumulate texture. Sulfides (1–5 vol %) are disseminated, blebby (0.5–2 mm), and net textured, consisting of pyrrhotite with intergrown chalcopyrite and pentlandite. The texture suggests that the sulfides were once monosulfide solid solution. The clinopyroxenite also contains minor chalcopyrite along cleavage planes of secondary actinolite (Fig. 7A).

Medium-grained dark gabbro (2c): This rock type occurs in the southern portion of the mapped area (Figs. 5–6B) and due to its dark color, including dark plagioclase in hand

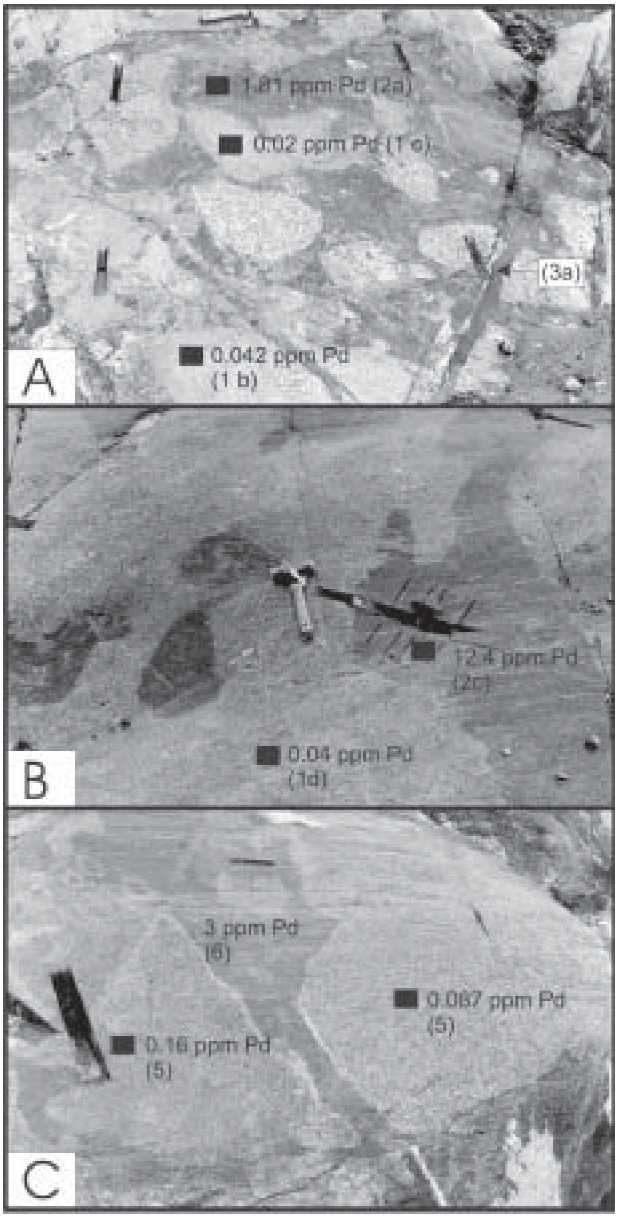

FIG. 6. Representative photographs of the ore zone and the concentrations of Pd in different rock types. Solid squares show the locations of samples used for Pd analysis after the photographs were taken. The Pd value of the melanonorite in the center of (C) is for a sample outside the field of view. The numbers in parentheses correspond to the rock types described in the text. Rock hammer for scale. A. Medium-grained melanogabbro breccia (2a) containing fragments of earlier leucocratic rocks (1b-c) in the northern section of the southern Roby zone. Note low concentrations of Pd in leucocratic rocks and a dike of late barren clinopyroxenite (3a) cutting the melanogabbro breccia (2a). B. Magma mingling between early leucogabbro (1d) and late melanogabbro (2c) from the southern portion of the southern Roby zone. C. Magmatic brecciation of late melanonorite (6) and earlier norite (5) in the Twilight zone.

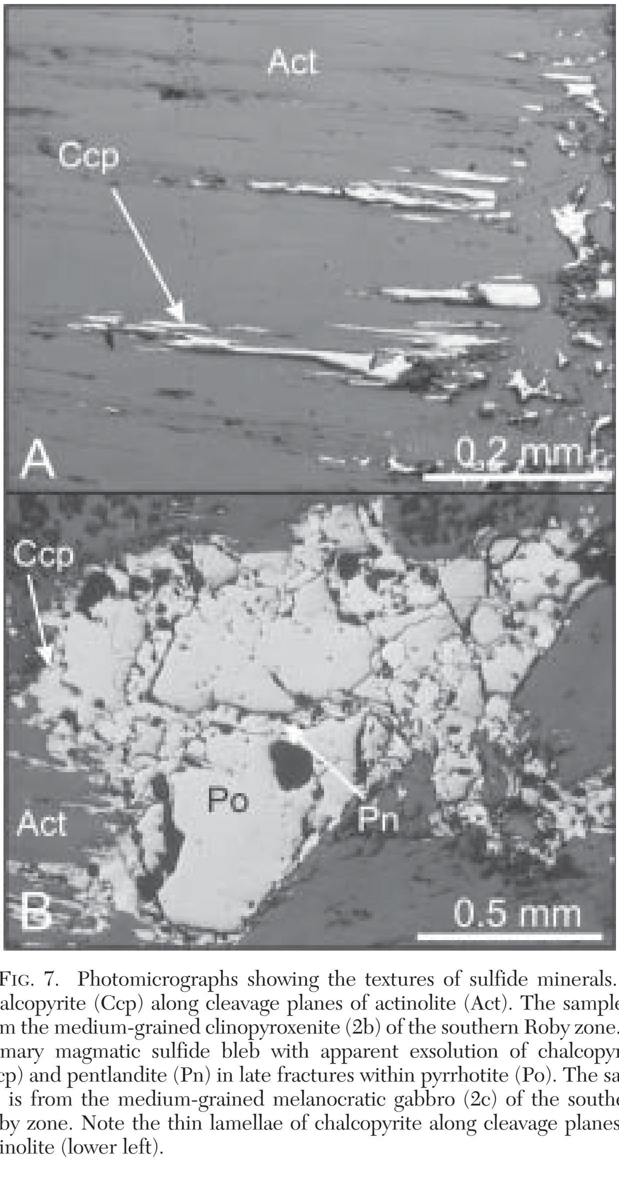

FIG. 7. Photomicrographs showing the textures of sulfide minerals. A. Chalcopyrite (Ccp) along cleavage planes of actinolite (Act). The sample is from the medium-grained clinopyroxenite (2b) of the southern Roby zone. B. Primary magmatic sulfide bleb with apparent exsolution of chalcopyrite (Ccp) and pentlandite (Pn) in late fractures within pyrrhotite (Po). The sample is from the medium-grained melanocratic gabbro (2c) of the southern Roby zone. Note the thin lamellae of chalcopyrite along cleavage planes of actinolite (lower left).

specimens, has been described in the field as melanocratic. However, it contains less than 60 vol percent of ferromagnesian minerals (40–60 vol % clinopyroxene, <5 vol % orthopyroxene). Disseminated, blebby sulfides (1–5 vol %), 1 to 5 mm in size, consist of intergrown pyrrhotite, chalcopyrite, pentlandite, and pyrite (Fig. 7B). Chalcopyrite is commonly observed along cleavage planes of secondary actinolite. The gabbro has an equigranular to orthocumulate texture with local adcumulus clinopyroxene. Cumulus phases are dominated by subhedral clinopyroxene (1–5 mm) and minor plagioclase, and the intercumulus material consists of plagioclase with minor clinopyroxene and orthopyroxene.

Pegmatite (2d): Pegmatite occurs as dikes and pods and is composed of coarse-grained plagioclase and clinopyroxene. Isolated pods of pegmatite on the surface are commonly connected to large pods of pegmatite through veinlets. The cores of the pods are commonly quartz rich and contain minor biotite, magnetite, ilmenite, pyrite, and traces of chalcopyrite. The sulfide aggregates commonly enclose fine-grained (<0.5-mm) calcite.

Late-stage intrusions (group 3)

Postmineralization intrusions include (3a) medium-grained, sulfide-free clinopyroxenite and (3b) medium-grained, salt-and-pepper-textured gabbro. The clinopyroxenite cuts earlier leucocratic rocks (group 1) and commonly displays magma mingling with the earlier clinopyroxenite (2b). The clinopyroxenite (3a) and gabbro (3b) display a cumulate texture and are altered with uralization of clinopyroxene and sericitization of plagioclase.

Intrusions unrelated to the Lac des Iles complex

Late intrusions that cut rocks of the southern Roby zone are felsic and diabase dikes. The felsic dikes are several centimeters to 1 m in width with random orientations and range in composition from tonalite to granodiorite. The dikes are commonly accompanied by narrow (<5-cm) symmetrical alteration halos with reddish K-feldspar. Very fine grained diabase dikes, ranging from a few centimeters to 1.5 m in width, cut all rock types.

Contact relationships between different rock types

The contacts between the early leucocratic rocks of group 1 and the melanocratic rocks of group 2 are well exposed on the outcrop. The latter contains fragments of leucocratic gabbro of group 1 (Fig. 6A) and also intruded the partially solidified leucocratic rocks, developing magma-mingling structures (Fig. 6B). This suggests that mafic magmas intruded prior to the solidification of the earlier magmas, which produced the leucocratic rocks. Varitextured and pegmatitic phases (rock type 2d) are commonly developed near the contact between groups 1 and 2, suggesting the release of aqueous fluids from the magmas that produced the melanocratic rocks.

Hydrothermal alteration

All rocks show some degree of alteration, especially melanocratic rocks which are pervasively altered, but rocks adjacent to the Roby zone, including those of the Twilight zone and East Gabbro, are not altered. Although minor faults occur in the southern Roby zone, as observed by Michaud (1998), alteration is not controlled by these faults. The alteration most likely took place at high temperatures and was possibly related to aqueous fluids released from the magmas for the melanocratic rocks. This interpretation is supported by abundant pods and veins of pegmatite associated with the melanocratic rocks.

The High-Grade zone within the Roby zone is composed of intensely altered medium-grained melanogabbro and pyroxenite, similar to the melanocratic rocks of group 2 in the southern Roby zone. Primary minerals are entirely replaced by secondary amphiboles, talc, anthophyllite, chlorite, sericite, and calcite. The occurrence of blue quartz is also common. Sulfide minerals are dominated by pyrite (up to 10 vol %), with lesser amounts of pyrrhotite, chalcopyrite, and pentlandite.

