Palladium–copper-rich platinum-group element mineralization in Legris Lake mafic–ultramafic complex, Western Superior Province, Canada

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Synopsis
The Legris Lake Complex is a northeast-trending, 7.3 km × 3.5 km, mafic–ultramafic intrusive complex located in the western Wabigoon Subprovince of the Archaean Superior Province. It is part of a circular series of mafic–ultramafic complexes, the most notable of which is the Lac des Iles Complex, *ca* 7 km northwest of the Legris Lake Complex, which hosts the Lac des Iles palladium mine. Four phases of exploration have been conducted on the Legris Lake Complex property since autumn, 1999, defining mineralized zones on surface and at depth, with drill-core intersections of up to 2.04 g/t Pd, 0.41 g/t Pt, 0.71 g/t Au, 0.42% Cu and 0.13% Ni over 9.95 m.

The Legris Lake Complex consists of mostly gabbroic rocks but also contains lithologies ranging from anorthosite to wehrlite and a variety of igneous breccias. The gabbroic rocks vary from melanogabbro to porphyritic leucogabbro. Medium-grained, massive, biotite-rich leucogabbro is the predominant exposed variety and probably caps the complex. The northwestern margin of the complex (2 km × 600 m), which contains all the known platinum-group element (PGE) mineralization, is characterized by heterolithic breccia with abundant fragments of sedimentary rocks and numerous gabbroic dykes and sills.

The PGE mineralization in the Legris Lake Complex has different characteristics from many PGE deposits, where the ore occurs in sulphide-rich bodies at the base of mafic and ultramafic rocks. In the Legris Lake Complex PGE enrichment occurs in sulphide-poor (1–10 vol%, mostly <5 vol%), medium- to coarse-grained, porphyritic leucogabbro (termed 'Main Showing-type') hosted within zones of intense magmatic brecciation. The mineralized leucogabbro is mineralogically highly evolved and exhibits a sill-like form near the stratigraphic top of the complex. The mineralization consists of disseminated to blebby sulphides rimmed by epidote and disseminated magnetite. The mineralized rocks typically contain Cu ranging from 0.2 to 0.4 wt% and Ni from 0.07 to 0.12 wt%, with low Pt/Pd ratios (*ca* 0.2) and high Cu/Ni ratios (*ca* 3). The PGE contents display a positive correlation with those of Cu and Ni. The origin of the mineralization is best explained by preferential partitioning of PGE into an immiscible sulphide melt in evolved silicate magma after fractional crystallization of olivine and clinopyroxene. The immiscible separation of sulphide melt may have been aided by incorporation of silica and sulphide from adjacent sedimentary rocks. Formation of magnetite and hydrous minerals in the mineralized zones suggests that the sulphide melt had high oxygen/(oxygen + sulphur) ratios and high contents of volatiles, most probably reflecting a high oxidation state and volatile-rich nature of the parental magmas. This primary magmatic PGE mineralization was followed by minor redistribution of PGE by deuteric hydrothermal fluids released from the parental magma.

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The Legris Lake Complex, located approximately 90 km north of Thunder Bay, Ontario, Canada, is a 7.3 km × 3.5 km mafic–ultramafic complex (Fig. 1). The complex is part of a circular array of mafic–ultramafic intrusions, the most notable of which is the Lac des Iles Complex (Fig. 2), which hosts the Lac des Iles mine with reserves of 145 600 000 t grading 1.57 g/t Pd and 0.17 g/t Pt, 0.12 g/t Au, 0.06% Cu and 0.05% Ni.[20] The Legris Lake Complex is located approximately 7 km southeast of the Lac des Iles Complex. The geology and mineralization of the Lac des Iles Complex have been described by several researchers,[3,12,15,29,30] but little documentation is available for the Legris Lake Complex and its mineralization. Details of the recently discovered mineralization in the complex are presented here.

Title to the Legris Lake Complex property is currently held jointly (50% each) by Avalon Ventures, Ltd., and Starcore Resources, Ltd., with Avalon as the operator. Placer Dome (CLA), Ltd., entered into an option/joint venture agreement in 2001 to spend $4 000 000 over four years to acquire a 50% interest in the property. Exploration since autumn, 1999, has resulted in the identification of three mineralized zones on the surface and at depth, with diamond drill intersections of up to 2.04 g/t Pd, 0.41 g/t Pt, 0.71 g/t Au and 0.42 wt% Cu over 9.95 m (drill-hole L00-08) and 4.50 g/t Pd, 0.62 g/t Pt, 0.20 g/t Au and 0.50 wt% Cu over 0.97 m (drill-hole L01-14).[21] A detailed exploration history of the complex appears in a report by Pettigrew.[21]

Geological setting

The Legris Lake Complex is located in the granite–greenstone Wabigoon Subprovince of the Archaean Superior Province of Canada (Figs. 1 and 2). It belongs to a series of mafic–ultramafic intrusions whose surface expression forms a circle approximately 30 km in diameter.[9,29] These include the platinum-group element-bearing Lac des Iles Complex (2692 +4/–2 m.y.[4,32]), Tib Lake Gabbro, Demars Lake, Wakinoo Lake, Towle Lake, Buck Lake, Taman Lake and Dog River intrusions[9] (Fig. 2). The country rocks surrounding the Legris Lake Complex consist of metasedimentary rocks and metabasalts. The sedimentary rocks are primarily fine-grained greywackes, conglomerates and siltstones with

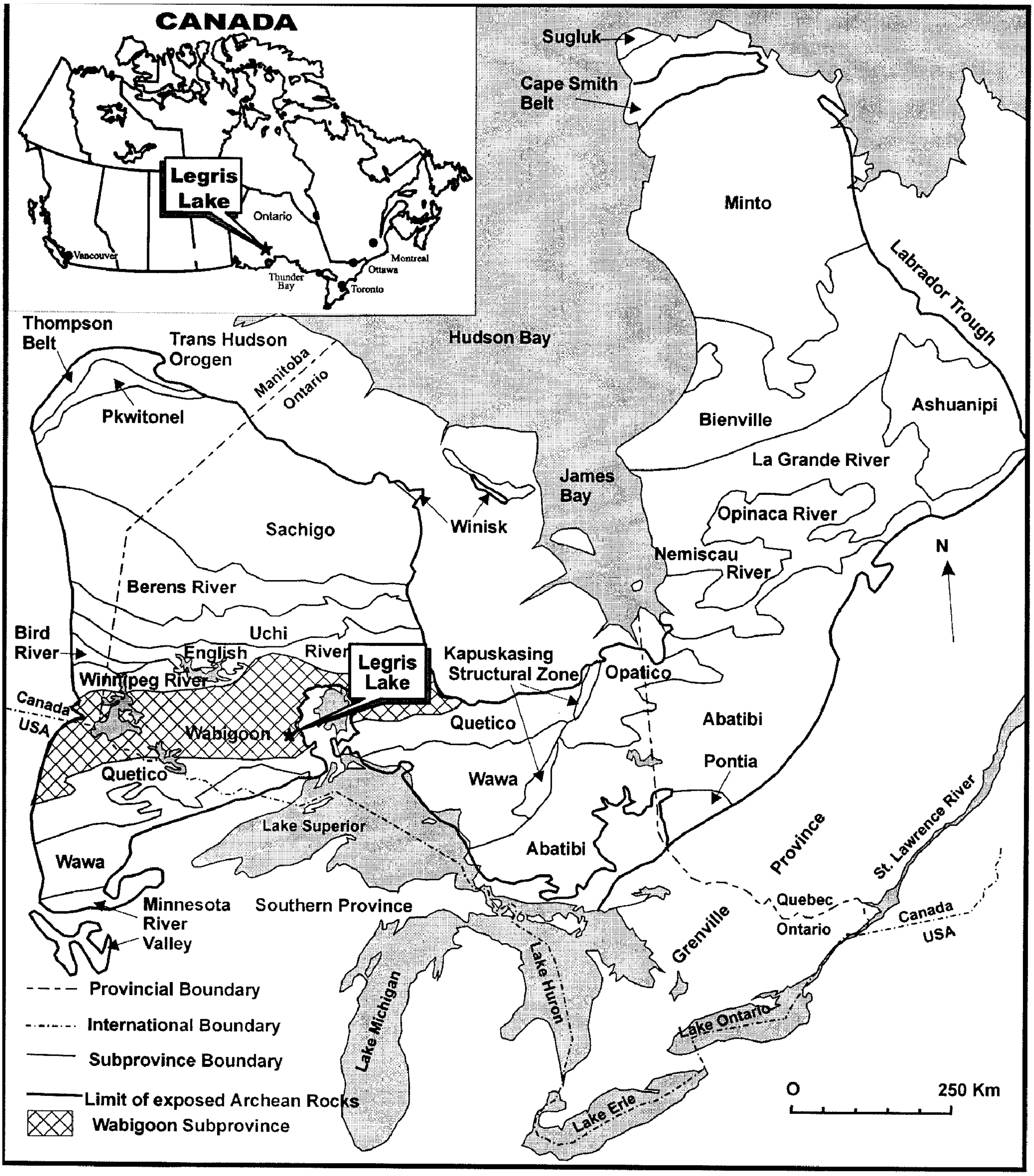

Fig. 1 Location map of mafic–ultramafic Legris Lake Complex in Superior Subprovince. Modified after Pye and Fenwick[25]

minor oxide-facies iron formations and argillaceous beds. All rocks, including the Legris Lake Complex, were intruded by late granodiorite dykes and quartz-feldspar pegmatite that branched out from later, voluminous granodiorite plutons.

