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Cu-Ni-PGE Mineralization and Petrogenesis of Mafic-Ultramafic Intrusions in the Western Quetico and Wabigoon Subprovinces, Northwestern Ontario, Canada

By
Neil Thomas Pettigrew

A thesis submitted to the School of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of M.Sc. in Earth Sciences

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Global Summary

This project focused on Cu-Ni-PGE mineralization and petrogenesis of mafic-ultramafic intrusions in the western Quetico and Wabigoon Subprovinces of the Superior Province. Two intrusions were singled out for detailed study: the Legris Lake Complex, part of circular series of mafic-ultramafic complexes, which includes the Lac des Iles Complex, located in the Wabigoon Subprovince, and the Samuels Lake Intrusion, part of the Quetico Intrusions, located in the Quetico Subprovince.

Legris Lake Complex

The Legris Lake Complex is a northeast-trending 7.3 by 3.5 kilometre mafic-ultramafic intrusive complex. It is part of a circular series of mafic-ultramafic complexes, the most notable of which is the Lac des Iles Complex, which is host to Canada's only palladium mine. 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 by 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 characteristics of the PGE mineralization in the Legris Lake Complex are distinctly different from many PGE deposits where the ore occurs in sulphide-rich bodies at the base of mafic and ultramafic rocks, such as the Sudbury contact ores and Noril'sk. PGE enrichment in the Legris Lake Complex occurs in sulphide-poor (1-10 vol.%, less than 5 vol.% in most cases), medium to coarse grained, porphyritic leucogabbro (termed 'Main Showing-type') underlain by clinopyroxenite. The mineralized leucogabbro and underlying clinopyroxenite exhibits a sill-like form and are hosted within zones of intense magmatic brecciation. 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 (~0.2) and high Cu/Ni ratios (~3.0). PGE contents display a positive correlation with those of Cu and Ni. The origin of the mineralization is best explained by preferential partition 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. The 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 likely 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.

The majority of the Cu-Ni-PGE mineralization displays Pt/Pd and Cu/Ni ratios, which are similar to those of the Lac des Iles and the River Valley mafic-ultramafic complexes. The lithologies in Legris Lake Complex also bear similarities to the heterolithic gabbro of the Twilight and Roby Zone deposits at the nearby Lac des Iles mine. However the mineralization at Legris Lake, which is restricted to leucogabbro overlying unmineralized clinopyroxenite, is similar to that of stratiform deposits such as the Stillwater and Munni Munni Complexes of Montana USA and Australia respectively.

Samuels Lake Intrusion

The Samuels Lake intrusion, ca 2688 +6/-5 Ma, located in the centre of the Quetico Subprovince possesses a northeast-southwest elliptical form (500 m by 250 m) and displays rough concentric zoning with a wehrlite core grading into clinopyroxenite border zone, which has been intruded by later hornblendite. Olivine-rich rocks commonly contain blebs of pyrrhotite + chalcopyrite + pentlandite with anomalous PGE values, ranging from 50 to 300 ppb, whereas the clinopyroxenite border zone contains disseminated to blebby PGE-rich Cu-sulphide mineralization.

The Samuels Lake Intrusion is part of the Quetico Intrusions, which have traditionally referred to an east-west striking, 45 km long array of mafic-ultramafic intrusions along the northern Quetico Subprovince boundary. This study demonstrates that this array extends an additional 80 km to southwest including the Stawson Lake, Samuels Lake, and Red Horse intrusions. The Quetico Intrusions range in size from 3-5 m thick dykes of limited length to elliptical stocks up to 3300 m by 1800 m and intrude metaturbidites. They typically contain clinopyroxenite cores and hornblendite rims. Larger intrusions commonly contain wehrlite cores surrounded by clinopyroxenite, hornblendite, gabbro, diorite and syenite with gradational boundaries. They are also characterized by the presence of a pegmatitic phase containing plagioclase-cored hornblende in a plagioclase matrix, which is commonly referred to as "appinite". These intrusions are also commonly accompanied by Cu-Ni-PGE mineralization

The Quetico Intrusions display many similarities with Alaskan/Ural-type zoned intrusions found in Phanerozoic orogenic belts. Both formed from wet magmas as indicated by abundant primary hornblende and biotite, early crystallization of clinopyroxene, and myrmekitic texture in late dioritic phases. The parental magmas were transitional between tholeiitic and calc-alkaline affinities and show subduction-related geochemical signatures, such as high concentration of LILE and low Nb, Ta and Ti concentrations. Other common features include concentric zoning of lithological units, mineralogy and, PGE mineralization.

Introduction

A broad array of mafic-ultramafic intrusions occurs in the northern Quetico Subprovince and southern Wabigoon Subprovince. They intruded supracrustal rocks during the late Archean cratonization of the Superior Province, which involved accretion and collision of the Quetico sedimentary belt to the Wabigoon Subprovince to the north and later docking of the Wawa greenstone belt to the south. Therefore, these intrusions may contain information relevant to the formation of Canadian continent. Yet, these intrusions are poorly documented. Furthermore, these intrusions are of economic interest because they are commonly accompanied by Cu-Ni-PGE mineralization. Exploration in the area has greatly increased in recent years due to the increased price of palladium and expansion of the Lac des Iles palladium mine in the southern Wabigoon Subprovince.