Petrology of the Twilight Zone

The Twilight zone (Fig. 8) is dominated by noritic and/or gabbronoritic intrusions, which are divided into three types, following from the rock types recognized in the southern Roby zone: (4) leuconorite and/or gabbronorite, (5) medium-brown norite and/or gabbronorite, and (6) sulfide-bearing melanonorite and/or gabbronorite. Minor phases include (7) anorthosite, (8) gabbro, (9) melanogabbro and/or clinopyroxenite, and (10) fine-grained gabbro. Late felsic and diabase dikes, similar to those in the Roby zone, are also present in the Twilight zone. They cut all other rock types and are not related to the Lac des Iles intrusive complex. This zone also has complex structures but alteration is not as intense and pervasive as in the Roby zone. Orthopyroxene has been variably replaced by talc and magnetite, clinopyroxene by actinolite, and plagioclase by sericite.

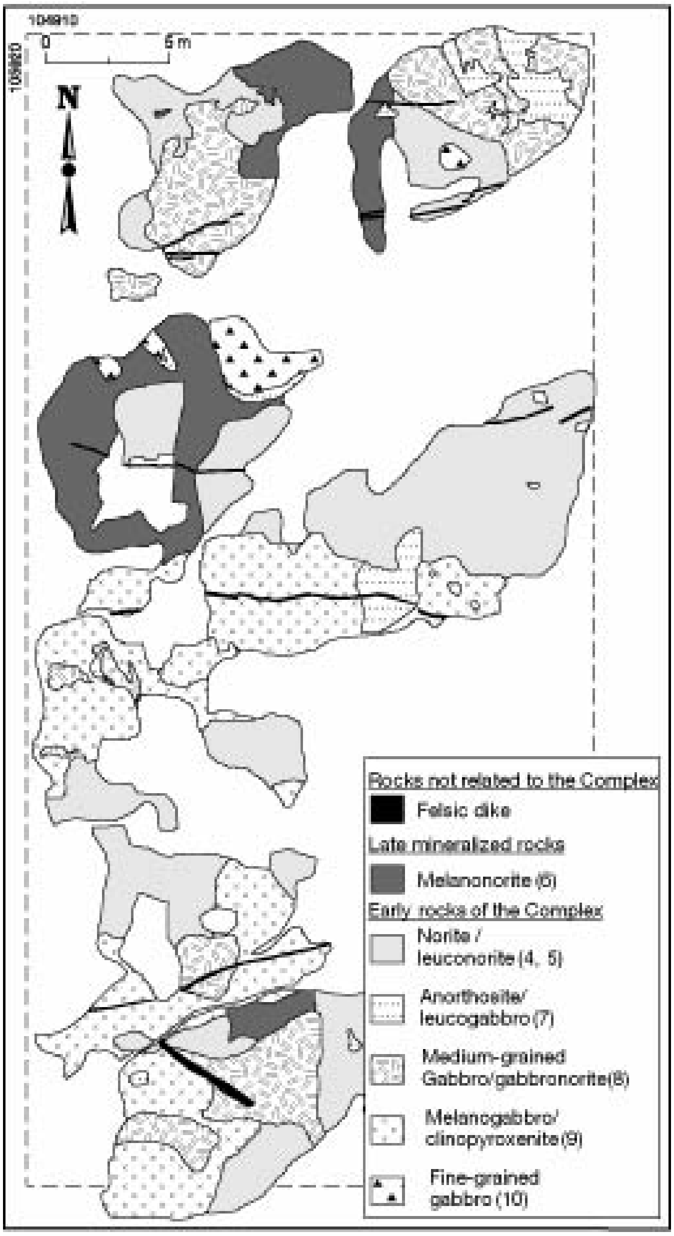

FIG. 8. Illustration of the complicated distribution of different rock types in the Twilight zone based on the 1:120 scale mapping by Hinchey et al. (2003). Dashed lines show the mine grid. The numbers in parentheses after rock names correspond to the rock types in the text. The mineralized melanonorite (6) is the latest rock type of the Lac des Iles intrusive complex in the outcrop. It shows the intrusive contacts with fine-grained gabbro (10), leuconorite (4), norite (5), and medium-grained gabbro (8).

All noritic and/or gabbronoritic intrusions (rock types 4–6) are medium grained with granular, orthocumulate textures and are relatively unaltered. The early leuconorite (4) and the medium-brown norite (5) are very similar in texture and mineralogy. The leuconorite and/or gabbronorite (4) consists of subhedral to euhedral cumulus orthopyroxene (2–4 mm, 20–30 vol %), equigranular plagioclase (60–70 vol %), and intercumulus clinopyroxene (<10 vol %). The medium-brown norite and/or gabbronorite (5) contain equal amounts of cumulus orthopyroxene and intercumulus plagioclase. Other minor intercumulus phases (<10 vol %) are clinopyroxene and biotite. Disseminated aggregates of sulfide and oxide (<1–2 vol %) occur in both rock types where they are in contact with melanonorite and/or gabbronorite (6), including intergrown pyrrhotite, chalcopyrite, and pentlandite, and rounded magnetite. Orthopyroxene crystals in both the early leuconorite (4) and the medium-brown norite (5) are locally poikilitic, containing smaller crystals of pyroxene and plagioclase. Some of the orthopyroxene crystals contain exsolution lamellae of clinopyroxene (inverted pigeonite).

The mineralized melanocratic norite and/or gabbronorite (6) have a texture similar to other norite and/or gabbronorite although it is rich in sulfides. This rock consists of subhedral to euhedral cumulus orthopyroxene (3–10 mm, 70–95 vol %), intercumulus plagioclase (5–30 vol %), intercumulus clinopyroxene (<10 vol %), minor biotite, and interstitial blebby sulfides and oxides (2–8 vol %). The sulfides consist of intergrown pyrrhotite, chalcopyrite, and pentlandite and oxides are magnetite and ilmenite. As in the other noritic and/or gabbronoritic rocks, clinopyroxene occurs as an exsolved phase in orthopyroxene (inverted pigeonite). Minor amounts of chalcopyrite and magnetite occur along the cleavage of secondary amphiboles.

Contact relationships of different rocks

The three noritic and/or gabbronoritic rocks display breccia and magma-mingling structures (Fig. 6C). Matrix and clast relationships indicate that the leucocratic norite and/or gabbronorite (4) is the earliest and that the melanocratic norite and/or gabbronorite orthopyroxene (6) is the youngest. The magma-mingling structures suggest that successive intrusions occurred while earlier intrusions were not completely solidified.

Anorthosite (7), gabbro (8), and melanogabbro and/or clinopyroxenite (9) were contemporaneous with the norite and/or gabbronorite (5). These rocks commonly occur as fragments in a matrix of norite and/or gabbronorite. Fragments of gabbro and anorthosite are especially common in the northern part of the Twilight zone. These rocks are medium grained, moderately to intensely altered, and free of sulfide.

The south-central portion of the Twilight zone is dominated by late, medium-grained melanogabbro and/or clinopyroxenite (9), which produces breccias containing fragments of norite, gabbronorite, and gabbro. The breccias and intrusions contain irregularly shaped pods and veins of pegmatite, which consist of plagioclase, pyroxene, quartz, magnetite, and sulfide dominated by pyrite. The rocks are more intensely altered than the volumetrically dominant norite and/or gabbronorite. Alteration has produced actinolite after clinopyroxene, and chlorite and sericite after intercumulus clinopyroxene and plagioclase. These rocks commonly contain blebs (up to 5 vol %) that consist of pyrrhotite, chalcopyrite, pentlandite, and minor magnetite. The textures and alteration are very similar to those of the melanogabbro and clinopyroxenite of the southern Roby zone.

Geochemistry of Mineralized Zones

Sampling and analytical methods

Samples representing various rock types were collected from the southern Roby and Twilight zones following detailed mapping. Samples of the High-Grade zone were collected from the pit. Major and minor elements were determined on fused disks using a Philips PW 2400 X-ray fluorescence spectrometer at the University of Ottawa. For samples with high Cu content, LiBr was added to prevent the fused glass from sticking to the Pt crucible. Precision based on 11 replicate runs was 0.35 percent for Al_2O_3, 0.48 percent for MgO, 3.7 percent for Sr, 1.3 percent for Cr, and 9.2 percent for Ni. The accuracy, which was monitored using international references MRG-1 and Sy-2, was within 0.039 percent for Al_2O_3, 0.28 percent for MgO, 3.5 percent for Sr, 3.4 percent for Cr, 4.0 percent for Ni, and better than 1 and 10 percent for other major and minor elements, respectively. Loss of ignition was determined after heating samples at 1,050°C for over 1 h. Sulfur contents were determined using an elemental analyzer (Carlo Erba 1110) at the University of Ottawa. Precision based on nine runs of one sample was 5.4 percent, and the accuracy based on a set of references was 1.4 percent. Blank samples yielded less than the detection limit of sulfur (0.001 wt %).

The concentrations of Ir, Os, and Ru were determined at the University of Ottawa by an isotope dilution technique using a solution enriched in ^{191}Ir, ^{190}Os, and ^{99}Ru. The analytical procedure was essentially identical to that described in Guillot et al. (2000). Precious metals in 3-g samples mixed with 6 g of $Na_2B_4O_7$ were concentrated into a Ni sulfide bead at 1,050°C. The bead was dissolved in HCl, and the insoluble residue was dissolved in HNO_3 before isotope ratio measurements using an inductively coupled plasma-mass spectrometry (ICP-MS; model HP-4500). Blank contributions of Ir, Ru, and Os, mostly from the Ni powder, were 0.005, 0.011, and 0.008 ng/g of flux, respectively, and less than 1 percent of the concentrations of the metals in the samples. Gold, Pt, Pd, and Rh were determined by a Pb collection fire assay followed by an ICP-MS analysis on 30-g sample splits at Acme Analytical Laboratories Ltd. in Vancouver, with detection limits of 1, 0.1, 0.5, and 0.05 ppb, respectively. Precision and accuracy of the analysis based on nine replicate analyses of a reference were 4.50 and 9.2 percent for Au, 0.61 and 2.03 percent for Pt, 0.49 and 4.68 percent for Pd, and 16.4 percent and an undetermined accuracy for Rh. The concentrations of REE and other trace elements were determined at Acme Analytical Laboratories Ltd., using ICP-MS after digesting samples with HNO_3-$HClO_4$-HF-HCl. Acid digestion technique rather than fusion technique was selected because of lower detection limits for many elements and because of the lack of refractory minerals in the samples. The precision of the REE analyses based on four replicates was mostly better than 10 percent, but the analyses of samples with concentrations close to the detection limits had precisions of only 28 percent. The precision and accuracy of REE analyses of reference materials with high concentrations of REE were better than 10 percent. Concentrations of Cu and other chalcophile elements were determined at Acme Analytical Laboratories Ltd. after aqua regia digestion followed by an ICP-MS analysis. The precision and accuracy of the Cu determinations based on replicate analyses were 0.85 and 0.87 percent, respectively.