The country rocks in the area were metamorphosed to greenschist facies and display a northeast-trending space cleavage parallel to the subprovince boundary (Fig. 2). Similar textures, common in the southern Wabigoon Subprovince, were probably developed during the accretion of the Quetico Subprovince on to the Wabigoon Subprovince.[39] The complex and rocks surrounding it were overprinted by a late north–south fracture set and intruded by diabase sills during the Mid-Continent Rift at 1100 m.y.[18] (Figs. 2 and 3).

Geology of Legris Lake Complex

The Legris Lake Complex formed through multiple injections of volatile-rich mafic magmas and extensive assimilation of sedimentary rocks. It consists, in consequence, of various gabbroic rocks with minor anorthosite and ultramafic rocks such as wehrlite. Of particular interest is a plagioclase (70–80 vol%) porphyritic leucogabbro with a matrix of fine-grained clinopyroxene. This texturally distinct, medium- to coarse-grained leucogabbro is termed the 'Main Showing type' and is abundant in the Northwestern Border area of the complex (Fig. 3). It is important because it hosts the majority of the known platinum-group element (PGE) mineralization. This

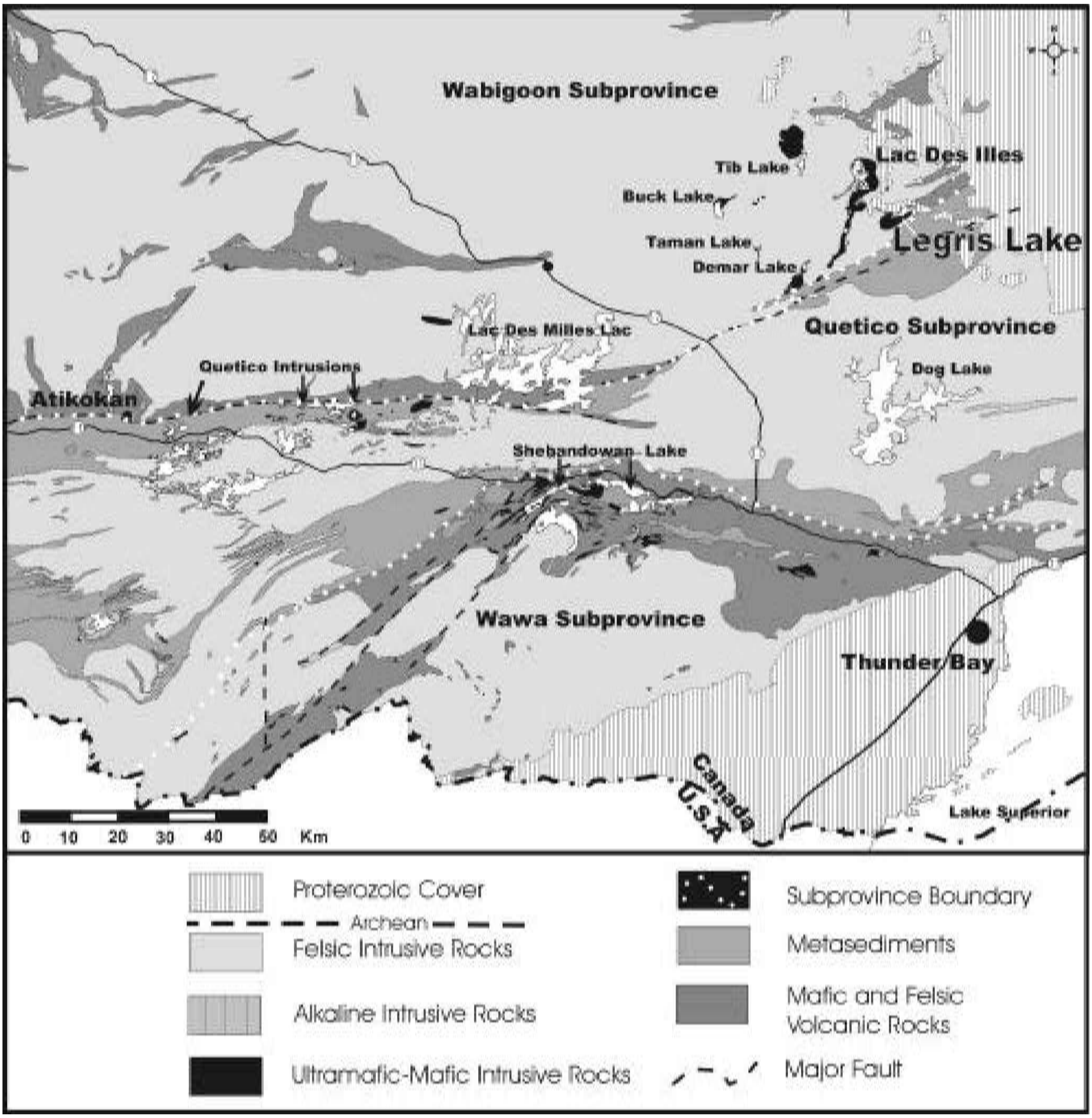

Fig. 2 Location of Legris Lake Complex and suite of co-genetic mafic–ultramafic complexes in southwestern Wabigoon Subprovince

Main Showing type is less evolved, with low SiO_2 (*ca* 50–53 wt%) and moderately high MgO (4–6 wt%) by comparison with other leucogabbro, which contains 58–61 wt% SiO_2 and 4–5 wt% MgO. The Main Showing-type leucogabbro has low overall concentrations of large-ion lithophile elements and displays different trace-element patterns from other leucogabbros (Fig. 4).

The complex also contains numerous dykes, sills and breccias incorporating fragments of cognate phases and metasedimentary country rocks. The interaction between the parental magmas and country rocks was so extensive that theboundary is not easily defined in some places. Gabbro with abundant sedimentary xenoliths grades into sedimentary rocks with abundant, irregular dyke stockworks. Fluids discharged from magmas and dehydrating sedimentary xenoliths produced significant deuteric alteration in phases that had solidified earlier. The alteration is particularly abundant in the Northwestern Border area, where complex textures are developed by numerous dykes and sills and abundant, partially melted, sedimentary xenoliths. The deuteric alteration resulted in uralization of clinopyroxene to hornblende ± actinolite, serpentinization of olivine and saussuritization of plagioclases. Such alteration may have contributed to the extensive conversion of mafic minerals to chlorite ± biotite. The rocks then underwent local, retrograde, greenschist-facies metamorphism around granodiorite dykes and pegmatite veins related to the voluminous granodiorite intrusion to the west of the complex (Fig. 3). This late event resulted in the oxidation of magnetite to hematite and the formation of biotite ± chlorite ± epidote ± carbonate ± albite.

On the basis of the lithological associations and textures the complex is divided into four areas: the Central Area, Northeastern Border, Southwestern Border and Northwestern Border.

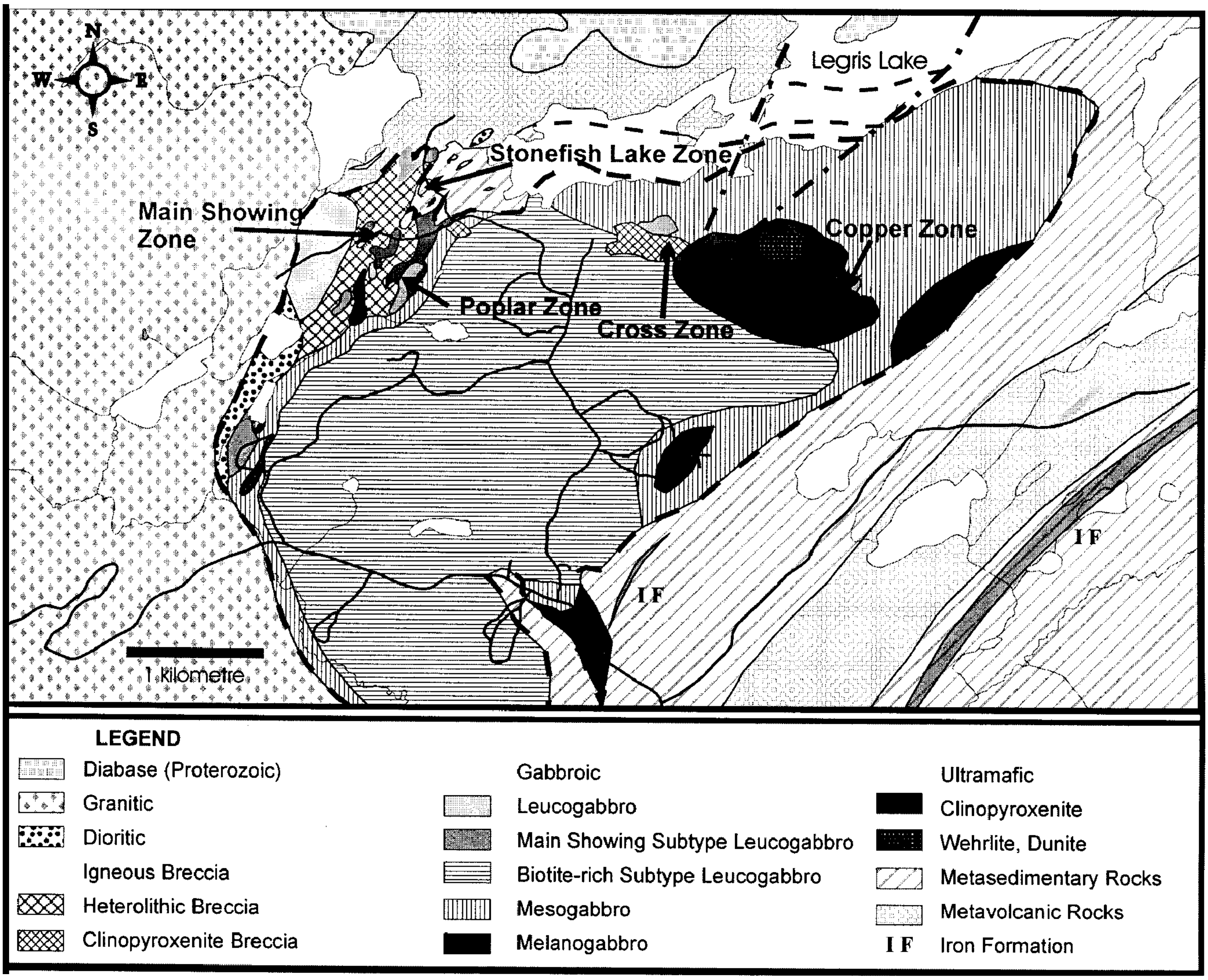

Fig. 3 Simplified geological map of Legris Lake Complex. Gabbro subdivided into leucogabbro, Main Showing-type leucogabbro, biotite-rich leucogabbro, mesogabbro and melanogabbro

Central Area

The Central Area has a surface exposure of several square kilometres and consists almost entirely of medium-grained, massive, biotite-rich leucogabbro with moderate magnetic susceptibilities. Several large, tongue-shaped blocks of metasedimentary rocks, which are interpreted to be roof pendants, extend up to 600 m from the contact with the sedimentary rocks into the complex (Fig. 3). Airborne and ground magnetic data show that more magnetite-rich phases are present at depth, suggesting that the biotite-rich leucogabbro represents a highly evolved unit, capping the complex.