The Samuels Lake Intrusion in the Quetico Subprovince and the Legris Lake Complex in the Southern Wagiboon Subprovince were selected for detailed studies. The Samuels Lake Intrusion is similar to a linear array of mafic-ultramafic intrusions referred to as the Quetico Intrusions whereas the Legris Lake Complex belongs to a circular series of mafic-ultramafic complexes, which includes the Lac des Iles Complex. The surface exposures of these intrusions are poor, however recent exploration activities in these areas provided the author excellent access to newly excavated trenches and numerous drill core samples.

The projects had the following objectives:

- produce detailed geological maps of the two intrusions
- document and propose models for the formation of the intrusions using bulk rock geochemistry, mineral geochemistry, and petrography
- document and propose models for the intrusions Cu-Ni-PGE mineralization
- compare these intrusions with other known types of mafic-ultramafic intrusions

Manuscript I and II are primarily based on the author's 16 months of field work in the Legris Lake Complex while a part-time student and an employee of Avalon Ventures Ltd. Manuscript I describes the geology of the Complex and the content has been presented at *Superior PGE 2001* hosted by the local chapter of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Geological Society in Thunder Bay in September, 2001. It was printed in Exploration and Mining Geology in 2001. Manuscript II focuses on the Cu-Ni-PGE mineralization in the Legris Lake Complex and was presented at *Palladium Deposits: Current and Future* hosted by the Mineral Deposits Studies Group of the Geological Society of London in Southampton (UK) in 2002. It was published in the Series B of Transactions of the Institution of Mining and Metallurgy (London) in 2002. Manuscript III is based on the author's two summers of field work in the Quetico intrusions as a full-time graduate student. It documents the Quetico Intrusions and proposes that the Quetico Intrusions are Archean equivalents of Alaskan/Ural-type intrusions in Phanerozoic orogenic belts. These data were presented at the *Annual Joint meetings of Western Superior Lithoprobe Transect and Western Superior NATMAP in* 2000 and 2001 in Ottawa, and the *Institute of Lake Superior*

Geology Annual Meeting in 2000 in Thunder Bay. An extended abstract of the presentation in 2000 appears in *Lithoprobe Report*, no. 77, p. 104-110 (2001). The summary of fieldwork appears in Geological Survey of Canada Current Research 2000-C20 in 2000. The appendices include bulk rock compositions, compositions of primary and secondary minerals, the Current Research 2000-C20 manuscript, and the 2001-2002 company report on the Legris Lake Complex produced by the author while in the employ of Avalon Ventures Ltd.

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Geology of the Palladium-Rich Legris Lake Mafic-Ultramafic Complex, Western Wabigoon Subprovince, Northwestern Ontario

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Footnote

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This manuscript was submitted prior to a major exploration program conducted on the Legris Lake Complex in 2001. This has resulted in refining of observations and interpretations presented in this manuscript.

ABSTRACT

The Legris Lake Complex is a northeast-trending, 7.3 kilometre long by 3.5 kilometre wide, mafic-ultramafic intrusive complex located in the western Wabigoon Subprovince of the Archean Superior Province. It is one of a series of mafic-ultramafic igneous complexes, the most notable of which is the Lac des Iles complex, host to Canada's only producing palladium (Pd) mine with reserves of 93.5 million tones grading 1.53 g/t Pd as of December 2001(North American Palladium Ltd., Annual Report 2001). Cu-Ni-PGE mineralization was first discovered in the Legris Lake Complex by a local prospector late in 1999. Shortly thereafter, the property was jointly optioned by Avalon Ventures Ltd. and Starcore Resources Ltd., who continue to discover significant Cu-Ni-PGE mineralization.

One of the most notable features of the Legris Lake Complex is the occurrence of extensive brecciation caused by multiple injections of volatile-rich magma. The Cu-Ni-PGE mineralization is hosted by leucogabbro within a 2 kilometre long by 600 metre wide, highly brecciated area in the Northwestern area of the Complex. The mineralized rocks contain disseminated to blebby sulphides (1 to 5 vol.%), comprising chalcopyrite + pyrite ± pyrrhotite + millerite ± pentlandite, typically surrounded by epidote. The majority of the Cu-Ni-PGE mineralization displays low ratios of Pt/Pd (~0.20) and high ratios of Cu/Ni (~2.9), which are similar to those of the Lac des Iles and the River Valley mafic-ultramafic complexes. The lithologies in Legris Lake Complex bear similarities to the heterolithic gabbro of the Twilight and Roby Zone deposits at the nearby Lac des Iles mine. However the mineralization at Legris Lake, which is restricted to leucogabbro overlying unmineralized clinopyroxenite, is similar to that of stratiform deposits such as the Stillwater and Munni Munni Complexes. The mineralization at Legris Lake is best explained by the late-stage, immiscible separation of a

sulphide melt from volatile-rich parental magmas and the subsequent minor redistribution of metals by deuteric fluids.