Compositional variation

In all of the studied rocks, $FeO_{(total)}$ (total Fe expressed as FeO) and MnO concentrations increase with MgO, whereas Al_2O_3, Na_2O, K_2O, and Sr decrease (Fig. 9). The higher concentrations of Al_2O_3, Na_2O, and Sr correspond to greater abundances of plagioclase in the rocks, whereas higher $FeO_{(total)}$ and MgO correspond to greater abundances of pyroxene and oxides in the rocks.

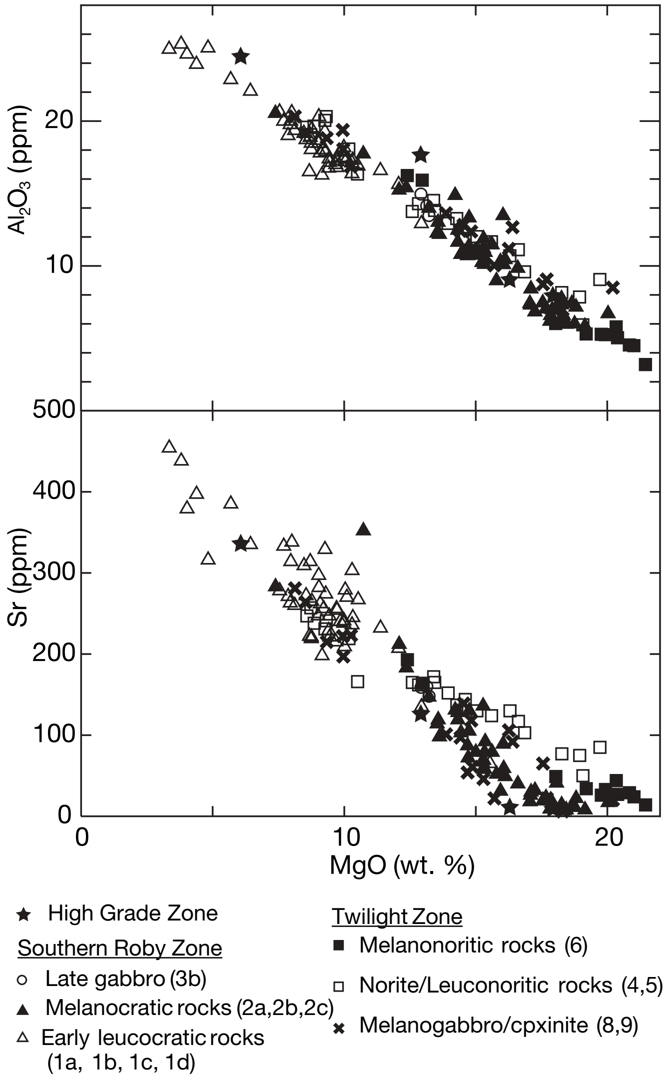

FIG. 9. MgO (wt %) vs. Al_2O_3 (wt %) and Sr (ppm) for whole rocks from the southern Roby, Twilight, and High-Grade zones. Note the well displayed correlations suggesting a common parental origin of all rock types. Numbers in parentheses are rock types in the text.

A positive correlation between Zr and Hf confirms a cogenetic origin for most rocks (Fig. 10; Pearce and Norry, 1979; Lesher et al., 1991; Jenner, 1996). The late clinopyroxenite (3a) has distinctly higher concentrations of incompatible elements than other rocks (not plotted in Figs. 10–20 for clarity), suggesting that this rock type is not related to other igneous rocks in the study area.

Almost all lithologic rock types, except the late clinopyroxenite (3a), show relatively unfractionated REE (Fig. 11). The average values of $(Ce/Yb)_{chondrite}$ for the melanocratic and leucocratic rocks from the southern Roby zone are 1.3 and 1.9, respectively, and the values for the melanonorite and the norite and/or leuconorite of the Twilight zone are 1.0 and 1.5, respectively. The late clinopyroxenite (3a) shows a fractionated REE pattern with overall higher concentrations of REE compared to the other rocks.

The concentrations of Pd, Pt, and Au vary widely within each rock type, but the melanocratic rocks (2a-c, with >14 wt % MgO) generally have higher metal concentrations than the leucocratic rocks (1a-d, with <10 wt % MgO; Fig. 12), suggesting that the bulk of PGE was introduced by the more Mg rich magmas. Within the melanocratic rocks, dark gabbro (2c) has the highest average concentrations of Pd, Pt, and Au, and the clinopyroxenite (2b) has higher concentrations than the melanocratic breccia matrix (2a; Table 1).

All rocks, except in the High-Grade zone, show positive correlations between sulfur and Pd (correlation coefficient r = 0.891), Pt (r = 0.907), and Ni (r = 0.901; Fig. 13). Although the rocks from the Roby zone have higher concentrations of metals than those of the Twilight zone, the two sets of data show the same positive correlations (Fig. 13), suggesting that the bulk of the PGE in these zones are associated with sulfide. This is further supported by a positive correlation between precious metals and Cu (Pd vs. Cu, r = 0.89; not plotted). The minor scatter between sulfur and Ni is most likely related to the Ni present in silicate minerals, such as pyroxene, as shown by the elevated Ni concentrations in sulfur-free

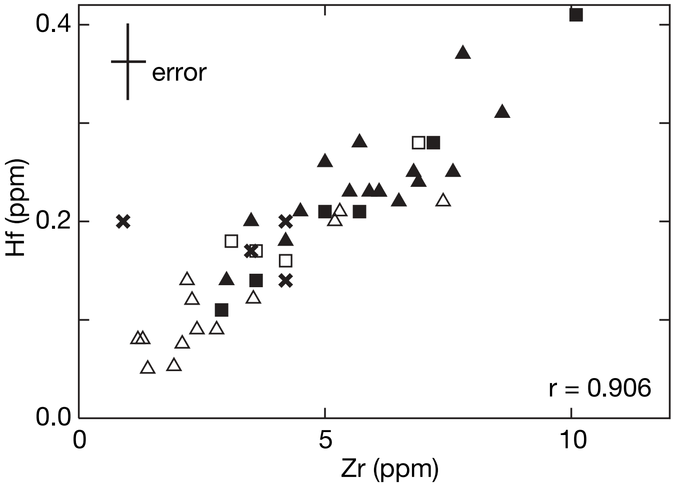

FIG. 10. Hf vs. Zr concentrations for the rocks from the southern Roby, Twilight, and High-Grade zones. Note the well displayed correlation suggesting a cogenetic origin of all rock types. See legend in Figure 9. Correlation coefficient (r) is shown in the lower right and error bars in 2σ are given in the upper left of the diagram.

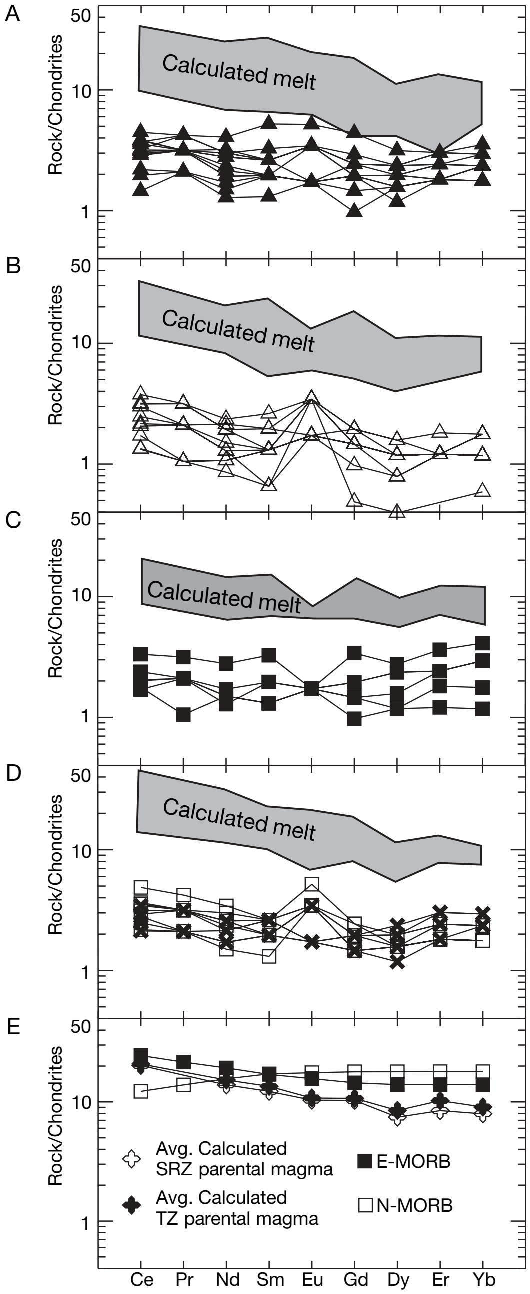

FIG. 11. Chondrite-normalized rare earth element (REE) plots for a variety of rocks: (A) the melanocratic rocks and (B) the leucocratic rocks from the southern Roby zone, (C) the melanonorite and (D) norite and/or leuconorite rocks from the Twilight zone, and (E) normal and enriched midoceanic ridge basalts (N- and E-MORB, respectively) compared to the hypothetical parental melt for the rocks in the southern Roby and Twilight zones. The composition of the hypothetical melt was calculated following the method of Bédard (1994). Note the low degrees of REE fractionation for both the bulk rocks and calculated melt. The calculation of the composition of the hypothetical melt used CIPW normative minerals of plagioclase, clinopyroxene, orthopyroxene, and olivine. The remaining is attributed to a trapped melt fraction. Using the REE concentrations of bulk rocks, the modal abundance of minerals, and partition coefficients of the minerals and melt, the concentrations of REE in different phases were calculated using mass balance. We used the concentration of REE in clinopyroxene and the partition coefficients between clinopyroxene and melt listed in Bédard (1994) to calculate the REE concentrations of the parental melt. Chondrite and MORB values are from McDonough and Sun (1995), and Sun and McDonough (1989), respectively.