Northeastern Border area

The Northeastern Border area consists of mostly mesogabbro and clinopyroxenite with many other minor phases, including leucogabbro and wehrlite. The area is very poorly exposed and much of the interpretation is based on geophysical and limited drill-core data. The area contains the largest ultramafic body in the complex, approximately 1 km in diameter (Fig. 3), consisting mostly of clinopyroxenite and wehrlite, both of which display weakly developed layering defined by variations in olivine content.

A large zone (500 m × 200 m) of clinopyroxenite breccia along the boundary with the Central Area, known as the Cross Zone, is characterized by abundant anorthosite to melanogabbro breccias in a strongly magnetic matrix of clinopyroxenite to melanogabbro. Anomalous contents of PGE (up to 300 ppb) occur in the matrix of this breccia.

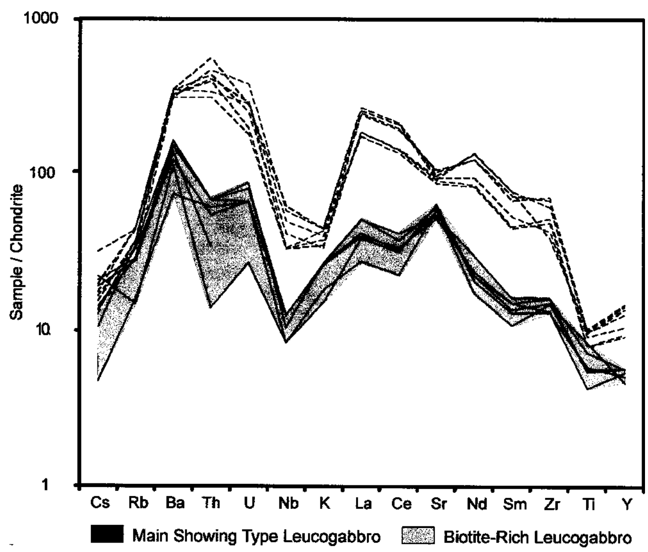

Fig. 4 Element concentrations of leucogabbros normalized to chondrite values; normalizing values are those of MacDonough and Sun.[15] Main Showing-type leucogabbro (*solid lines*) shows low concentrations of large-ion lithophile elements by comparison with biotite-rich leucogabbro (*dashed lines*)

Southwestern Border area

The Southwestern Border area consists mostly of mesogabbro and coarse-grained leucogabbro (Main Showing-type) and is homogeneous by comparison with the rest of the complex (Fig. 3). This area also contains a dyke-shaped body of magnetite-rich ultramafic rocks. The narrow (less than 50 m wide) ultramafic rocks show concentric zoning with a melanogabbro exterior grading into a thin (*ca* 10 m) lherzolite–dunite core with abundant magnetite.

near-complete disaggregation of conglomerates and transformation of cobbles into rounded xenoliths in a gabbroic matrix. Furthermore, fluids expelled by dehydration of the sedimentary rocks and solidifying magmas caused extensive brecciation.

The sedimentary rocks generally contain pyrite (up to 1 vol%) and the assimilation of such rocks probably contributed to saturation of sulphur in the magma and the formation of Cu–Ni–PGE mineralization in this area.

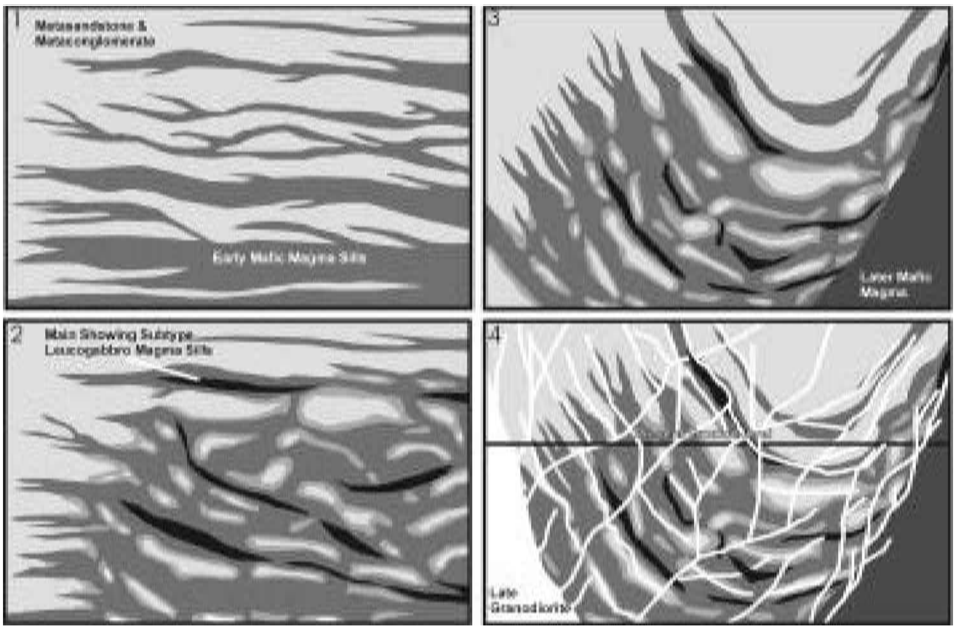

Fig. 5 Schematic diagrams showing origin of Northwestern Border area. (1) Intrusion of gabbroic sills. (2) Partial melting and assimilation of intervening metasedimentary lenses between intrusions caused them to fail; Cu–Ni–PGE mineralization most probably occurred during this period as the intrusion of the Main Showing-type leucogabbro postdated the bulk of the brecciation and does not appear to be related to the later, voluminous mafic magma forming the footwall of the Northwestern Border area. (3) Emplacement of later, biotite-rich leucogabbro, possibly causing compression of Northwestern Border area. (4) Intrusion of granodiorite dykes branching out from nearby granodioritic plutons

Northwestern Border area

The Northwestern Border area is extremely heterogeneous in texture and composition, consisting predominantly of sediment-rich heterolithic breccias and a wide variety of igneous rocks from anorthosite to clinopyroxenite; magmatic layering occurs within individual sills. This area contains the majority of the Main Showing-type leucogabbro. The heterolithic breccias contain abundant dykes and sills and xenoliths of metasedimentary rocks (Fig. 3); the xenoliths vary widely in size and shape and most are highly distorted and internally deformed. The localized nature of the deformation suggests that these xenoliths were incorporated into semi-solidified, dynamic magmas.

The area displays numerous injections of gabbroic magmas as sills and dykes in clastic metasedimentary rocks (Fig. 5). The intervening metasediment lenses between these sills and dykes were partially melted and assimilated into the magmas, which caused them to fail, producing textures and structures akin to those produced by the sedimentary processes of slumping and soft-sediment deformation (Fig. 5). The assimilation of sedimentary rocks combined with fractional crystallization produced a wide spectrum of magmas ranging in composition from diorite to melanogabbro.

The matrix of the conglomerates within the metasedimentary rocks was most susceptible to assimilation, resulting in

Mineralization

The Legris Lake Complex displays three styles of mineralization: Cu–Pd-rich; Cu–Ni-poor, Pd-rich; and Cu–Ni-poor, Rh–Pd-rich types. The Cu-Pd-rich style is the most abundant and economically significant. The bulk of the mineralization occurs in three zone—the Main Showing, Poplar and Stonefish Lake Zones (Figs. 3 and 6). The Main Showing and Poplar Zones are Cu–Pd-rich, whereas the Stonefish Lake Zone is poor in Cu and Ni and rich in Pd. The third style of mineralization, characterized by low Cu and Ni and high Rh and Pd, was found only in drill-hole L00-03 at depth near the Main Showing Zone.