INTRODUCTION

The 7.3 kilometre long by 3.5 kilometre wide Legris Lake Complex, located 85 kilometres north of the city of Thunder Bay, Canada, is part of the 12,680 acre claim group collectively called the Legris Lake property (Fig. 1). The Legris Lake Complex is located approximately 8 kilometres southeast of the open pit in the Roby Zone deposit of North American Palladium's Lac des Iles palladium mine (Lavigne and Michaud 2002). Placer Dome Ltd. entered into an option/joint venture agreement in April of 2001 to spend $4,000,000 over the next four years to acquire a 50% interest in the Legris Lake property. Previous work on the Legris Lake Complex has included: an aeromagnetic survey by the Ontario Department of Mines – Geological Survey of Canada in 1962; regional mapping in 1965 and 1985 (Kay, 1969; Sutcliffe and Smith, 1988); and airborne EM and VLF surveys, combined with limited ground-based HLEM, in 1988 by Heenan Senlac Resources Ltd.

Copper-nickel-platinum group element (Cu-Ni-PGE) mineralization was first discovered on the property in the fall of 1999 when Joe Hackl, a local prospector, collected a sample that returned an assay of 3.26 grams/ton (g/t) combined PGE. The property was subsequently jointly optioned by Avalon Ventures Ltd. and Starcore Resources Ltd. in November 1999, with Avalon Ventures Ltd. acting as the operator of all exploration programs. Avalon Ventures Ltd. commenced line cutting and geophysical surveying in the winter of 1999-2000 and reconnaissance prospecting, stripping, channel sampling, and drilling in the summer of

2000. The initial results were very encouraging with Cu-Ni-PGE mineralization being intersected beneath the discovery showing in diamond drill hole (DDH) L00-01 (grading 0.61 g/t palladium (Pd), 0.16 g/t platinium (Pt), 0.10 g/t gold (Au), 0.17% copper (Cu), and 0.09% nickel (Ni) over 12 m) and in DDH L00-02 (grading 1.22 g/t Pd, 0.24 g/t Pt, 0.17 g/t Au, 0.32% Cu, and 0.10% Ni over 10.7 m). In addition, a new mineralization, located 500 metres southeast of the original discovery showing, was recognized at the top of DDH L00-04 (grading 0.52 g/t Pd, 0.16 g/t Pt, 0.19 g/t Au, 0.28% Cu, and 0.07% Ni over 4.70 m).

An extensive exploration program consisting of additional line cutting, geophysical surveying, prospecting, grid mapping, and diamond drilling was completed in the fall of 2000. This also yielded encouraging results: for example, DDH L00-08 intersected three separate mineralizations: 2.04 g/t Pd, 0.41 g/t Pt, 0.71 g/t Au, 0.42% Cu, and 0.013% Ni over 9.95 metres; 1.94 g/t Pd, 0.34 g/t Pt, 0.64 g/t Au, 0.29% Cu, and 0.11% Ni over 3.80 metres; and 1.32 g/t Pd, 0.27 g/t Pt, 0.30 g/t Au, 0.33% Cu, and 0.10 Ni over 3.00 metres. In addition, a third zone was discovered 500 metres northeast of the original discovery showing (termed the Main Showing) during prospecting. The vertical extent of this third zone was tested by DDH L00-07, which intersected a mineralized zone grading 0.96 g/t Pd, 0.15 g/t Pt, 0.10 g/t Au, 0.13% Cu, and 0.04% Ni over 4.92 metres. Expenditures to as of December 2000 on the property by the Avalon/Starcore joint venture total approximately $400,000. A more detailed description of the exploration history appears in Pettigrew (2000, 2002) and that of the mineralization in Pettigrew and Hattori (2002).

REGIONAL GEOLOGY

The Legris Lake Complex is situated in the southern Wabigoon Subprovince of the Archean Superior Province (Fig. 1). It is one of a series of mafic-ultramafic intrusions that form a circular pattern approximately 30 kilometres in diameter (Sutcliffe, 1986), which includes the PGE-bearing Lac des Iles complex, the Tib Lake intrusion, Demars Lake intrusion, Wakinoo Lake intrusion, Towle Lake intrusion, Buck Lake intrusion, the Taman Lake intrusion, and the Dog River intrusion (Fig. 1).

Deformation and Metamorphic History

Structural studies of supracrustal rocks completed elsewhere in the Wabigoon Subprovince suggest three deformation events in the area (Blackburn et al., 1991). Steeply-plunging early folds (F_1) were refolded with an east-trending axis of unknown plunge (F_2), and both of these folds were refolded about northeast-plunging axes during the emplacement of the adjacent granitoid rocks (D_3) (Blackburn et al., 1991). The supracrustal rocks have undergone greenschist facies regional metamorphism with middle amphibolite grade around the late granitoid batholiths (Ayers, 1978) after the major episode of folding (Poulsen et al., 1980).

Intrusions

Granitic rocks in the Wabigoon subprovince have been subdivided into three groups (Blackburn et al., 1991):

1. The tonalitic igneous rocks (*circa* 3 Ga);

2. Granitoid complexes (2732-2708 Ma), with Na-rich marginal phases, which are accompanied by rare mafic to ultramafic stocks. These granitoids are associated with co-magmatic volcanic rocks (Davis et al., 1982; Edwards and Davis, 1984); and
3. Post-tectonic granitoid stocks (2709-2685 Ma), in and marginal to the greenstone belts. The voluminous, late granodiorite pluton located to the west of the Legris Lake Complex belongs to this group.