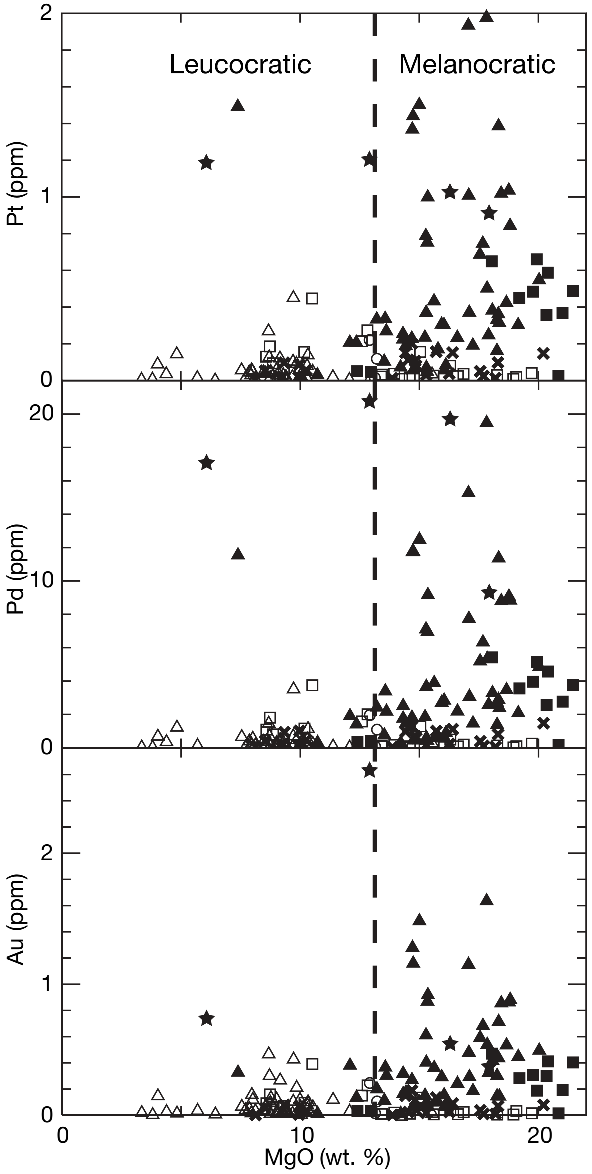

FIG. 12. Bivariate plots of MgO (wt %) vs. Au, Pd, and Pt (ppm). Note the high concentrations of precious metals in the melanocratic rocks in the southern Roby and Twilight zones. The dashed line broadly separates the melanocratic from the leucocratic rocks.

rocks (Fig.13). The scatter of Pt and Pd in Figure 13 may be explained by the subsolidus mobility of PGE or by nugget effects of PGM. Although we do not discount the mobility of PGE by hydrothermal fluids, the variation of PGE concentrations in Figure 13 is most likely due to the presence of discrete PGM. Mineralogic studies carried out by Watkinson and Dunning (1979) and Edgar and Sweeny (1991) showed that the bulk of the PGE in the ore form discrete PGM.

Primitive mantle-normalized plots of Ni, Cu, and PGE in mineralized rocks show low Ni, Os, Ir, and Ru compared to Cu, Rh, Pt, Pd, and Au (Fig. 14). The High-Grade zone samples have slightly higher ratios of platinum-group PGE (Pt-PGE) to iridium-group PGE (Ir-PGE) than other samples (Fig. 14). The Pt-PGE include Pt, Pd, and Rh and the Ir-PGE

TABLE 1. Representative Whole-Rock Major and Trace Element Compositions of Various Rock Types from the Southern Roby, Twilight, and High-Grade Zones

Rock type[1]	Leucogab	Varitextured gabbro		M.g. gabbro		Light gabbro		Melanogabbro		Clinopyroxenite		Dark gabbro		Pyx/mgab.	Leuconor.	Norite		Melanonorite		Mgab.
Unit	1a	1b		1c		1d		2a		2b		2c		n/a	4	5		6		9
Sample no.	JH02-012	JH02-006	JH02-016	JH02-079	JH02-121	JH02-136	JH02-141	JH02-037	JH02-140	JH02-138	JH02-089	JH02-144	JH02-146	JH-02-SZ1	JH02-183	JH02-159	JH02-165	JH-02-181	JH02-173	JH02-186
Location	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	SRZ	HGOZ	TZ	TZ	TZ	TZ	TZ	TZ
(wt %)																				
SiO_2	52.08	50.12	51.45	50.58	49.53	51.58	51.42	48.54	47.58	47.84	50.43	49.79	48.43	48.00	49.83	49.47	51.68	50.94	51.25	50.16
TiO_2	0.05	0.07	0.07	0.08	0.09	0.09	0.12	0.22	0.14	0.19	0.25	0.18	0.17	0.16	0.15	0.19	0.25	0.34	0.26	0.21
Al_2O_3	24.62	17.00	17.15	19.99	19.35	18.02	17.39	10.80	10.43	5.97	7.11	10.81	10.76	7.93	19.65	13.27	11.89	5.30	5.04	12.83
CaO	10.01	10.52	11.66	10.11	9.53	10.01	9.85	7.91	6.57	7.24	9.59	7.48	7.48	8.50	10.35	7.09	7.07	4.95	3.81	7.48
K_2O	0.77	0.49	0.71	0.76	0.76	0.80	0.74	0.34	0.56	0.05	0.22	0.64	0.94	0.05	0.24	0.19	0.18	0.11	0.06	0.67
MgO	4.03	9.68	9.45	7.70	8.12	9.22	9.43	14.44	15.34	18.44	18.07	15.00	14.71	17.93	8.86	14.28	14.60	19.20	20.39	14.54
MnO	0.06	0.13	0.12	0.10	0.11	0.13	0.15	0.20	0.19	0.24	0.22	0.23	0.22	0.20	0.12	0.18	0.21	0.26	0.24	0.17
Na_2O	4.24	2.37	2.29	2.97	3.16	2.52	2.55	1.57	0.93	0.23	0.79	0.92	0.93	0.28	1.91	1.24	1.20	0.38	0.33	1.28
P_2O_5	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.02	0.02
$FeO_{(total)}$	3.66	6.22	5.61	5.17	5.87	6.62	6.94	10.36	10.74	13.26	10.92	12.51	11.55	13.79	7.73	10.61	12.52	16.64	16.52	10.23
S	0.23	0.07	0.06	0.05	0.07	0.08	0.01	0.60	0.67	1.35	0.82	1.25	1.02	2.27	0.12	0.03	0.10	0.67	0.57	0.04
L.O.I.	1.28	0.85	1.05	1.17	1.58	2.14	2.10	2.73	2.68	3.52	3.60	3.81	3.95	4.65	0.77	0.07	0.65	1.41	1.80	3.23
(ppm)																				
Sc	8.3	27.3	29.1	19.3	24.2	27.2	29.5	43.6	27	39.8	38.3	35.5	34.2	n/a	21.1	27.7	30	45.9	44.1	29.5
Cr	63	215	154	119	140	129	157	310	370	516	890	313	310	585	297	519	435	598	683	485
Ni	658	333	340	386	336	294	352	974	1,530	2,080	1,840	3,090	3,080	2,300	417	467	481	1,390	1,740	538
Cu	860	110	130	330	260	190	200	1,360	2,390	3,430	2,290	3,900	3,440	2,540	540	60	80	1,810	2,270	120
Rb	5.6	11.5	18.6	15.2	17.3	24.3	21.7	8.3	18.2	1.7	4.2	17	29.4	n/a	4.6	5.5	4.6	3.9	1.1	19.4
Y	0.5	1.7	1.7	1.6	1.6	1.7	2.2	3.5	2.5	3.1	5.1	2.7	2.5	n/a	2	2.2	2.9	4.2	3.3	2.8
Zr	1.4	1.2	1.3	2.4	2.3	2.8	5.2	5.5	6.5	6.1	7.8	5.9	6.1	8	4.2	3.6	6.9	10.1	5.7	0.9
La	1	<0.1	1	1	1	1	1	1	1	<0.1	1	1	1	n/a	2	1	1	1	1	<0.1
Ce	1.05	0.81	0.82	1.26	1.95	1.32	1.92	2.19	1.82	1.2	1.98	1.76	1.9	n/a	1.91	1.33	2.17	2.04	1.23	2.11
Pr	0.1	0.1	0.1	0.2	0.3	0.2	0.3	0.3	0.3	0.2	0.4	0.3	0.3	n/a	0.3	0.2	0.3	0.3	0.2	0.3
Nd	0.4	0.5	0.5	0.6	0.9	0.6	0.9	1.3	1.1	0.7	1.9	1	0.9	n/a	1.1	0.7	1.4	1.3	0.8	1.2
Sm	0.1	0.2	0.2	0.1	0.2	0.2	0.3	0.4	0.3	0.3	0.8	0.3	0.3	n/a	0.3	0.2	0.4	0.5	0.3	0.4
Eu	0.2	0.1	0.1	0.1	0.2	0.1	0.2	0.2	0.1	0.1	0.3	0.1	0.1	n/a	0.2	0.2	0.2	0.1	0.1	0.2
Gd	0.1	0.2	0.3	0.3	0.3	0.3	0.4	0.5	0.3	0.4	0.9	0.4	0.4	n/a	0.3	0.3	0.5	0.7	0.4	0.4
Tb	<0.1	0.1	<0.1	<0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	n/a	0.1	0.1	0.1	0.1	0.1	0.1
Dy	0.1	0.2	0.3	0.3	0.2	0.3	0.4	0.6	0.4	0.5	0.8	0.5	0.4	n/a	0.4	0.4	0.5	0.7	0.6	0.5
Ho	<0.1	0.1	0.1	<0.1	<0.1	0.1	0.1	0.1	0.1	0.1	0.2	0.1	0.1	n/a	0.1	0.1	0.1	0.2	0.1	0.1
Er	<0.1	0.2	0.2	0.2	0.2	0.2	0.2	0.5	0.3	0.3	0.5	0.3	0.3	n/a	0.3	0.3	0.4	0.6	0.4	0.4
Tm	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.1	0.1	0.1	0.1	<0.1	n/a	<0.1	<0.1	0.1	0.1	0.1	<0.1
Yb	0.1	0.2	0.2	0.2	0.2	0.2	0.3	0.5	0.4	0.4	0.6	0.4	0.3	n/a	0.3	0.3	0.4	0.7	0.5	0.4
Lu	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.1	0.1	0.1	0.1	0.1	0.1	n/a	<0.1	0.1	0.1	0.1	0.1	0.1
Hf	0.05	0.08	0.08	0.09	0.12	0.09	0.2	0.23	0.22	0.23	0.37	0.23	0.23	n/a	0.16	0.17	0.28	0.41	0.21	0.2
(ppb)																				
Au	146	12	10	39	32	20	42	174	868	855	416	1,480	1,280	372	44	3	12	282	411	24
Pt	88	19	3	9	9	1	4	190	752	1,020	382	1,500	1,370	912	94	8	17	449	587	112
Pd	670	41	7	30	141	11	37	1,460	6,940	8,790	3,280	12,480	11,720	9,300	801	26	87	3,560	4,570	1,220
Rh	2.56	0.12	<0.1	<0.1	<0.1	<0.1	<0.1	1.11	4.14	5.22	1.01	6.63	6.76	2.03	0.89	<0.1	0.20	4.96	7.89	1.82
Ru	n/a	n/a	n/a	n/a	n/a	n/a	n/a	1.10	3.77	4.49	n/a	6.13	5.35	4.25	n/a	n/a	n/a	3.90	5.10	n/a
Os	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.41	1.42	1.50	n/a	2.21	1.99	1.66	n/a	n/a	n/a	1.05	1.32	n/a
Ir	n/a	n/a	n/a	n/a	n/a	n/a	n/a	0.26	0.88	1.05	n/a	1.40	1.18	1.28	n/a	n/a	n/a	0.77	1.06	n/a