Copper–palladium-rich mineralization

Cu–Pd-rich mineralization occurs in sill-like structures (200 m long × 25 m wide) in the Northwestern Border area (Fig. 7). Within the sill-like bodies the mineralization is confined in the Main Showing-type leucogabbro overlying layered, medium-grained pyroxenite and local melanogabbro with a sharp to gradational (up to 30 cm wide) contact. The magmatic layering is well preserved in the northwestern portion of the Poplar Zone (Fig. 8), although it is disrupted by large sedimentary xenoliths, brecciation and later intrusions. In addition, the primary layering has been disturbed by the

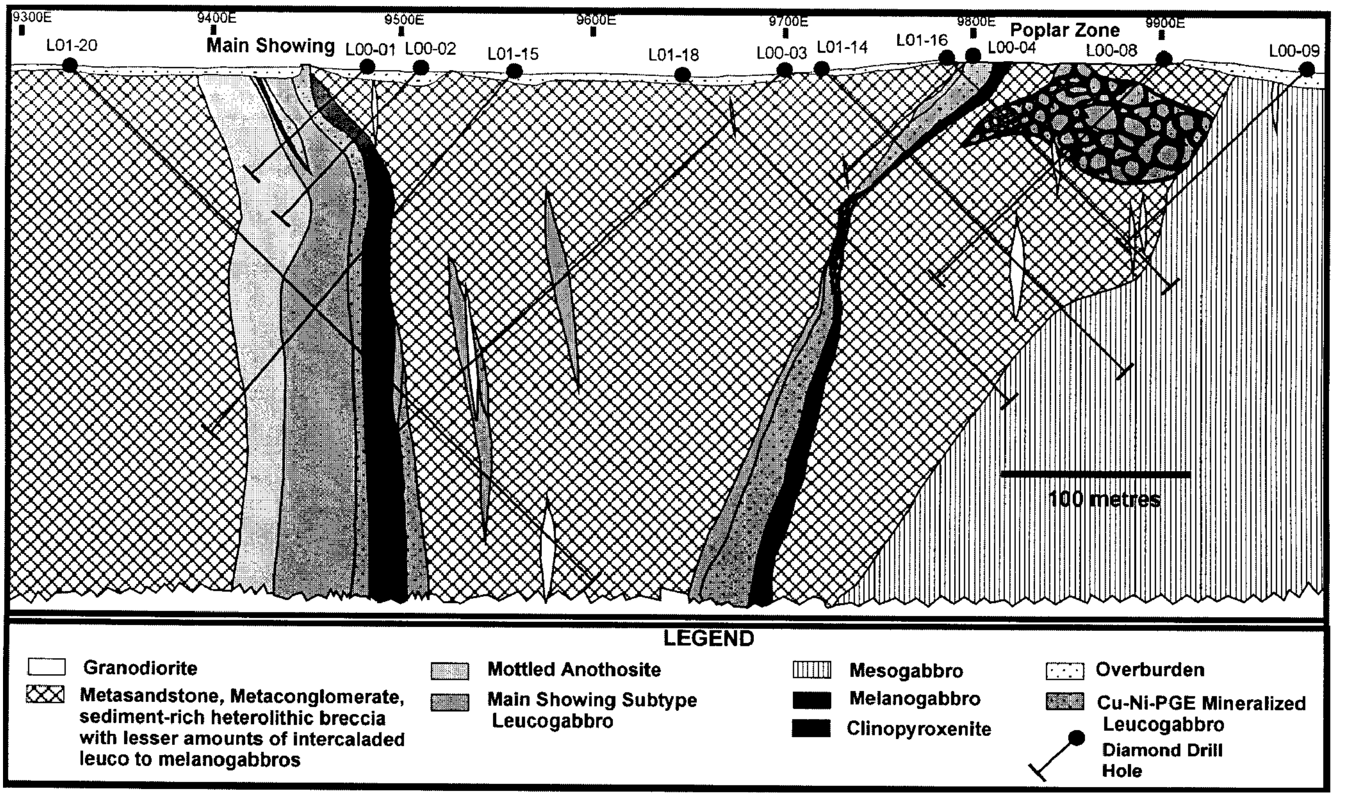

Fig. 6 Simplified vertical cross-section across Northwestern Border area based on diamond drill core and geophysical data. 'Mottled anorthosite' refers to highly altered anorthosite with poikiolitic interstitial clinopyroxene

injection of crystal mushes from underlying phases into overlying phases. For example, the earlier crystallized clinopyroxenite unit injected into the overlying leucogabbro in the southeastern portion of the Poplar Zone (Fig. 5) and the northwestern portion of the Poplar Zone (Fig. 6).

The distribution of the Cu–Ni–PGE mineralization in this

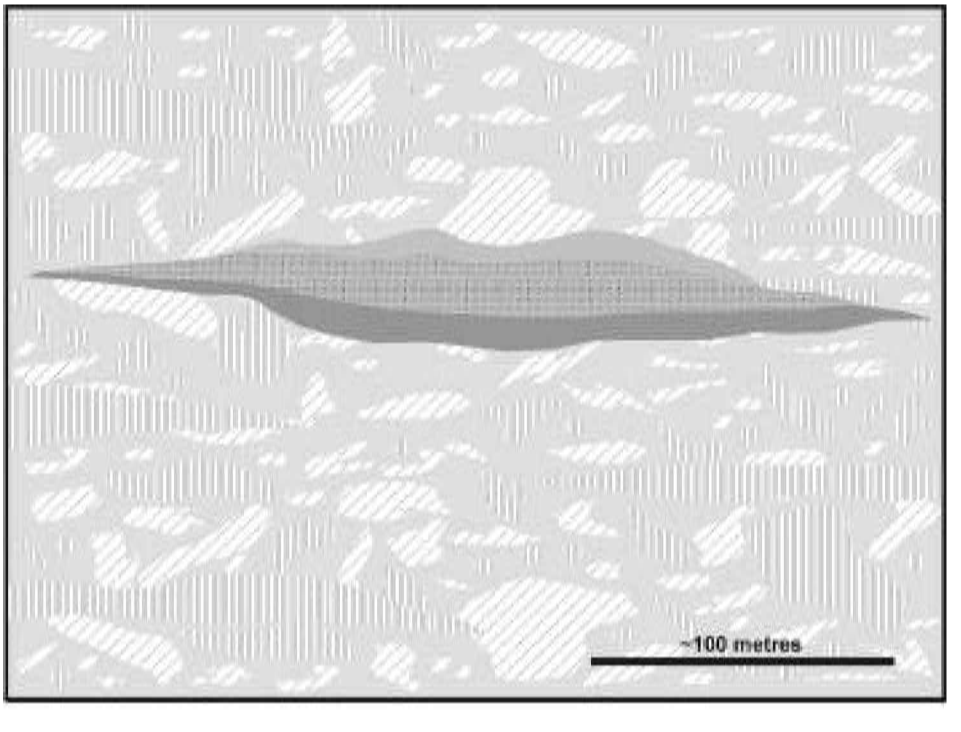

Fig. 7 Schematic diagram showing Cu–Ni–PGE mineralization in sill-shaped intrusion hosted by breccia zone

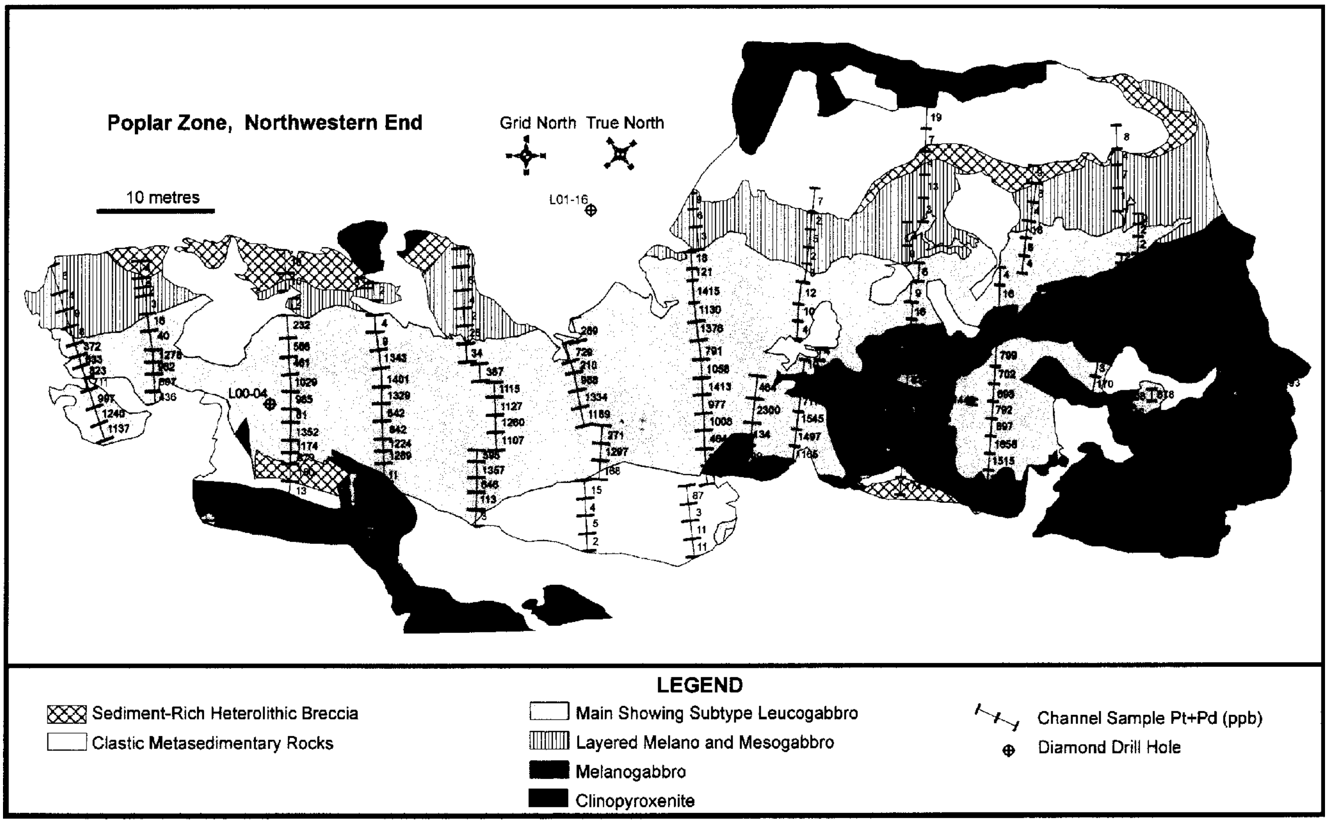

Fig. 8 Detailed geological map of trench in northwestern portion of Poplar Zone showing Pt and Pd contents of channel samples and sample locations. Numbers beside sampling locations are Pt + Pd, ppb