Mafic-ultramafic intrusions in the Wabigoon Subprovince are subdivided into three groups (Blackburn et al., 1991):

1. Serpentinized ultramafic intrusions, such as the Chrome Lake-Puddy lake intrusion, which are interpreted to have been emplaced in a manner similar to that of Phanerozoic, Alpine-type intrusions (Whittaker, 1980);
2. Synvolcanic sills, such as the Bad Vermilion and Mulcahy intrusions; and
3. Mafic to ultramafic intrusions of largely tholeiitic character (Blackburn et al., 1991; Sutcliffe et al., 1989) that are associated with the post-tectonic granitoids emplaced at *circa* 2.69 Ga. The Legris Lake Complex belongs to this group, which also includes the Lac des Iles Complex ($2692^{+4}/_{-2}$, Davis and Edwards, 1986; Sweeny and Sutcliffe, 1986) and the Entwine Lake intrusion (Davies, 1965).

GEOLOGY OF THE LEGRIS LAKE AREA

Country rocks

Metasedimentary rocks (unit 2): Sandstone (unit 2b) is the most common sedimentary rock in the area. It consists of fine- to medium-grained, arkose to greywacke that has a dull light brown colour in the field. This unit always displays a well-developed space cleavage and commonly contains red garnet close to the contact with the Legris Lake Complex, indicating that it has undergone at least lower amphibolite facies contact metamorphism. Poorly-sorted pebble to cobble conglomerate (unit 2a) with a greywacke matrix is common in the western part of the area. Clasts in the conglomerates are well rounded and comprise a variety of rock types including sedimentary, volcanic, and dioritic and granitic rocks. A low to moderate degree of flattening of the clasts is common. Minor siltstone to pelitic beds (unit 2c), and thin oxide facies (magnetite) iron formations are commonly interbedded within sandstone beds.

Basaltic rocks (unit 1a): Voluminous mafic volcanic rocks occur both north and southeast of the Complex. This fine-grained unit displays a good space cleavage, and is generally non-magnetic.

Granitic Rocks (unit 7 and 6): Granitic rocks in the area range in composition from tonalite to granite with minor diorite and are associated with the intrusion of the voluminous granodiorite pluton west of the Legris Lake Complex. Medium-grained granodiorite (Fig 3A) is the most common intrusive rock type in contact with the western and southern parts of the Legris Lake Complex. It contains ~50 vol.% plagioclase, ~25 vol.% quartz, ~10 vol.% hornblende, ~15 vol.% biotite, and variable amounts of magnetite. This marginal phase of the pluton displays moderate to strong foliation defined by the preferred orientation of biotite and is strongly magnetic with high contents of magnetite, whereas the interior of the pluton is massive and non-magnetic. The granodiorite pluton post-dates the Legris Lake Complex as numerous granodiorite dykes and sills related to the former cut the Complex.

Deformation of the Country Rocks

The Legris Lake area records only one major regional deformation event. This event corresponds to the northeast striking, southeast dipping, space-cleavages associated with greenschist facies metamorphic conditions. This space cleavage is parallel to the Wabigoon-Quetico Subprovince boundary and most likely formed during the accretion of the Quetico onto the Wabigoon Subprovince. Primary sedimentary textures, such as slumping and cross-bedding, are commonly preserved in the country rocks. Deformation intensifies proximal to the Legris Lake Complex, where local penetrative foliations, mineral lineation, and tight chaotic folds are well developed under amphibolite facies metamorphic condition (Fig. 3A). The occurrence of intense deformation and amphibolite grade metamorphism only in the areas proximal to the Complex suggests that they formed during the intrusion of the Complex. The lack of any penetrative fabric (space-cleavage or foliation) within the Legris Lake Complex and destruction of the regional space cleavage in the adjacent country rocks indicates that it intruded after or possibly contemporaneous with the regional deformation/metamorphism.

A later north-south trending fracture set formed under subgreenschist facies condition overprints all Archean rocks in the area

Dykes in the Legris Lake Complex

Granodiorite dykes related to the voluminous granodiorite pluton lack a space cleavage and are commonly associated with narrow feldspar-quartz pegmatites and retrograde alteration halos in the Complex. Quartz-feldspar porphyry dykes (unit 7d) are distinguished from the more abundant granodiorite dykes. These dykes are narrow (<3 m wide), of limited length, and only observed in the northwestern area of the Complex. The quartz-feldspar porphyry dykes are typically medium-grained (~2 mm), non-magnetic, and quartz-rich (~40 vol.%), with few mafic minerals (<5 vol.%). These dykes lack wide alteration halos and post-dated the majority of the deformation in the Legris Lake Complex. The evidence suggests that these felsic dykes are similar in age, but cross-cutting relationships among different dykes are not observed.

Rare melanogabbro dykes also cut the northwestern part of the Complex and have also been observed to cut the voluminous granodiorite pluton. The dykes, dubbed the Stonefish Lake subtype, are medium- to coarse-grained, consisting of elongate plagioclase phenocrysts (up to 1 cm by 2 mm) in a fine-grained, biotite-bearing matrix. These dykes locally contain thin (~2 cm) magnetite-rich lenses.