Notes: Major element, Cr, and Ni data by X-ray fluorescence; S data by elemental analyzer; L.O.I. data determined after heating samples to 1,050oC for over 1 h; Cu data by aqua regia digestion with inductively coupled plasma mass-spectrometry; Au, Pt, Pd, and Rh data by Pb collection fire assay inductively coupled plasma-mass spectrometry; Ir, Os, Ru data by isotope dilution followed by inductively coupled plasma-mass spectrometry; remaining trace element data by four acid inductively coupled mass spectrometry

[1] leucogab = leucogabbro, leuconor = leuconorite, mgab = melanogabbro, m.g.gabbro = medium-grained gabbro, pyx = pyroxenite; HGOZ = High-Grade ore zone, SRZ = southern Roby zone, TZ = Twilight zone; L.O.I. = loss on ignition, n/a = not analyzed, FeO(total), T = total Fe expressed as FeO

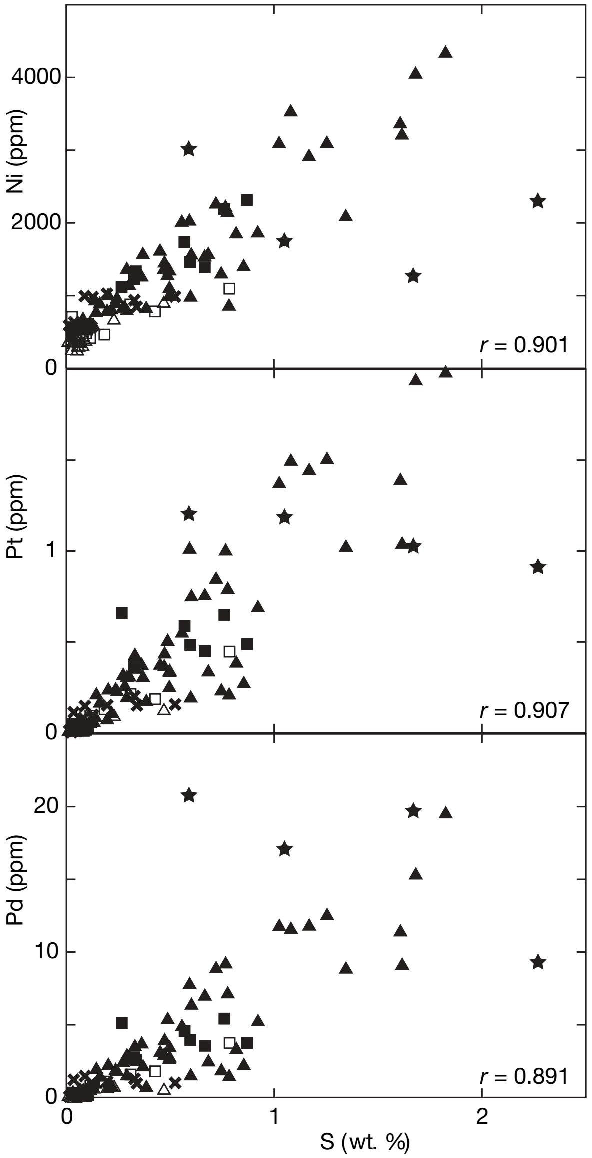

FIG. 13. Bivariate plots of sulfur (wt %) vs. Ni, Pt, and Pd (ppm). Note the positive correlations, suggesting a sulfide control on mineralization. Elevated Ni concentrations in samples without sulfides suggest the presence of minor Ni in silicate minerals. Preliminary electron microprobe data confirm that clinopyroxene contains significant Ni. Correlation coefficients (*r*) are calculated for samples, excluding the High-Grade zone.

include refractory Ir, Os, and Ru. This is also illustrated by the low Ir/Pd, with an average value of 1.5 × 10^{-4} (Fig. 15A).

Element mobility during alteration and metamorphism

The total concentrations of REE and Zr show a positive correlation (Fig. 16A), suggesting that REE acted as immobile elements during alteration. In contrast, considerable scatter is evident in the plot of Rb versus Zr (Fig. 16B), as expected for a mobile alkali element. The immobile behavior of the REE is further supported by the similar, relatively flat patterns of chondrite-normalized REE for all rocks, regardless of the intensity of alteration (Fig. 11). As light REE are more soluble in fluids than heavy REE, this pattern would have been modified during alteration.

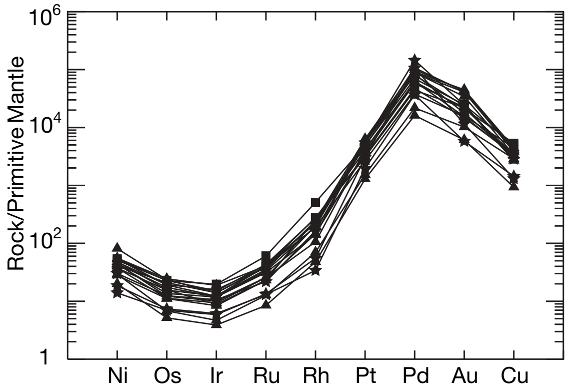

FIG. 14. Primitive mantle-normalized plot for Ni, Cu, and PGE of the southern Roby, Twilight, and High-Grade zones. The data have been recalculated to 100 percent sulfide following Naldrett (1981). Note similar patterns for all rocks with low concentrations of Ni, Ir, Os, and Ru and high concentrations of Cu, Rh, Pt, and Pd. Primitive mantle values for Ni and Cu are from McDonough and Sun (1995) and PGE values from Guillot et al. (2000).

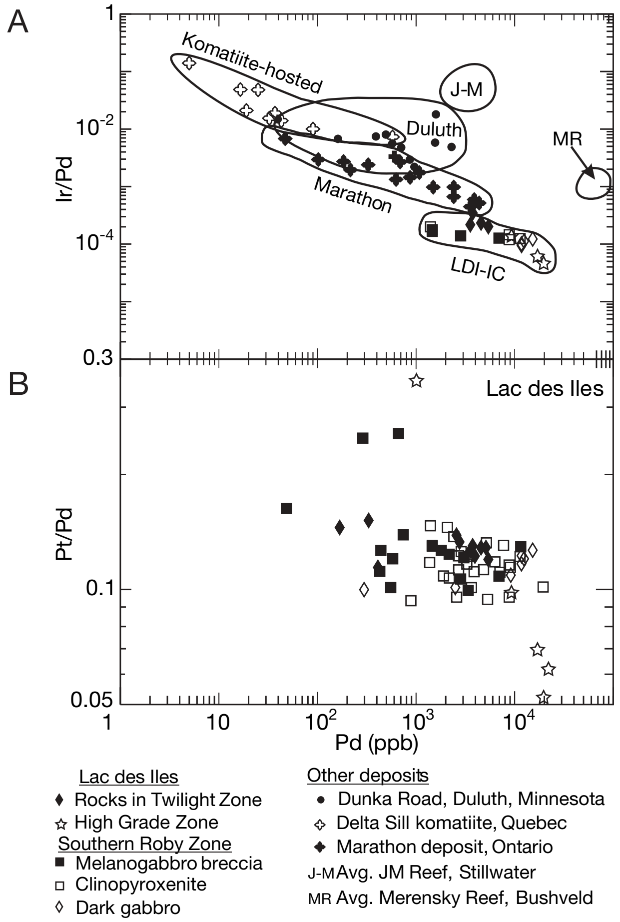

FIG. 15. A. Plot of Pd (ppm) vs. Ir/Pd for samples from the southern Roby, Twilight, and High-Grade zones compared to other PGE deposits. Note that the Lac des Iles data plots along the general trend of other orthomagmatic deposits. B. Plot of Pd (ppm) vs. Pt/Pd for rocks from the Lac des Iles deposit. Note that the majority of the melanocratic rocks show comparable Pt/Pd ratios, but samples from the High-Grade zone have higher Pd and therefore low Pt/Pd. The scatter is most likely due to a nugget effect of coarse-grained platinum group minerals. Data sources: Komatite-hosted deposits (Picard et al., 1995); Marathon deposit in the Coldwell Complex, Ontario (Good and Crocket, 1994); Duluth Complex (Theriault et al., 1997); J-M reef (J-M: Naldrett, 1981); Merensky reef, Bushveld Complex (M: Naldrett, 1981).