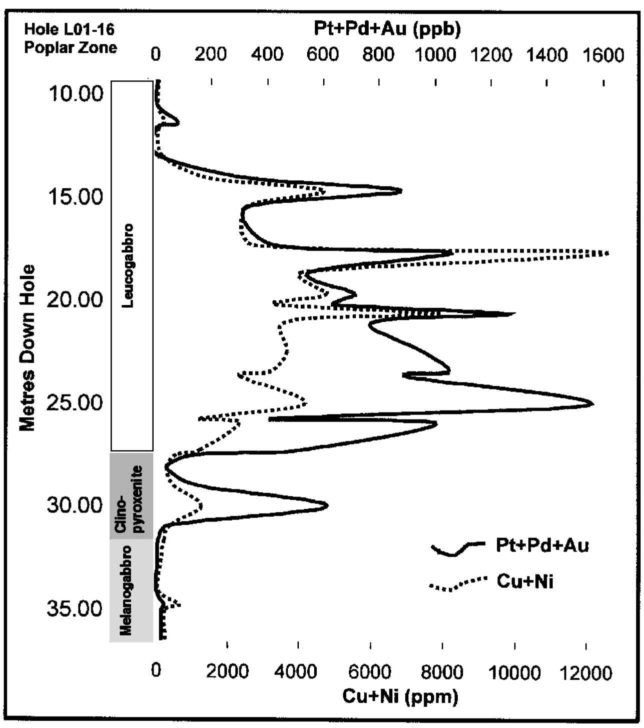

Fig. 9 Downhole profile of total PGE and (Cu + Ni) versus depth in diamond drill-hole L01-16, passing through Poplar Zone

leucogabbro 'sill' is best illustrated in drill-hole L01-16 (Figs. 8 and 9), which intersected the upper portion of the Poplar Zone. The Pd contents increase abruptly in the leucogabbro at the contact with clinopyroxenite, the highest grades being at or near this contact (Figs. 8 and 9). The Cu and Ni contents increase in the upper part of the mineralized leucogabbro and decrease near the upper contact of the leucogabbro sequence (Fig. 9).

The mineralization is characterized by disseminated to locally net-textured sulphides that consist of pyrite + chalcopyrite ± pyrrhotite ± millerite ± pentlandite ± magnetite. The sulphides are commonly accompanied by coarse apatite crystals and epidote haloes (Figs. 10 and 11). The alteration changes the colour of the mineralized leucogabbro (Fig. 10) from white to dark green in hand samples. Plagioclase is albitized (An_{51}–An_{58}), saussuritized and locally altered to epidote; clinopyroxene in the matrix is altered to hornblende, chlorite and actinolite.

Microprobe analyses of PGE minerals (PGM) show that they are mostly Pd–Bi tellurides with minor Pt–Pd–Bi tellurides and Pd sulphides (Fig. 12). All PGM occur in close proximity to, but are not enclosed by, Cu–Ni sulphides. With one exception, where a PGM was enclosed by pyrite, all PGM were found in the epidote halo surrounding the sulphides (Fig. 11).

The mineralized rocks display consistent Pt/Pd ratios of *ca* 0.2 with a slightly more variable Cu/Ni ratio of *ca* 3 and an erratic Au/(Pt + Pd) ratio of around 0.1 (Fig. 13(*a*), (*b*) and (*c*)). The Pd contents are positively correlated with those of Cu, Ni and total PGE (Fig. 13(*d*), (*e*) and (*f*)). This style of mineralization also occurs in the Vande, Stinger and Powder Hill Zones, which are located to the south of the Legris Lake Complex along the boundary between the Towle Lake intrusion and country metasedimentary and pyroclastic volcanic rocks (Powder Hill is *ca* 15 km from the Poplar Zone).

Copper–nickel-poor, palladium-rich mineralization

Cu–Ni-poor, Pd-rich mineralization is best exhibited in the Stonefish Lake Zone, which protrudes into the metasedimentary rocks from the Northwestern Border area (Fig. 3). The host rock for this style of mineralization is a heterolithic,

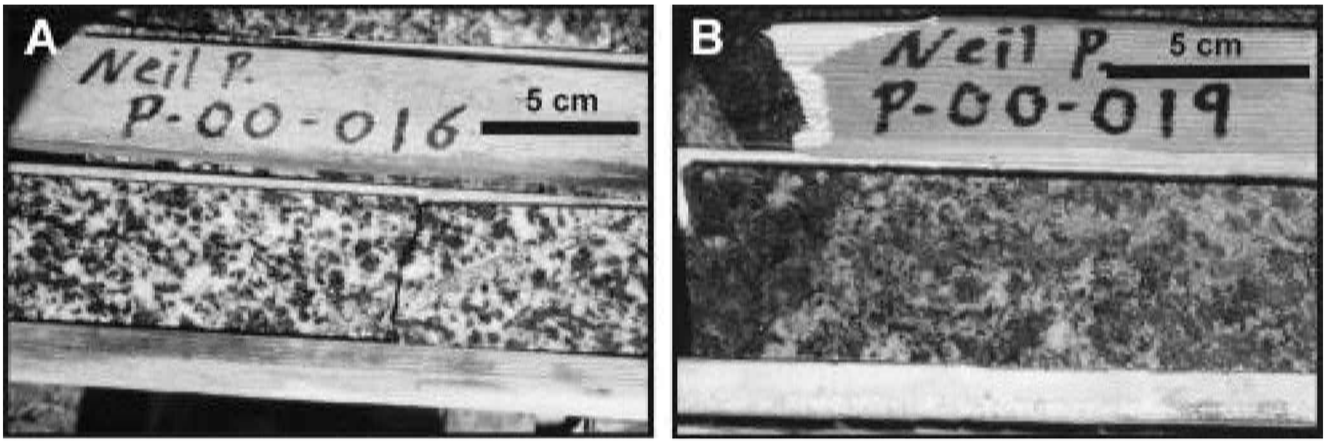

Fig. 10 (*a*) Unmineralized leucogabbro (Main Showing type) from Main Showing Zone (drill-hole L00-01). (*b*) Mineralized leucogabbro (Main Showing type) from Main Showing Zone displaying epidote alteration (*grey*) surrounding finely disseminated Cu–Ni sulphides

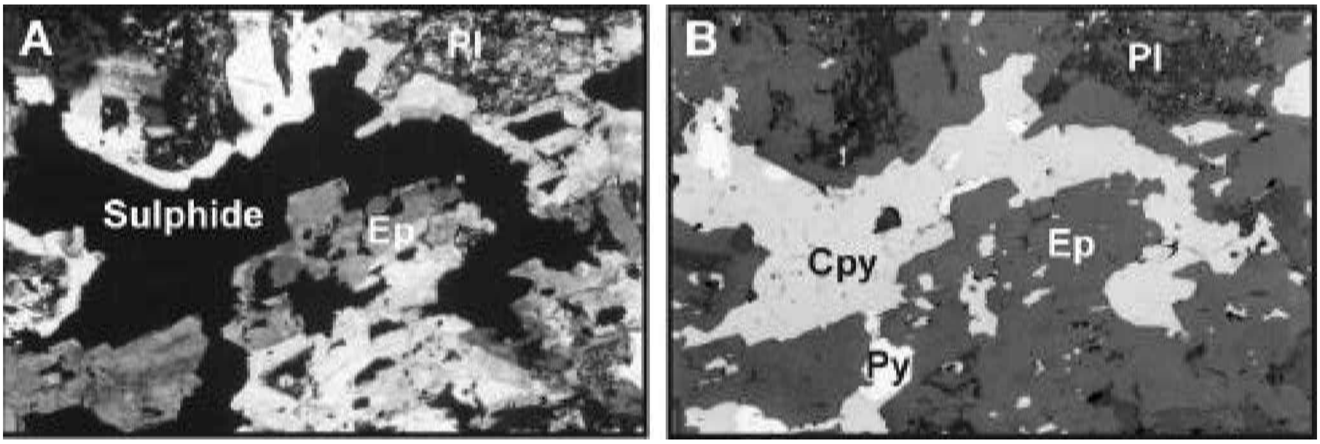

Fig. 11 Photomicrograph showing composite bleb of sulphide minerals surrounded by epidote (Ep) in leucogabbro (drill-hole L00-01); field of view, 2.5 mm: (*a*) transmitted-light microscopy; (*b*) reflected-light microscopy showing distribution of chalcopyrite (Cpy) and pyrite (Py)