The Legris Lake Complex is also cut by rare Keweenawan (~1.1 Ga) diabase dykes and sills. Dykes are aphanitic and sills are medium-grained. A few erosional remnants of previously overlying diabase sills are found on nearby Archean rocks (Fig. 2).

Overburden

The area has been glacially scoured, leaving consistent glacial striations with an orientation of ~245°. The property is covered by basal and ablation till, which is in turn overlain by glaciofluvial deposits. The rock exposure in the northwestern part of the Complex comprises less than 3% of the area as it is evenly covered by basal and ablation tills, small eskers, and several large boulder-strewn bogs. The western and southwestern parts of the Complex also have poor rock exposure (< 5% of the area), being covered by a combination of glaciofluvial gravel and cobbles, several large eskers, and paleo-delta deposits. The centre of the Complex has better exposure (~20 % of the area) with less than 1 metre of overburden. The eastern part of the Complex has very poor exposure (<1% of the area) and thick (>3 m) overburden consisting of glaciofluvial sand and several large gravel eskers.

The Legris Lake Mafic-Ultramafic Complex

The distribution of mafic-ultramafic intrusions in the area suggests that the Legris Lake Complex (Fig. 1) was most likely emplaced contemporaneously with the Lac des Iles mafic-ultramafic complex of 2692 $^{+4}/_{-2}$ Ma (Davis and Edwards 1986). The Legris Lake Complex comprises a wide range of intrusive rock types from leucogabbro to dunite in composition, with biotite-rich leucogabbro (unit 5ab) being the predominant rock type (Fig. 2). Based on the distribution of lithological units, the Complex is divided into five areas; the Central, Northwestern Border, Southwestern Border, Northeastern Border, and Southeastern Border areas (Fig. 2). The Central area, located in the core of the Complex, is composed almost entirely of biotite-rich leucogabbro (unit 5ab; Figs. 2 and 5) that locally contains up to 10 vol.% quartz.

The Northwestern Border area is economically important since it hosts all of the Cu-Ni-PGE mineralization discovered to date (Figs. 2 and 5). Geological mapping in this area was hindered by the poor rock exposure, the heterogeneity of the lithologies, and the apparent disagreement between the nature of the exposed rocks and the attendant geophysical signatures. To investigate the geology of the Northwestern Border area, 540 metres of trenching were completed. The trenching revealed the complicated unpredictable distribution of the rocks types. Lithologies commonly change over distances of less than 5 metres. Diamond drill-holes DDH L00-01, -02, -03, -04, -08, and -09 were drilled along a fence between lines 9500N and 9600N, parallel to the trench, in an attempt to provide subsurface data of the area (Fig. 6). The diamond drilling revealed that the complexity observed on surface is also present at depth. Although trench and drill sections generally did not correlate, mineralized leucogabbro displayed good down-dip continuity. The Northwestern Border area appears to have a very moderate to steep boundary with the mesogabbro (unit 5b) and leucogabbro (unit 5ab) of the Central area of the Complex, with the boundary being between DDH L00-08 and L00-09 (Fig. 6).

The complicated interaction of melt, semi-solidified crystal mush, and solidified magmas has produced various textures and structures such as the local alignment of minerals and fragments, and shearing in the Legris Lake Complex. The shear sense is mostly sinistral and may have been influenced by contemporaneous regional deformation. Small- to medium-scale folding is also observed, although these structures display no consistent patterns. These structures are commonly in the form of ductile S folds, but also occur as discordant open undulating folds, and as rare refolded folds.

The Southwestern Border area is characterized by the second largest body of leucogabbro (unit 5a*), and also by the lack of any heterolithic breccia. It exhibits a less complicated assemblage of lithologies and structures than the Northwestern Border area (Fig. 2 and 5). It also hosts a magnetite-rich, zoned ultramafic dyke, which is not exposed on surface, but was intersected by DDH L00-06.

The Northeastern Border area comprises most of the northeastern half of the Legris Lake Complex (Fig. 2). It consists mostly of mesogabbro (mesocratic gabbro) but also contains several large (up to 600 by 400 m) ultramafic (unit 3a and 3b) bodies, large metasedimentary xenoliths or roof pendants, and a large zone of clinopyroxenite breccia (unit 4d), which is similar to that at the Lac des Iles mine. This area has the poorest exposure of the five areas; therefore much of the geological interpretation of the area is based mainly on geophysical data. This area has received only reconnaissance prospecting and mapping.

The Southeastern Border area, 1.8 by 1.0 kilometres, consists of rock types ranging from biotite-rich leucogabbro (unit 5ab) to poikilitic (clinopyroxene enclosing clinopyroxene) clinopyroxenite, with minor igneous breccia, which are in contact with country, clastic metasedimentary rocks with thin, interbedded oxide facies iron formations (Fig. 2). The area is characterized by the presence of large (up to 1.0 by 0.3 km) metasedimentary roof pendants (Fig. 2). The roof pendants are composed of mostly massive but locally bedded wacke to arkosic sandstone and appear to be a thin veneer as several windows expose underlying gabbroic rocks. The metasedimentary rocks of the roof pendants locally show evidence of partial melting, indicated by local melt segregations and fluidic flow textures. The tectonic fabric that is common in metasedimentary country rocks has also been obliterated. Most metamorphic minerals in these roof pendants appear to have retrograded to biotite with only a few garnets remaining. This area also possesses a distinct type of igneous breccia consisting of coarse-grained clinopyroxenite broken up on a mineral scale by a dioritic to granodioritic matrix. This area has also received only reconnaissance prospecting and mapping.