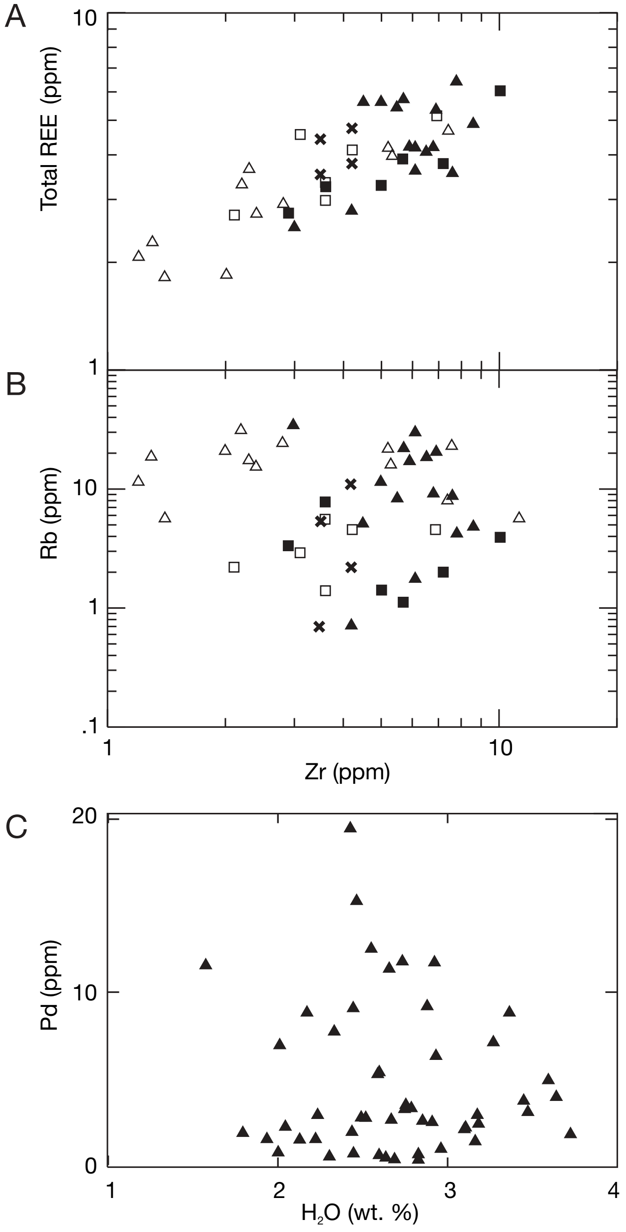

FIG. 16. A. Plot of total REE vs. Zr for all rock types. Zirconium is an incompatible and immobile element. The positive correlation suggests that the REE were also immobile. B. Plot of Rb vs. Zr, illustrating that Rb acted as a mobile element during alteration. C. Plot of H_2O (wt %) vs. Pd (ppm) for variably altered melanocratic rocks of the southern Roby zone. The lack of any positive correlation suggests that aqueous fluid likely was not important in the concentration of Pd.

Discussion

Parental magma composition

Most rocks of the study area are cumulates and the bulk chemical compositions do not represent those of their parental magmas. Therefore, we calculated the compositions of parental melt following the method described by Bédard (1994). This method requires the primary mineralogy of rocks. Due to the variable degree of alteration in the rocks, we used CIPW normative minerals of plagioclase, clinopyroxene, orthopyroxene, and olivine in the calculation. The remaining fraction is assigned as a trapped melt, which ranged up to 12 wt percent, with an average of 9.5 wt percent.

The REE in the calculated parental melt for each rock type showed relatively flat normalized patterns, about 10 to 15× chondrite values (Fig. 11). The primary melt would have contained less than the calculated values because the magmas were enriched in REE through fractional crystallization of chromite and olivine that do not incorporate REE. The average $(\mathrm{Ce/Yb})_{\mathrm{chondrite}}$ for the parent magmas of the melanocratic and leucocratic rocks in the southern Roby zone are 2.4 and 2.5, respectively, whereas the average values for the melanonorite and the norite and/or leuconorite of the Twilight zone are 1.7 and 2.6, respectively.

Light REE are preferentially incorporated into a melt during partial melting. The relatively unfractionated REE patterns of our samples suggest that the source was a moderately refractory mantle where previous partial melting resulted in lower light REE than heavy REE. This interpretation is further supported by the similarity between the calculated concentrations and patterns of REE in the parental melts and enriched midoceanic ridge basalts. The melt for typical oceanic ridge basalts forms through relatively high degrees of partial melting in the moderately depleted mantle (e.g., Saunders, 1984).

The MgO content of the parental melt of the melanocratic rocks is calculated to be 8.9 wt percent, using the partition coefficient for MgO between clinopyroxene and melt of Hart and Dunn (1993) and an MgO content of 15.7 wt percent for clinopyroxene in group 2 rocks. The primary melt probably had much higher concentrations of MgO due to fractional crystallization of olivine. For example, 20 percent fractional crystallization of olivine (Fo_{92}) from the melt yields 17.3 wt percent MgO in the original parental melt. Fo_{92} is the composition of olivine in equilibrium with mantle peridotites (e.g., Arai, 1992), but the choice of olivine composition does not significantly affect the result. Therefore, the MgO content of the primary melt was similar to that of picritic or komatiitic basalts which form through high degrees of partial melting in the mantle. We suggest that the primary magmas for the Lac des Iles intrusive complex were most likely products of relatively high degrees of partial melting of a moderately depleted, refractory mantle source. This interpretation is further supported by Nd isotope compositions of the mineralized rocks. Recalculation of $\varepsilon_{\mathrm{Nd}}$ values at 2690 Ma from data obtained by Brügmann et al. (1997) yields values ranging from 1.0 to 1.5 for most rocks in the Mine Block intrusion. The values are similar to the $\varepsilon_{\mathrm{Nd}}$ value of 2 for Late Archean igneous rocks derived from a depleted mantle (e.g., Stern et al., 1989; Hattori et al., 1996).

Sulfur saturation in the parental magma

The ratio of Cu/Pd changes in a magma during sulfide separation because Pd has a higher partition coefficient between sulfide and silicate melt than Cu at a given temperature and f_{O_2} (i.e., ~34,000 vs. 1,400; Peach and Mathez, 1996, Crocket, 2002). Therefore, the ratio of Cu/Pd reflects the timing of sulfur saturation in the silicate magmas (e.g., Barnes et al., 1993). A lower Cu/Pd ratio than that of the primitive mantle implies that there was no early removal of sulfide from the magma. Higher ratios of Cu/Pd imply early removal of sulfide from the magma or the retention of sulfide at the source. Samples from the Lac des Iles complex have a large range of Cu/Pd ratios (Fig. 17). The majority of the melanocratic rocks have lower Cu/Pd than the primitive mantle (Fig. 17), suggesting that there was no early separation of sulfide melt. In contrast, the leucocratic phases have high Cu/Pd, suggesting early removal of sulfide from the magma or that residual sulfide remained in the mantle source.

High Pt-PGE/Ir-PGE in the ore

Mineralized rocks from the southern Roby and Twilight zones have similar primitive mantle-normalized PGE patterns (Fig. 14), suggesting a common origin for the mineralization in these zones. Palladium has a high solubility in aqueous fluids compared to other PGE (e.g., Wood, 2002), but the pattern and ratios of Pt-PGE/Ir-PGE are similar, regardless of the H_2O contents of the rocks, which vary from 0.1 to 5.5 wt percent. There is no correlation between Pd and H_2O (Fig. 16C; high H_2O values not shown), suggesting that aqueous fluids had a limited role in concentrating Pd. In contrast, the samples from the High-Grade zone show extreme enrichment of Pd, as indicated by low Ir/Pd and Pt/Pd ratios (Fig. 15). In addition, there is no correlation between Pd and S. This is consistent with the hydrothermal enrichment of Pd, as suggested by previous workers (Talkington and Watkinson, 1984).

There are two possible processes for mafic magmas to acquire fractionated PGE with high Pt-PGE: low degrees of partial melting and fractional crystallization. Ir-PGE are preferentially incorporated into olivine, chromite, and high-temperature PGM, such as laurite and iridosmine (Puchtel and Humayun, 2001; Andrews and Brenan, 2002; Sattari et al., 2002; Righter et al., 2004). Retention of these minerals in the mantle during low degrees of partial melting results in low Ir-PGE in the melt. This is consistent with low Ir/Pd in gabbro-hosted deposits compared to komatiite-hosted deposits (Fig. 15). Evolved magmas also have fractionated PGE because olivine, chromite, and high-temperature PGE are removed during the early stages of fractional crystallization. We discount low degrees of partial melting of the parental magmas as the cause of high Pt-PGE because this is not consistent with the flat normalized REE patterns and the high MgO contents of the calculated parental magmas. Therefore, high Pt-PGE in our samples is best explained by the removal of Ir-PGE during early crystallization of the magmas.

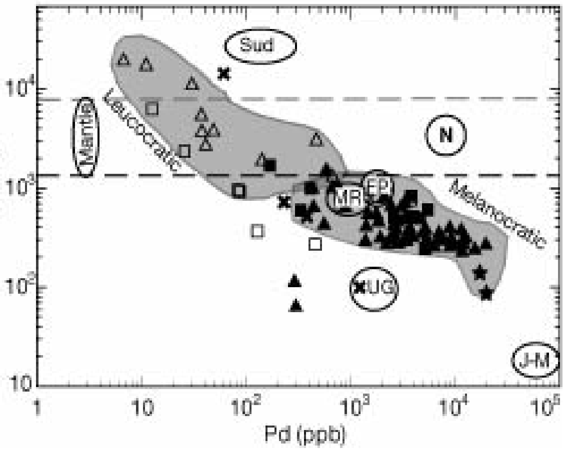

FIG. 17. Pd vs. Cu/Pd plot for samples from the southern Roby and Twilight zones compared to other PGE deposits. Note that the rocks from Lac des Iles show a wide variation in Cu/Pd ratios. The mineralized melanocratic rocks show low Cu/Pd ratios, similar to those for other primary PGE deposits, whereas the barren leucocratic rocks display high Cu/Pd ratios. Abbreviations: JM = JM reef, Stillwater, United States (Barnes and Naldrett, 1985); MR = Merensky reef, Bushveld (Maier et al., 1996) and UG = UG2 reef, Bushveld (Maier and Bowen, 1996), South Africa; N = Noril'sk (Smirnov, 1966), FP = Federov Pansky (Schissel et al., 2002), Russia; Sud = Sudbury, Canada (Naldrett, 1981).