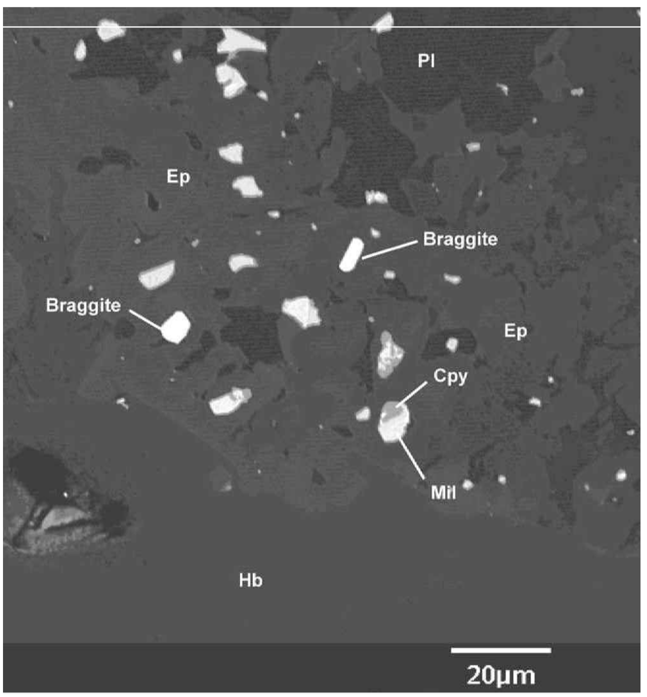

Fig. 12 Back-scattered electron image of braggite grains (PdS) enclosed in portion of epidote alteration halo surrounding large sulphide bleb (outside field of view). Sample collected from Main Showing-type leucogabbro in Main Showing Zone. Ep, epidote; Cpy, chalcopyrite; Hb, hornblende; Mil, millerite; Pl, plagioclase

leucogabbro breccia, which displays highly variable compositions and grain sizes (vari-textured) in the matrix. This zone occurs at a higher stratigraphic level than the Poplar and Main Showing Zones and contains abundant metasedimentary xenoliths in various degrees of assimilation and minor, cognate gabbroic to pyroxenitic fragments. The vari-textured leucogabbro breccia grades locally into mottled anorthosite, which, in turn, grades into quartz–plagioclase-rich micropegmatite with minor tourmaline. Extensive hydrothermal alteration of anorthosite resulted in cloudy and diffused grain boundaries of plagioclase, forming mottled anorthosite.

Enrichment of PGE occurs erratically in the vari-textured leucogabbro breccia and mottled anorthosite. Cu–Ni sulphides are not common and they are not correlated with the enrichment of PGE (Fig. 14). This observation suggests that this style of PGE enrichment was the result of primarily hydrothermal processes caused by deuteric fluids derived from the parental magmas of the Legris Lake Complex.

Copper–nickel-poor, rhodium–palladium-rich style of mineralization

Cu–Ni-poor, Rh–Pd-rich mineralization was intersected only near the bottom of drill-hole L00-03 (Fig. 6), where grades of up to 0.52 g/t Rh and 0.91 g/t Pd were encountered. This style occurs within a coarse-grained mesogabbro displaying foliation defined by actinolite. The mesogabbro commonly contains disseminated to locally abundant magnetite (up to *ca* 15 vol%). The mineralized rocks are rich in V (0.11 wt%) and TiO_2 (1.86 wt%) and low in Cr_2O_3 (<0.01 wt%), sug-

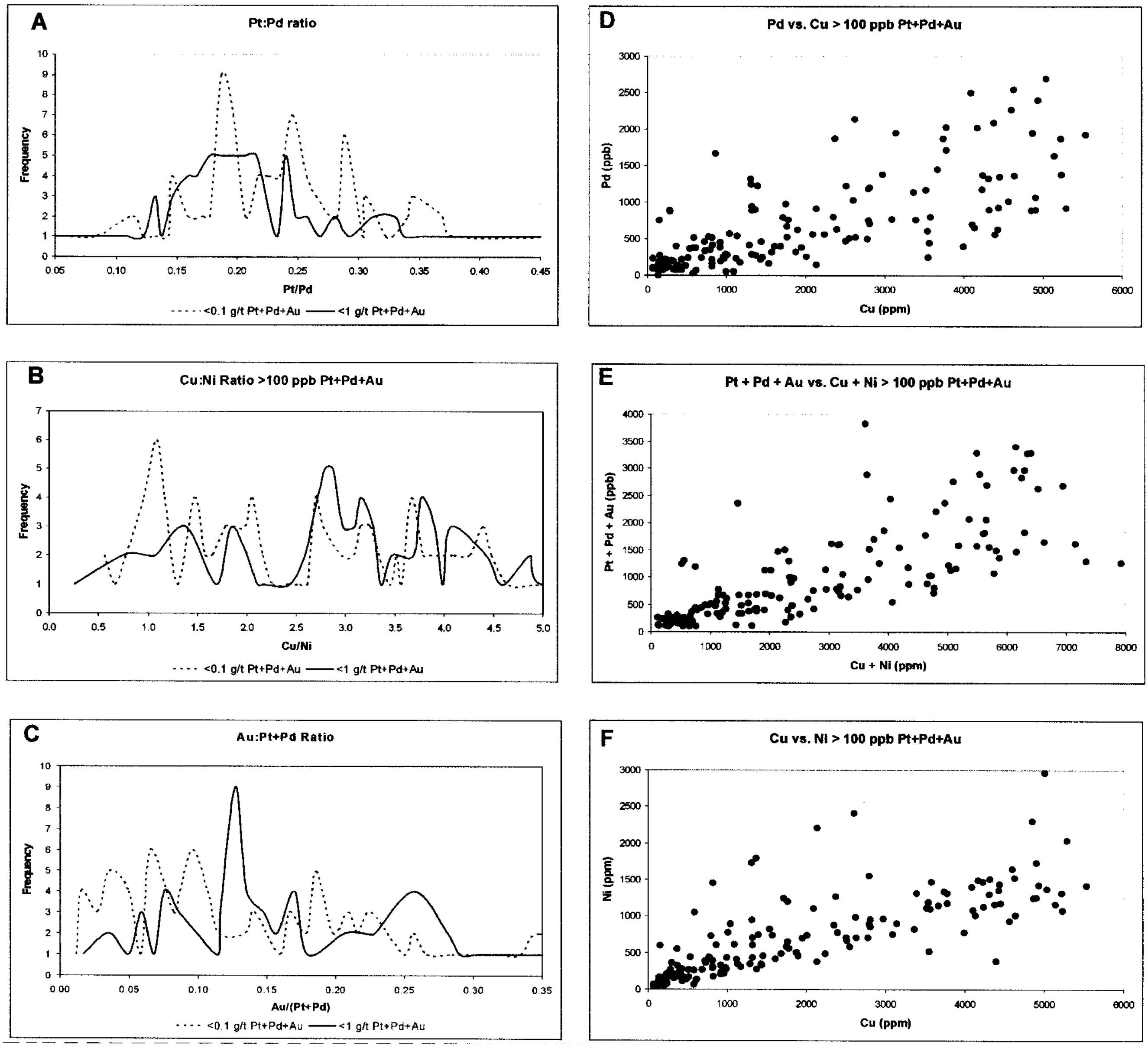

Fig. 13 Legris Lake Complex—element ratios: (*a*) histogram of Pt/Pd ratios of Cu–Ni–PGE mineralization; (*b*) histogram of Cu/Ni ratio of Cu–Ni–PGE mineralization; (*c*) histogram of ratios of Au/(Pt+Pd); (*d*) Pd versus Cu in mineralized rocks; (*e*) (Pt+Pd) versus (Cu+Ni) in mineralized rocks; (*f*) Cu versus Ni in mineralized rocks. Values compiled from drill-core assay data

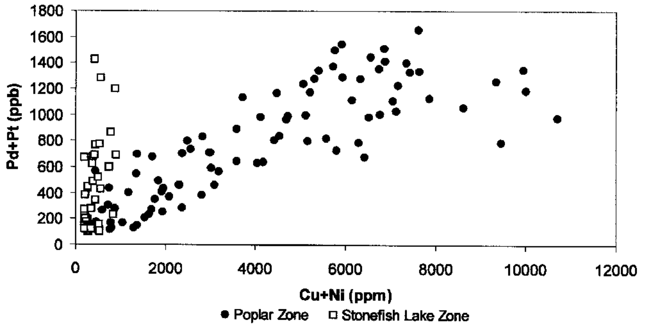

Fig. 14 (Pt+Pd+Au) versus (Cu+Ni) for Cu–Ni-poor, Pd-rich Stonefish Lake Zone and Cu–Pd-rich Poplar Zone. Values compiled from channel-sample assay data

gesting that this coarse gabbro represents a pegmatitic phase. Several Pd–Bi tellurides and Pd–Hg arsenides were identified with the use of an electron microprobe. All PGM are enclosed by actinolite in close proximity to finely disseminated sulphides of pyrite + millerite + chalcopyrite.

Discussion

Many mantle-derived, mafic melts contain high Pd relative to the other PGE. The cause of this enrichment of Pd appears to be that Pd has a more incompatible nature than Pt in mantle minerals.[20,23,36] Like many other mafic magmas, the parental magmas for the Legris Lake Complex probably contained high Pd relative to the other PGE. Before the parental magmas were injected into the site they underwent fractional crystallization of olivine at depth, leading to the depletion of Ni. The magmas were apparently undersaturated with S, and incompatible metals, such as Pd and Cu,[8,20,24,32] were enriched in the parental magmas. Pd was more enriched than Pt during this fractional crystallization owing to its more incompatible nature.[23,36]

The Cu–Pd-enriched magmas were then injected into the Northwestern Border area of the complex as sill-like bodies. The injected magmas in the sill-like bodies underwent further crystallization of clinopyroxene and orthopyroxene, which produced clinopyroxenite at the base of the sill (Figs. 7 and 8). Continuing crystallization reduced the volume of silicate melt, which led to sulphur saturation of the magma and immiscible separation of sulphide melt. The sulphur saturation was aided by the assimilation of clastic metasedimentary rocks, which not only commonly contain up to 1 vol% pyrite but also have high contents of SiO_2, which lowers the solubility of sulphur in mafic melt.[14,38] The assimilation of sedimentary rocks also promoted the evolution of the parental magmas to leucocratic composition.