Leucogabbro (unit 5a): This unit contains many different phases and has been further divided into four subtypes (Figs. 2, 5, and 6):

Main showing subtype (unit 5a)*: This subtype hosts nearly all of the Cu-Ni-PGE mineralization discovered thus far in the Complex. It is easily identified in the field by its striking white plagioclase phenocrysts and black to dark green interstitial clinopyroxene that is altered to hornblende (Fig. 4A). Unit 5a* is medium- to coarse-grained (4-8 mm), and is composed of ~65 vol.% plagioclase, ~35 vol.% clinopyroxene (typically altered and pseudomorphed by hornblende), ~1.5 vol.% quartz, up to 3 vol.% magnetite, with trace amounts of apatite and zircon. Apatite contents are high as 5 vol.% in some rocks. This unit has been brecciated locally by the intrusion of fine-grained, magnetite-rich leucogabbro and melanogabbro.

Varitextured subtype (unit 5aa): This subtype exhibits a wide variation in the size and shape of plagioclase phenocrysts and locally contains fine- to coarse-grained pegmatitic pods. It grades into the leucogabbro of the Main showing subtype (unit 5a*) in several locations. Unit

5aa also locally contains Cu-Ni-PGE mineralization, and is similar in texture and composition to the varitextured gabbro unit of the Lac des Iles Complex (Lavigne and Michaud 2002).

Biotite-rich subtype (unit 5ab): This subtype occurs in the centre of the Complex and is massive with locally weak fabrics. It contains abundant primary and secondary biotite (Fig. 4B). Unit 5ab is typically medium-grained (2-4 mm), and consists of plagioclase (~60 vol.%), altered clinopyroxene (~25 vol.%), quartz (<5 vol.%), biotite (>10 vol.%) and apatite (< 5 vol.%). Primary clinopyroxene is entirely replaced by secondary hornblende, and locally by secondary biotite. It has undergone intense saussuritization (fine-grained sericite-epidote-carbonate alteration) of feldspar, and developed large patches (tens of metres in size) of orange hematitic alteration. Unit 5ab is moderately magnetic (unaltered) to non-magnetic (altered) depending on the degree of feldspar alteration. No Cu-Ni-PGE mineralization has yet been discovered in unit 5ab, but pyrite (up to 2 vol.%) may be present locally.

Mottled Anorthosite (unit 5ac): This subtype is found predominant in the Northwestern Border area of the Complex. The most voluminous occurrence is at the Main Showing where it forms a thick unit in contact with the mineralized 5a* leucogabbro (Fig. 18). The anorthosite possibly represents more fractionated phase of the leucogabbro. The anorthosite is medium- to coarse-grained, overall nonmagnetic, and composed of highly saussuritized plagioclase with interstitial clinopyroxene mottles, which occasionally contain disseminated magnetite. The clinopyroxene mottles defines a foliation in the Main Showing and they have been completely altered to hornblende and subsequently to chlorite ± biotite. Copper-Ni-PGE mineralization (up to 200 ppb PGE) has been intersected by diamond drilling in this rock type at the Main Showing but it is generally unmineralized.

Mesogabbro (unit 5b): This is primarily a transitional unit between the biotite-rich leucogabbro (unit 5ab) and the melanogabbro (unit 5c).

Melanogabbro (unit 5c): The melanograbbro unit contains several phases. All phases are medium-grained (~3 mm) with abundant plagioclase, and clinopyroxene that is altered to hornblende (Fig. 4C). This unit commonly grades into clinopyroxenite (Figs. 2 and 5). The unit is commonly strongly magnetic because of the occurrence of up to 15 vol.% interstitial magnetite. It may contain sulphide minerals (up to 3 vol.%) as blebs of pyrrhotite and pyrite. Some contain chalcopyrite as an exsolved phase. This unit in DDH L00-08 is intensely chloritized with locally high concentrations of Cu (up to 760 ppm) and Ni (up to 256 ppm), but low contents of PGE (typically <5 ppb with one exception of 100 ppb PGE).

Clinopyroxenite (unit 3a): This medium- to very coarse-grained unit is common near the western contact of the Legris Lake Complex (Figs. 2 and 5) where it commonly grades into melanogabbro. The clinopyroxene is mostly altered to a mixture of hornblende, actinolite, and chlorite. This unit is moderately to strongly magnetic. No Cu-Ni-PGE mineralization has been discovered in this unit, however it is always in contact with mineralized leucogabbro (unit 5a*). This spatial relationship suggests that the two units are likely related.