High palladium in the southern Roby and Twilight zones

The average concentration of Pd in the melanocratic rocks, excluding the High-Grade zone, is estimated to be ~4 ppm, on the basis of average grade, tonnage, and abundance (~20 vol %) of mineralized melanocratic rocks in the Roby zone. This is very high compared to average Pd concentrations of basalts (0.46 ppb) and komatiites (~11 ppb; Crocket, 2002). Various processes were suggested for such enrichment of Pd. Watkinson and Dunning (1979) proposed that sulfur, Ni, Cu, and PGE were enriched during evolution of the parental magmas, followed by immiscible separation of Pd-bearing aqueous fluid from the magmas. Talkington and Watkinson (1984) argued for an important role of hydrothermal activity in the mineralization, based on the occurrence of PGM containing Te, As, and Bi and the spatial association of PGM with secondary hydrous minerals and pyrite. Macdonald (1988) also suggested hydrothermal enrichment of PGE by fluids that originated from the parental magmas, also based on the abundant hydrothermal minerals in the mineralized zones. Brügmann et al. (1989) proposed "constitutional zone refining" for the enrichment of Pd and other Pt-PGE relative to Ir-PGE. Constitutional zone refining (McBirney, 1987) involves the formation of volatile-rich magmas through fractional crystallization and partial melting of earlier formed cumulates. Brügmann et al. (1989) suggested that a volatile-rich silicate magma remelted gabbro cumulates and selectively incorporated the Pt-PGE from sulfides in the cumulates, and that the melanocratic and leucocratic rocks in the Roby zone represent the residue and partial melt, respectively. In another model, Lavigne and Michaud (2001) suggested that the mineralization involved the forceful intrusion of a PGE-, Ni- and Cu-rich immiscible sulfide liquid into the partially crystallized overlying magma chamber. Exsolution of aqueous fluids from magmas resulted in the redistribution of precious metals.

Our data, showing positive correlations between sulfur and base and precious metals, are not consistent with hydrothermal concentration of Pd in the southern Roby and Twilight zones. Furthermore, our detailed mapping shows that the bulk of PGE are in late melanocratic rocks. Hydrothermal processes cannot explain the preferential enrichment of Pd in the mafic rocks. Therefore, we discount any significant contributions of hydrothermal fluids to the Pd mineralization in the southern Roby and Twilight zones. However, aqueous fluids may have been responsible for mineralization in the High-Grade ore samples as indicated by the scatter in the plots of sulfur and base and precious metals (see below).

The zone-refining process is also not consistent with our data. First, the zone-refining process produces leucocratic melt and melanocratic and ultramafic rocks as the residue (Brügman et al., 1989). Our detailed mapping shows that melanocratic rocks carry most of the Pd, and leucocratic rocks are essentially barren (Fig. 12, Table 2). Second, the zone-refining process involves partial melting of a cumulate (Brügmann et al., 1989) containing clinopyroxene, orthopyroxene, and a solidified, trapped melt. Partial melting would dissolve the solidified melt first, then clinopyroxene. The solidified melt contains high concentrations of incompatible elements, such as REE, compared to any other phases. Clinopyroxene also contains high concentrations of incompatible elements compared to olivine and orthopyroxene. Therefore, any partial melt should contain elevated incompatible elements compared to earlier rocks. The late clinopyroxenites (3a) are the only rock type with high REE, but these rocks are free of sulfides and barren of Pd. Similar concentrations of REE in all rocks in the southern Roby and Twilight zones (Fig. 11) argue against the zone-refining process. Dissolution of significant amounts of clinopyroxene would have increased the Sc content of the melt, as Sc is preferentially included in clinopyroxene, but this is inconsistent with the similar Sc/Y ratios of all rocks (Fig. 18).

We suggest that Pd in the late melanocratic magmas was enriched by incorporating preexisting sulfide melt formed by earlier magmas. This is consistent with all data, including low Cu/Pd ratios in the ore and high Cu/Pd in earlier leucocratic rocks (Fig. 17). Earlier magmas lost sulfide melt with low Cu/Pd at depth, and later melanocratic magmas incorporated the sulfide melt.

Enrichment of palladium in the High-Grade zone of the Roby zone

Although the High-Grade zone was not the focus of this investigation, it is important because it contains high Pd, ~8 ppm in most samples, and hosts approximately 35 percent of the Pd in the mine. The samples from the High-Grade zone do not plot on the correlation trends of sulfur versus base metals and sulfur versus precious metals (Fig. 13). The data suggest that Pd enrichment in this zone may have been caused by aqueous fluids. This interpretation is supported by abundant quartz aggregates, the lack of exsolution textures in sulfides, and the common occurrence of pyrite.

The High-Grade zone is located on the eastern margin of the Roby zone, adjacent to East Gabbro that is older than the rest of the Mine Block intrusions. The High-Grade zone is adjacent to high-grade breccia ore in the Roby zone (Lavigne and Michaud, 2001), suggesting a genetic link between the two. We propose that aqueous fluid exsolved from late fertile melanocratic magmas migrated into the area of the High-Grade zone. The barren East Gabbro would have acted as a physical barrier for such an aqueous fluid, resulting in precipitation of Pd along the boundary with the East Gabbro. The mineralized zone is subvertical at present, but this steepening probably occurred during the docking of the Quetico accretionary prism and Wawa arc to the Wabigoon subprovince to the north (Percival, 1989).

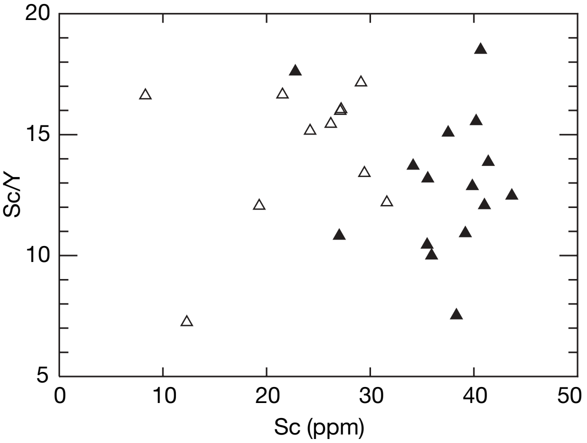

FIG. 18. Sc vs. Sc/Y for samples from the southern Roby zone. Note that the Sc/Y ratios of the melanocratic rocks are similar to or lower than those of the leucocratic rocks.

A model of igneous activity and PGE mineralization at Lac des Iles

This section summarizes the evolution of the southern Roby and Twilight zones, which is illustrated schematically in Figure 19. First, relatively high degrees of partial melting in a moderately depleted mantle formed the parental magmas of early gabbroic rocks. These magmas became enriched in Cu and Pt-PGE during the fractional crystallization of olivine, chromite, and high-temperature PGM. The magmas eventually reached sulfur saturation, forming an immiscible sulfide melt with low Cu/Pd in the conduit, which resulted in high Cu/Pd ratios in the evolving magma. The magmas reached

TABLE 2. Palladium, Platinum, and Gold Concentrations in Various Rock Types in the Southern Roby Zone and Twilight Zone (reported as median, first quartile, and third quartile values in ppb)

			Palladium			Platinum			Gold		
Rock type	Zone	No. of samples	Median	1st q'til	3rd q'til	Median	1st q'til	3rd q'til	Median	1st q'til	3rd q'til
Leucocratic rocks	SRz	55	150	45.9	382	28.6	7.2	55.9	37.5	17.0	103
Melanogabbro (2a)	SRz	16	1,460	554	2,830	190	69.7	302	153	70.0	292
Clinopyroxenite(2b)	SRz	25	3,560	2,460	6,900	402	303	777	441	307	606
Dark Gabbro (2c)	SRz	6	11,700	9,800	12,300	1,400	1,090	1,490	1,150	975	1,250
Norite-Leuconorite	Tz	31	184	84.8	1,120	36.2	21.8	142	24.0	8.5	92.5
Melanogabbro	Tz	17	8,900	267	1,270	109	40.6	155	74.0	24.3	142
Melanonorite	Tz	10	3,560	1,490	4,260	449	204	537	282	110	355