PGE in the melt partitioned preferentially to the sulphide melt[5] (Fig. 13(*f*)), leading to the formation of disseminated sulphides and high Pd in leucogabbro (Fig. 9). As the partition coefficients for Pd and Pt between sulphide melt and silicate melt are very high (greater than 10 000),[5] the early-formed, less voluminous sulphide melt efficiently incorporated much of the Pd and Pt from the silicate melt, producing a higher (Pd + Pt)/(Cu + Ni) ratio near the transition from clinopyroxenite to Main Showing-type leuocogabbro. The later, more voluminous sulphide has a lower (Pt + Pd)/(Cu + Ni) ratio since much of the PGE had already been leached from the magma. This resulted in the Pt + Pd and Cu + Ni peaks being offset (Fig. 9). This stratigraphic zonation of Cu–Ni–PGE mineralization is commonly observed in large, layered mafic–ultramafic complexes.[1,35]

The common occurrence of magnetite in the complex suggests that the parental magmas had high oxygen fugacity. Furthermore, abundant magnetite grains within and near sulphide blebs suggest that the sulphide melt had high oxygen/(oxygen + sulphur) ratios. Magmatic sulphides formed in basalts are known to contain high oxygen, with oxygen/(oxygen + sulphur) ratios up to 0.5.[6] Experimental studies have confirmed high oxygen contents in sulphide melts that form in oxidizing silicate melts.[7] The high magnetite content of the Legris Lake Complex indicates a high oxygen content in the sulphide melt and oxidizing conditions in the parental magma.

The presence of a hydrous alteration halo around sulphide blebs suggests that the sulphide melt was rich in volatiles. These volatile elements were probably exsolved from solidifying sulphide melt, thus producing the hydrous alteration halo, just as magnetite formed in the halo of sulphides. The lack of PGM enclosed within sulphide minerals and the occurrence of PGM within the hydrous alteration halo (Fig. 12) suggest transport of PGE by aqueous fluids discharged from the sulphide melt during solidification. Such magmatic fluids would have been high in Cl.[2] Saline fluids are known to dissolve PGE significantly, especially at elevated temperatures.[28,40] Thus, PGE were expelled from sulphide minerals during the solidification of sulphide melt and deposited in the hydrous alteration halo.

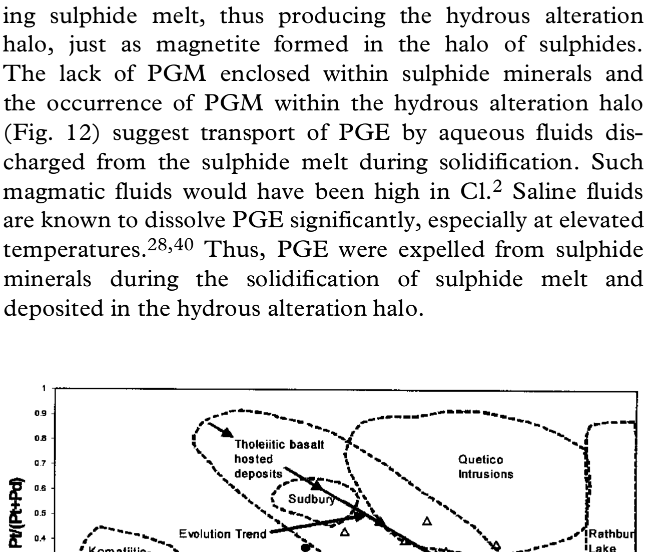

Fig. 15 Cu/(Cu+Ni) versus Pt/(Pt+Pd). Note that mineralized rocks at Legris Lake Complex cluster in lower right corner of tholeiitic field and display weaker trend parallel to Lac des Iles deposit. Modified after Naldrett and Cabri[17] with additional data from Quetico intrusions by MacTavish[13] and from Lac des Iles Complex by Michaud[16]

The highly evolved nature of the Cu–Pd-rich style of mineralization is illustrated by the trends on a Cu/(Cu + Ni) versus Pt/(Pt + Pd) diagram, in which the bulk of the data from the Legris Lake Complex cluster in the lower right corner of the tholeiitic field (Fig. 15). Tholeiitic-hosted PGE deposits formed by sulphur saturation of primitive magmas plot in the upper left corner, whereas those formed by evolved magmas plot in the lower right corner.[17] Some data, especially lower-grade samples from the Legris Lake Complex, also form an array parallel to that of the Lac des Iles deposit, suggesting that hydrothermal processes similar to those at the Lac des Iles Complex[12] may have helped to enrich magmatically concentrated PGE at the Legris Lake Complex.

The Stonefish Lake Zone is quite distinct from the rest of the mineralization in the complex. It has a very low sulphide content—less than 0.2 vol%—and erratically distributed, anomalous to moderate PGE contents—up to 1.46 g/t—in vari-textured leucogabbro breccia and along narrow (<0.5 m) ductile shears. The authors consider that this mineralization is a result of hydrothermal mobilization by deuteric fluids of PGE. Magmatic fluids are highly saline[2] and PGE, especially Pd, are soluble in hot, saline fluids.[27,40] Such magmatic fluids derived from the parental magmas probably collected along distal pegmatitic sills and in breccias and shear zones, where they precipitated PGE. The small size of this type of mineralization suggests limited hydrothermal activity in the Legris Lake Complex.

Comparison with other PGE deposits

The Legris Lake Complex and the nearby Lac des Iles Complex (Fig. 2) are considered to be co-genetic.[9,31] They share many geological features, such as abundant igneous breccias, a wide variety of lithologies, multiple injections of magma, widespread magmatic alteration, overall low sulphide contents and Pd-rich PGE mineralization. Reflecting the complicated textures and geology of the Lac des Iles deposit, several hypotheses for the genesis of PGE mineralization have been put forward. They include Pd enrichment by 'constitutional zone refining' of earlier gabbroic rocks,[3] magma mixing between PGE-rich magmas and volatile-rich magmas[31] and immiscible separation of sulphide melt followed by hydrothermal enrichment of Pd.[16,33] A major expansion of the Lac des Iles mine in 1999 involved the stripping of large areas and extensive diamond drilling, which led to better understanding of the relationships between the mineralization and the lithologies and of the three-dimensional distribution of different lithologies. The high-grade (>5 g/t Pd) mineralization is hosted by sulphide-poor, talc-rich clinopyroxenite between a large area of igneous breccia and a cohesive gabbroic rock.[11] Lavigne *et al.*[11] recently proposed that aqueous fluids were exsolved from a PGE–volatile-rich gabbroic magma that brecciated the earlier gabbroic rocks, producing Pd-rich pegmatites and hydrothermal alteration. The high-grade Pd mineralization hosted by the clinopyroxenite is a result of fluid flow focused by the adjacent, impermeable gabbroic rock.[11]

The Legris Lake Complex also shares many geological features with the River Valley mafic–ultramafic complex, south of Sudbury. The River Valley Complex (2475 m.y.[19]) is part of a suite of gabbro-anorthitic complexes, the East Bull Lake intrusive suite, which were intruded during the early Proterozoic rift in the Southern Province. This complex also contains abundant igneous breccias, gnessic country-rock xenoliths in the mineralized zones, wide variations of lithology ranging from leucocratic to ultramafic rocks over a short distance and a high abundance of chalcopyrite compared with pyrrhotite and pentlandite.[10,19] In addition, the mineralization is confined to within several hundred metres of the contact with country rocks and displays evidence of deuteric alteration.[10,19]

Although the geological setting of the mineralization at the Legris Lake Complex is similar to that of Lac des Iles mine and the East Bull Lake Suite, the style of mineralization differs substantially from these two. The bulk of Lac des Iles mine's mineralization is hosted within a matrix of igneous breccias[11] and displays little correlation between Pd and base-metal sulphides. In the River Valley intrusion, which is one of the East Bull Lake suite intrusions, the contact-type mineralization is mostly confined to the boundaries of the intrusion with country rocks. The mineralization also appears to be independent of lithological type, occurring in both breccia clasts and matrices. The bulk of the mineralization at the Legris Lake Complex, however, displays lithological and stratigraphic control, occurring only in leucogabbro near the contact with underlying pyroxenite in layered, sill-shaped intrusions, which are hosted within brecciated zones near the contact with country rocks (Fig. 7). In this sense the stratigraphic position of the mineralization of the Legris Lake Complex is similar to that of many layered intrusions, although the Legris Lake Complex as a whole is not a layered intrusion. PGE mineralization in layered intrusions typically occurs near the boundary between ultramafic-dominated and overlying mafic-dominated sequences. Examples include the Critical Zone of the Bushveld Complex,[37] the main Sulphide Zone of the Great Dyke,[22] the J-M Reef of the Stillwater Complex[26,35] and the Porphyritic Websterite Zone of the Munni Munni Complex in Western Australia.[1]

Summary

The surface exposure of the Legris Lake Complex consists mostly of medium-grained, massive, biotite-rich leucogabbro with lesser amounts of other mafic and ultramafic rocks. This highly evolved leucogabbro unit is interpreted to cap the underlying, less evolved rocks of the complex. In contrast to the majority of the complex, the Northwestern Border area underwent multiple injections of primitive magmas and displays abundant breccia. Fractional crystallization of these magmas and extensive assimilation of sedimentary rocks produced a variety of magma compositions ranging from anorthosite to wehrlite. The magmas were enriched in volatiles during crystallization through the assimilation and dehydration of sedimentary xenoliths and volume reduction of the magma. The discharge of such fluids from the magmas resulted in extensive brecciation and deuteric alteration of the already solidified rocks.