Wehrlite (unit 3b) and Dunite (unit 3c): Both units are not exposed on surface and are only observed in DDH L00-06. The two phases grade into one another as the content of clinopyroxene varies. They are fine- to medium-grained (1-3 mm) rocks consisting of clinopyroxene, olivine, and magnetite (~10 vol.%). The clinopyroxene is altered to hornblende and minor actinolite. All olivine grains are serpentinized, forming net-textured and patches of magnetite. They are not accompanied by PGE mineralization. Low Ni contents (<335 ppm) in dunite suggest that Ni may have been removed by sulphide melt from the parental magma before the crystallization of olivine.

Heterolithic breccia (unit 4a): This is the most common type of breccia in the Legris Lake Complex (Fig. 4D), forming a 600 metre by 2 kilometre wide area in Northwestern Border area (Figs. 2 and 5) over which the metasedimentary country rocks grade into the breccia unit. The breccia contains abundant partially assimilated metasedimentary rocks, minor gabbroic rocks, and exotic rocks that are not exposed in the area. The matrix of the heterolithic breccia varies from quartz diorite, leucogabbro, to granodiorite. Fragments of metasedimentary rocks have undergone retrograde alteration subsequent to becciation transforming garnet to biotite.

The heterolithic breccia (unit 4a) has been intruded by several later gabbroic phases. All of the mineralized leucogabbro (*i.e.* Main showing subtype of unit 5a*) is spatially associated with the heterolithic breccia. The breccia unit may represent the product of the incorporation of a thin veneer of sedimentary rocks overlying the Legris Lake Complex, an interpretation that is supported by the exposure of a large finger of metasedimentary rocks extending into the heterolithic gabbro from the north-northwest contact of the intrusion (Fig. 2).

Alternatively, the heterolithic breccia unit may represent the remnants of a structural corridor, located along the northwest margin of the Legris Lake Complex, exploited by intruding magmas and escaping volatiles in a manner similar to the formation of the heterolithic gabbro at Lac des Iles and the breccia zone lining the western contact at the River Valley intrusion.

Leucogabbro breccia (unit 4b): This unit, which is defined as a breccia with predominantly gabbroic clasts in a leucogabbroic matrix, is relatively uncommon. The unit in DDH L 00-07 contains Cu-Ni-PGE mineralization. The mineralized unit contains chloritized clasts of leucogabbro (unit 5a*) and a fine-grained, magnetite-rich leucogabbroic matrix. Both the clasts and matrix are mineralized.

Meso- to melanogabbro breccia (unit 4c): This unit is common in the Complex (Figs. 2 and 5) and appears to be more abundant at deeper levels in the Northwestern Border area than on the surface (Fig. 6). Predominantly gabbroic clasts are set in a matrix of mesocratic to melanocratic gabbro. Metasedimentary clasts are common in the Northwestern Border area.

Clinopyroxenite breccia (unit 4d): This unit contains predominantly gabbroic clasts set in a clinopyroxenite matrix (Fig. 4F, 5), and is very similar to the igneous breccia at Lac des Iles. Another type of clinopyroxenite breccia is found near the eastern contact of the intrusion. The latter type consists of fractured clinopyroxenite in a matrix of plagioclase and quartz.

Alteration in the Legris Lake Complex

The Legris Lake Complex displays at least two stages of alteration: amphibolite facies deuteric alteration associated with the intrusion of the Complex and greenschist facies retrograde alteration associated with late granitoid emplacement and associated dykes and pegmatites. Deuteric alteration took place during successive phases of injection and solidification of mafic magma in the Complex, and resulted in: 1) the uralization of clinopyroxene to produce hornblende, and the serpentinization of olivine; 2) the destruction of garnet in metasedimentary xenoliths; 3) minor sericitization and saussurization of plagioclase; and 4) local, intense chloritization of gabbroic phases and actinolite alteration of secondary hornblende after clinopyroxene.

Local retrograde alteration under greenschist facies conditions occurred contemporaneously with the intrusion of the large granitoid pluton to the west of the Complex. The alteration is most intense where the Complex is in contact with pluton and along the margins of its associated granitic to dioritic dykes, which intrude the Legris Lake Complex and overprint the effects of the earlier deuteric alteration. This event caused widespread saussurization and hematitic alteration of plagioclase, and the destruction of magnetite in the mafic-ultramafic rocks. Biotite alteration occurs pervasively in metasedimentary xenoliths and country rocks in the Northwestern Border area and in gabbros along the margins of granitic dykes and semi-ductile shear planes. Apple-green epidote alteration occurs mostly along the contacts with the granitic dykes and in shear planes, intense alteration produces rocks composed of nearly pure epidote over widths of several metres flanking the dykes (such as those observed in DDH L00-05). Albitization is less intense and is usually associated with areas of orange, hematitic alteration; but intense albitization does occur in rock with intense epidote alteration. Orange, hematitic alteration and albitization are common adjacent to narrow (<1 m wide) granodiorite dykes. Chlorite commonly pseudomorphs secondary hornblende, and actinolite also replaces secondary hornblende. This event is also accompanied by the formation of narrow (<1 cm) veins of quartz ± chlorite ± calcite ± epidote. Very narrow carbonate veinlets are commonly accompanied by the obliteration of primary igneous textures and by the presence of pervasive carbonate alteration halos several centimetres in width. Narrow (<1 m) shear zones may also be filled with ankerite ± pyrite.