Abbreviations: SRz = southern Roby zone, Tz = Twilight zone

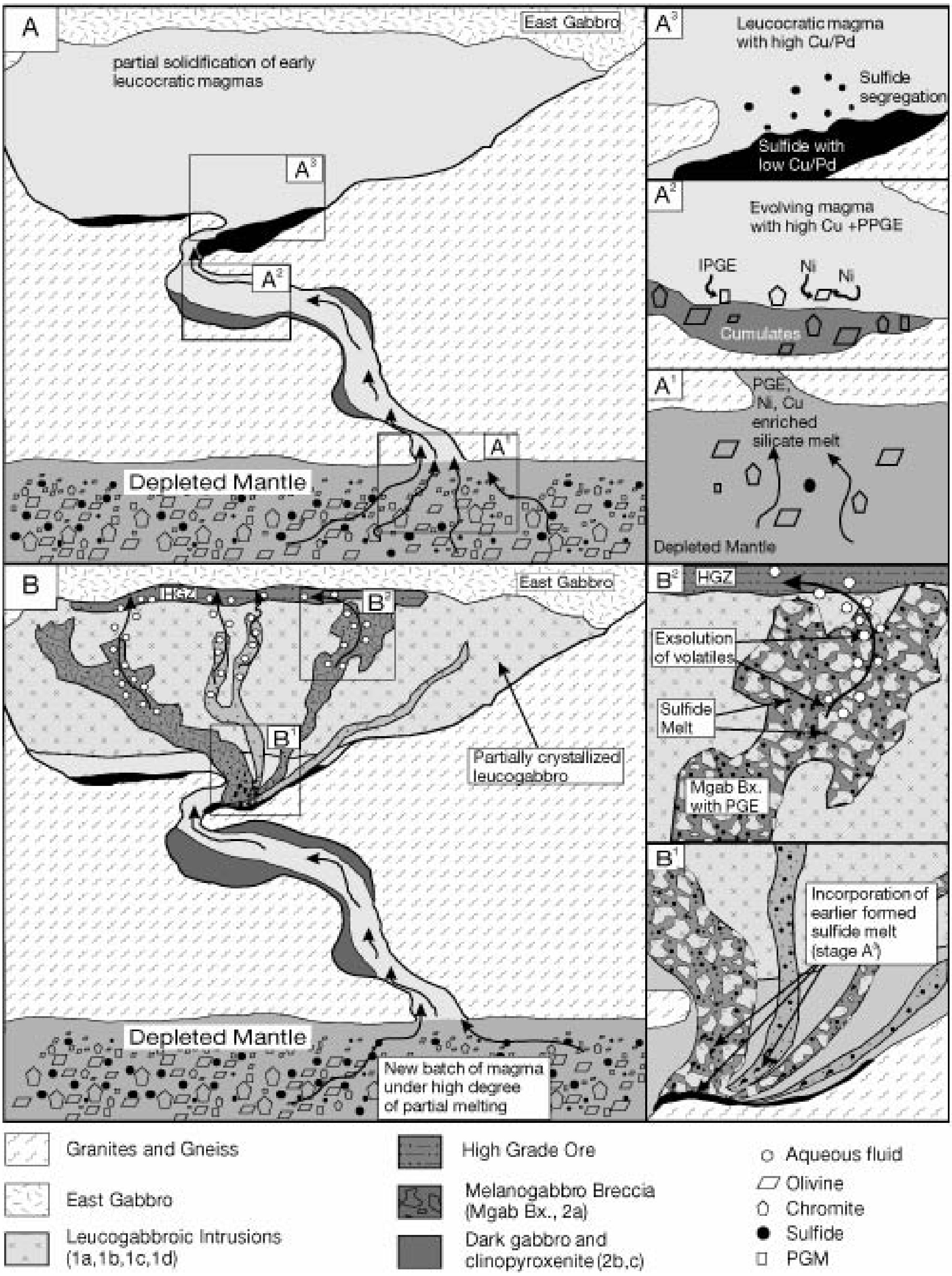

Fig. 19. Schematic model showing the history of mineralization at the southern Roby zone. Magmas formed by a high degree of partial melting in a depleted mantle source (A^1) became enriched in Cu, Pt, and Pd through fractional crystallization of olivine, chromite, and high-temperature PGM (A^2), segregated sulfide melt that had low Cu/Pd ratios along the conduit and the base of the magma chamber (A^3), and solidified as the early leucocratic gabbros. A second episode of partial melting in the mantle source produced another batch of fertile magma. As with the early magma, this magma was enriched in Cu, Pt, and Pd through fractional crystallization (A^2). This magma incorporated the earlier sulfide melt and intruded forcefully into the partially crystallized leucocratic rocks (B^1), causing brecciation and magma mingling, and solidified as fertile melanocratic gabbro. Aqueous fluids that separated from the melanocratic magma percolated through the cumulates, partially dissolving Pd and concentrating it in the High-Grade ore zone adjacent to barren East Gabbro (B^2).

the site of the deposit and partly solidified as leucocratic gabbros. A new batch of magmas, also formed by relatively high degrees of partial melting of a similar source, passed through the same conduit as the earlier, leucocratic magmas and incorporated the preexisting sulfide melt formed by the earlier magmas. The melanocratic magmas reached sulfur saturation, forming a second sulfide melt and inheriting the low Cu/Pd ratios of the earlier sulfide melt. In this model the late mafic magmas became rich in water and other volatiles, which caused the brecciation and pegmatite formation observed in the surface outcrops. The hydrothermal fluids released from melanocratic magmas migrated upward along the boundary between the East Gabbro and mineralized gabbroic rocks, resulting in intense hydrothermal alteration at the margin of the Roby zone and forming the High-Grade zone.

Comparison with other types of PGE mineralization

Major PGE deposits occur as stratiform layers in large layered intrusions or are hosted by Ni sulfides at the base of large mafic igneous intrusions. The former type includes the Merensky reef in the Bushveld (Von Gruenewaldt et al., 1985; Schoenberg et al., 1999), the Main sulfide zone in the Great Dyke (Wilson and Prendergast, 2001), and the J-M reef of the Stillwater Complex, Montana (Todd et al., 1982). PGE ore in layered intrusions is interpreted to result from additions of significant volumes of magma or pulses of relatively primitive magmas into quiescent magma chambers (Todd et al., 1982; Von Gruenewaldt et al., 1985; Maier et al., 1998; Schoenberg et al., 1999). The Ni sulfide-hosted deposits include the Noril'sk and Sudbury ore deposits (Lightfoot and Naldrett, 1994). Contact-type deposits are represented by the River Valley-East Bull Lake suite of intrusions in Ontario (Peck et al., 2001), the Coldwell Complex, Ontario (Barrie et al., 2002), the Federov Pansky intrusion in Russia (Schissel et al., 2002), and the Portimo intrusion, Finland (Alapieti et al., 1989). Typical contact-type deposits occur near the basal inclusion-rich zones of the intrusions that contain abundant xenoliths of country rocks and felsic intrusive rocks. The partial digestion of these fragments is thought to have resulted in increased H_2O and SiO_2 contents in the magmas, forming breccias and pegmatites, and leading to sulfide saturation (Barrie et al., 2002).

Comparison with contact-type PGE mineralization

The southern Roby and Twilight zones of the Lac des Iles intrusive complex share many characteristics with contact-type deposits. They include low sulfide abundance in the mineralized rocks, high Pd compared to other PGE, and the common occurrence of breccias and pegmatite. However, the PGE mineralization at the southern Roby and Twilight zones is not localized near the contacts with country rocks. Instead, the mineralization is in the center of the Mine Block intrusion. In addition, there is no evidence that enrichment of SiO_2 resulted in sulfur saturation in the ore deposit. In contrast, the most primitive, melanocratic rocks are the most PGE and sulfide rich. Thirdly, there is no evidence suggesting the interaction between mineralized mafic magmas and felsic magmas and/or rocks. Sutcliffe (1989) and Sutcliffe et al. (1989) described contemporaneous emplacement of granitoid magmas with gabbroic rocks, but later studies (e.g., Michaud, 1998; Lavigne and Michaud, 2001), including our study, failed to identify any xenoliths of granitic rocks in the area of mineralization. Minor inclusions of tonalitic rocks are present, but they are restricted to the barren margin of the Mine Block intrusion adjacent to the surrounding tonalite. These observations suggest that the origin of Pd mineralization at Lac des Iles is fundamentally different from that of the contact-type deposits.

Comparison with stratiform-type mineralization in large layered intrusions

We propose that the bulk of Pd mineralization was introduced by pulses of primitive magmas, as illustrated by the sequence of intrusions with various compositions (Fig. 20). The proposed mode of the mineralization is analogous to that suggested for typical stratiform deposits. However, the mode of emplacement of magmas is different. Unlike the quiescent magma chambers necessary for the formation of large, continuous ore horizons in stratiform deposits, the intrusive environment at Lac des Iles was apparently dynamic, forming breccias and magma mingling instead of layering. In addition, the Lac des Iles intrusive complex shows highly fractionated PGE with high Pd compared to the ore in layered intrusions, although the Lac des Iles ore lies in the general trend of Ir/Pd versus Pd defined by many deposits (Fig. 15).

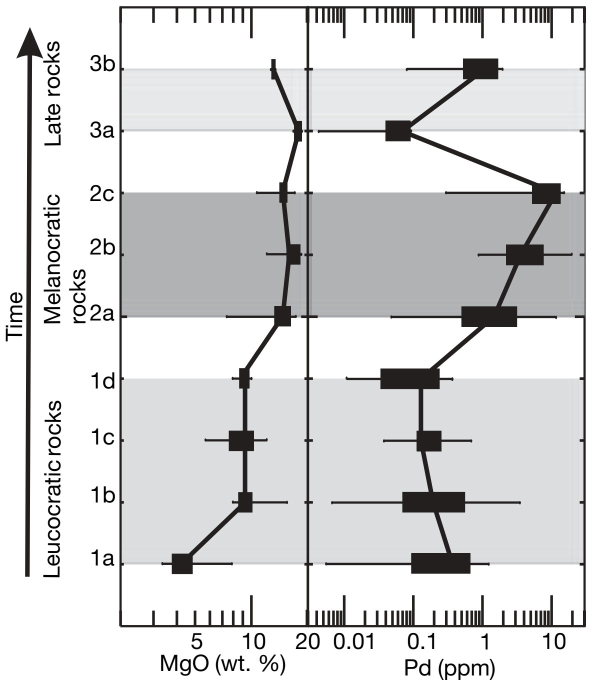

FIG. 20. Temporal evolution of palladium mineralization at the southern Roby and Twilight zones, Lac des Iles mine. The concentrations of MgO (wt %) and Pd (ppb) are shown by box-whisker plots where a box is defined by the 1st and 3rd quartile values. The total ranges of values are shown as lines and the median values of rock types are connected by the thick line. Note the increased MgO and Pd concentrations associated with the sulfide-bearing melanocratic rocks. The numbers on the left side of the diagram correspond to the rock types: 1a = leucogabbro and/or anorthosite, 1b = varitextured gabbro, 1c = medium-grained light gray gabbro, 1d = medium-grained gabbro, 2a = matrix of melanogabbro breccia, 2b = clinopyroxenite, 2c = dark gabbro, 3a = late clinopyroxenite, and 3b = late gabbro.

Conclusions

Our detailed mapping of the southern Roby and Twilight zones shows multiple intrusions of gabbroic rocks, which are divided into a group of early barren leucocratic gabbros and late mineralized melanocratic rocks. All rocks, except for late clinopyroxenite, are cogenetic formed from magmas generated by high degrees of partial melting in a moderately depleted mantle. Positive correlations between sulfur and precious and base metals and exsolution textures in sulfide grains suggest that the mineralization is of primary magmatic origin where PGE were concentrated in an immiscible sulfide melt in the parental magmas. Very high ratios of Pt-PGE/Ir-PGE and the extreme enrichment of Pd, which characterize the mineralization at Lac des Iles, are attributed to fractional crystallization of parental magmas and two stages of PGE enrichment. Earlier magmas, which evolved to the parental magmas of leucocratic gabbro, separated immiscible sulfide melt at depth. Later magmas, which formed the melanocratic gabbros, incorporated the early formed magmatic sulfide melt.

The mineralization at Lac des Iles is commonly compared to contact-type PGE ore because of similar textures in both types of deposits, but the Lac des Iles ore shows no evidence for host-rock assimilation. In addition, the ore is not localized near contacts with the country rocks. The Lac des Iles mineralization also shows similarities with PGE deposits in large layered intrusions, with the bulk of the PGE in both types being introduced by pulses of fertile primitive magmas. However, the intrusion of this fertile magma was much more energetic and dynamic at Lac des Iles than that associated with the quiescent magma chambers in large layered deposits.

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