The majority of the PGE mineralization is accompanied by disseminated magmatic sulphides (generally less than 5 vol%) and occurs in leucogabbro overlying basal ultramafic and mafic units within sill-shaped gabbro bodies. The mineralization is Cu- and Pd-rich with a Pt/Pd ratio of *ca* 0.2 and Cu/Ni ratio of *ca* 3 and bulk rock samples show a positive correlation between PGE and base metals. The mineralization is explained by sulphur saturation in the parental magmas due to volume reduction of the melt and incorporation of silica and sulphur from metasedimentary rocks. The complex also contains subordinate Cu–Ni-poor, Pd-rich and Cu–Ni-poor, Rh–Pd-rich styles of mineralization, which are most probably of hydrothermal origin.

The geology of the Legris Lake Complex displays many similarities to contact-style PGE mineralization, such as that in the East Bull Lake intrusive suite.[19] The occurrence of mineralization in leucogabbro near the contact with underlying ultramafic rocks, however, exhibits similarities to stratiform-style mineralization in large, layered, mafic–ultramafic complexes.

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References

1. Barnes S. J., Keays R. R. and Hoatson D. M. Distribution of sulphides and PGE within the porphyritic websterite zone of the Munni Munni Complex, Western Australia, *Aus. J. Earth Sci.*, **39**, 1992, 289–302.
2. Boudreau A. E. Chlorine as an exploration guide for the platinum-group elements in layered intrusions. *J. geochem. Explor.*, **48**, 1999, 21–37.
3. Brügmann G. E., Naldrett A. J. and Macdonald A. J. Magma mixing and constitutional zone refining in the Lac des Iles Complex, Ontario: genesis of platinum-group element mineralization. *Econ. Geol.*, **84**, 1989, 1557–73.
4. Davis D. W. and Edwards G. R. Crustal evolution of Archaean rocks in the Kakagi Lake area, Wabigoon Subprovince, Ontario as interpreted from high precision U–Pb geochronology. *Can. J. Earth Sci.*, **23**, 1986, 182–92.
5. Fleet M. E. *et al.* Laboratory partitioning of platinum-group elements (PGE) and gold with application to magmatic sulphide–PGE deposits. *Lithos*, **47**, 1999, 127–42.
6. Francis R. D. Sulphide globules in mid-ocean ridge basalts (MORB) and the effect of oxygen abundance in Fe–S–O liquids on the ability of those liquids to partition metals from MORB and komatiite magmas. *Chem. Geol.*, **85**, 1990, 199–213.
7. Gaetani G. A. and Grove T. L. Wetting of mantle olivine by sulphide melt; implications for Re/Os ratios in mantle peridotite and late-stage core formation. *Earth Planet. Sci. Lett.*, **169**, 1999, 147–63.
8. Gaetani G. A. and Grove T. L. Partitioning of moderately siderophile elements among olivine, silicate melt and sulphide melt: constraints on core formation in the Earth and Mars. *Geochim. cosmochim. Acta*, **61**, 1997, 1829–46.
9. Gupta V. K. and Sutcliffe R. H. Mafic–ultramafic intrusives and their gravity field; Lac des Iles area, northern Ontario. *Geol. Soc. Am. Bull.*, **102**, 1990, 1471–83.
10. Hrominchuk J. L. Geology, stratigraphy, geochemistry and copper–nickel–platinum group element mineralization in the River Valley intrusion. In *Summary of field work and other activities 2000. Open File Rep. Ont. geol. Surv.* 6032, 2000, 29-1–11.
11. Lavigne M. J. *et al.* Field trip 2 and 4 Lac des Iles mine. Field trip guidebook, Superior PGE 2001, CIM Geological field conference, 16–19 Sept. 2001. www.cim.org.
12. Macdonald A. J. Platinum-group element mineralization and the relative importance of magmatic and deuteric processes; field evidence from the Lac des Iles deposits, Ontario, Canada. In Prichard H. M. *et al.* eds *Geo-platinum 87*, 1988, 215–36.
13. MacTavish A. D. The mafic–ultramafic intrusions of the Atikokan–Quetico area, northwestern Ontario. *Open File Rep. Ont. geol. Surv.* 5997, 1999.
14. Mavrogenes J. A. and O'Neill H. S. C. The relative effects of pressure, temperature and oxygen fugacity on the solubility of sulphide in mafic magmas. *Geochim. cosmochim. Acta*, **63**, 1999, 1173–80.
15. McDonough W. F. and Sun S-S. The composition of the Earth. *Chem. Geol.*, **120**, 1995, 223–53.
16. Michaud M. J. The geology, petrology, geochemistry and platinum-group element–gold–copper–nickel ore assemblage of the Roby Zone, Lac des Iles mafic–ultramafic complex, northwestern Ontario. M.Sc. thesis, Lakehead University, Ontario, 1998.
17. Naldrett A. J. and Cabri L. J. Ultramafic and related mafic rocks, their classification and genesis with special reference to the concentration of nickel sulphides and platinum-group elements. *Econ. Geol.*, **71**, 1976, 1131–58.
18. Paces J. B. and Miller Jr. J. D. Precise U–Pb ages of Duluth Complex and related mafic intrusions, northeastern Minnesota: geochronological insights to physical, petrogenetic, paleomagnetic and tectonomagmatic processes associated with the 1.1 Ga mid-continent rift system. *J. Geophys. Res.*, **98**, 1993, 13997–14013.

19. Peck D. C. *et al.* Controls on the formation of contact-type platinum-group element mineralization in the East Bull Lake intrusion. *Econ. Geol.*, **96**, 2001, 559–81.
20. Peck D. C. and Keays R. R. Insights into the behavior of precious metals in primitive, S-undersaturated magmas; evidence from the Heazlewood River complex, Tasmania. *Can. Miner.*, **28**, 1990, 553–7.
21. Pettigrew N. T. Report on 1999–2000 exploration Legris Lake palladium–platinum property, Avalon Ventures, Ltd./Starcore Resources, Ltd., Joint Venture company report, 2000.
22. Prendergast M. D. The geology and economic potential of the PGE-rich Main Sulphide Zone of the Great Dyke, Zimbabwe. In Prichard H. M. *et al.* eds *Geo-platinum 87* (London: Elsevier, 1988), 281–302.
23. Puchtel I. and Humayun M. Platinum group elements in Kostomuksha komatiites and basalts. Implications for oceanic crust recycling and core–mantle interaction. *Geochim. cosmochim. Acta*, **64**, 2000, 4227–42.
24. Puchtel I. S. and Humayun M. Platinum group element fractionation in komatiitic basalt Lava Lake. *Geochim. cosmochim. Acta*, **65**, 2001, 2979–93.
25. Pye E. G. and Fenwick G. Atikokan–Lakehead sheet. Ontario Dept of Mines, Compilation Series, map 2065, 1964, scale 1 : 253400.
26. Raedeke L. D. and McCallum I. S. Investigations of the Stillwater Complex, II. Petrology and petrogenesis of the Ultramafic series. *J. Petrology*, **25**, 1984, 395–420.
27. Rehkamper M. *et al.* Ir, Ru, Pt and Pd in basalts and komatiites: new constraints for the geochemical behavior of the platinum-group elements in the mantle. *Geochim. cosmochim. Acta*, **63**, 1999, 3915–34.
28. Sassani D. C. and Shock E. L. Solubility and transport of platinum-group elements in supercritical fluids: summary and estimates of thermodynamic properties for ruthenium, rhodium, palladium and platinum solids, aqueous ions and complexes to 1000°C and 5 kbar. *Geochim. cosmochim. Acta*, **62**, 1998, 2643–71.
29. Sutcliffe R. H. Regional geology of the Lac des Iles area, District of Thunder Bay. *Misc. Pap. Ont. geol. Surv.*, **132**, 1986, 70–5.
30. Sutcliffe R. H. Magma mixing in late Archaean tonalitic and mafic rocks of the Lac des Iles area, Western Superior Province. *Precamb. Res.*, **44**, 1989, 91–101.
31. Sutcliffe R. H., Sweeny J. M. and Edgar A. D. The Lac des Iles Complex, Ontario: petrology and platinum-group elements mineralization in an Archaean mafic intrusion. *Can. J. Earth Sci.*, **26**, 1989, 1408–27.
32. Sweeny J. W. and Sutcliffe R. H. Geology and platinum group element mineralization of the Roby Zone, Lac des Iles Complex. In *Summary of field work and other activities 1986. Misc. Pap. Ont. geol. Surv.*, **132**, 1986, 82–4.
33. Talkington R. W. and Watkinson D. H. Trends in the distribution of the precious metals in the Lac des Iles Complex, northwestern Ontario. *Can. Miner.*, **22**, 1984, 125–36.
34. Tatsumi Y., Oguri K. and Shimoda G. The behaviour of platinum-group elements during magmatic differentiation in Hawaiian tholeiites. *Geochem. J.*, **33**, 1999, 237–47.
35. Todd S. C. *et al.* The J-M platinum–palladium reef of the Stillwater Complex, Montana: I. Stratigraphy and petrology. *Econ. Geol.*, **77**, 1982, 1454–80.
36. Vogel D. C. and Keays R. R. The petrogenesis and platinum-group element geochemistry of the Newer Volcanic Province, Victoria, Australia. *Chem. Geol.*, **136**, 1997, 181–204.
37. Von Gruenewaldt G., Sharpe M. R. and Hatton C. J. The Bushveld Complex: Introduction and review. *Econ. Geol.*, **80**, 1985, 803–12.
38. Wendlandt R. F. Sulphide saturation of basalt and andesite melts at high pressures and temperatures. *Am. Miner.*, **67**, 1982, 877–85.
39. Williams H. R. Subprovince accretion tectonics in the south-central Superior Province. *Can. J. Earth Sci.*, **27**, 1990, 570–81.
40 Xiong Y. and Wood S. A. Experimental quantification of hydrothermal solubility of platinum-group elements with special reference to porphyry copper environments. *Mineral. Petrol.*, **68**, 2000, 1–28.

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