COPPER-NICKEL-PLATINUM-GROUP ELEMENTS MINERALIZATION

Distribution of the Mineralization

Copper-Ni-PGE mineralization is mostly restricted to leucogabbro (units 5a* and 5aa) in the Northwestern Border area of the Complex (Figs. 5 and 6). Mineralized leucogabbro bodies, such as the one which hosts the Main Showing, display northeast strikes with both southeast and northwest steep to moderately dips (Fig. 6). These mineralized leucogabbro bodies always share a lower contact with unmineralized clinopyroxenite or melanogabbro (Fig. 6), with Cu-Ni-PGE focused at the contact between the two units.

Diamond drill-hole L-00-07, located ~500 metres northeast of the Main Showing, intersected leucogabbro breccia with significant Cu-Ni-PGE mineralization. In the latter occurrence, mineralization occurs in clasts and matrix, suggesting that the mineralization was continuous during and after brecciation. High PGE contents were also observed in a magnetite-rich leucogabbro in DDH L00-03, which is significantly different in texture from the Main Showing subtype (unit 5a*) leucogabbro (Fig. 6). The discovery of Cu-Ni-PGE mineralization in these rocks suggests that undiscovered mineralization may exist in other units of the Complex.

Characteristics of the Cu-Ni-PGE Mineralization

The Cu-Ni-PGE mineralization typically occurs as disseminated to blebby sulphides (locally representing up to 15 vol.% of the rock) that comprise a mixture of chalcopyrite + pyrite ± pyrrhotite + millerite ± pentlandite. Chalcopyrite is the predominant metallic mineral, comprising greater than 40 vol.% of the sulphides. Typically, all sulphide minerals are surrounded by halos of coarse-grained epidote (Figs. 7A and 7B) which, when strongly Cu-Ni-PGE mineralized give the rock a characteristic very dark green colour (Fig. 7A). Rare carbonate inclusions are also found in sulphide aggregates, and chlorite is common near the sulphide blebs.

Geochemical Characteristics of the Cu-Ni-PGE Mineralization

The Cu-Ni-PGE mineralization is characterized by consistently low Pt/Pd ratios of ~0.20 (Fig. 8A), and variable Cu/Ni ratios between 5.6 and 0.1 (Fig. 8B) with an average value of 2.9. The enrichment of PGE is positively correlated with the enrichment of Cu (Fig. 8C) and Ni (Fig. 8D). Consequently, the concentration of PGE in the Complex is related to the amount of Cu and Ni sulphides (Fig. 8E). The concentration of Au is also positively correlated with that of PGE (Fig. 8F). The ratios of Au/(Pt+Pd) display considerable scatter, ranging in values from 0.97 to 0.02 with an average value of 0.13.

Ten rock samples containing greater than 1 g/t combined PGE were selected for rhodium (Rh) analysis. The Cu-rich samples (n = 9) from DDH L00-01, -02, -04, -07, and -08 all contain low concentrations of Rh (<40 ppb), however one sample at depth (from the interval between 285.18 and 285.95 m in DDH L00-03) yielded a much higher concentration of Rh (520 ppb), together with values of 910 ppb Pd, and 185 ppb Pt, 18 ppb Au, 103 ppm Cu, and 720 ppm Ni. This Rh-rich sample is composed of coarse-grained leucogabbro, but is distinct from the unit (5a* leucogabbro) in that it contains abundant magnetite and only trace amounts (<0.25 vol.%) of sulphide (Fig. 9); features that suggest the possible presence of a second type of PGE mineralization in the Legris Lake Complex.

GEOPHYSICAL CHARACTERISTICS

The Legris Lake Complex displays a highly variable geophysical signature reflecting its heterolithic composition. The Complex is covered by a 1:63,360 scale aeromagnetic survey completed by the O.D.M – G.S.C. in 1962 and recently by ground-based magnetometer and induced polarization surveys, which were conducted on the western side of the intrusion during the exploration programs in 2000.

Magnetic Survey

Leucogabbros (units 5a* and 5aa) are commonly magnetic, the melanogabbros (units 5C and 5D) are strongly magnetic, the ultramafic rocks are always strongly magnetic, and the heterolithic breccia (unit 4a) is nonmagnetic. Country rocks, such as granodiorite, metasedimentary rocks, and basalt are typically nonmagnetic. The ground magnetometer survey illustrated the heterogeneous distribution of various rocks in the Northwestern Border area of the Complex. Several areas where rocks on surface contain up to 5 vol.% magnetite did not produce high magnetic anomalies, whereas the areas with no magnetite produced strong magnetic anomalies. This made magnetic survey useful in identifying unexposed igneous bodies, although it is difficult to define lithological contacts using the data. Magnetite contents vary within a unit and magnetite is commonly obliterated by hematitic alteration. For example, mineralized leucogabbro (unit 5a* and 5aa) can be nonmagnetic, such as is the case at the Main Showing area and in drill-holes DDH L00-01, L00-02; or it can be strongly magnetic such as is the case in drill-holes DDH L00-04 and DDH L00-08.

Induced Polarization Survey

Chargeability highs and resistivity lows correspond to stronger magnetic anomalies, indicating that magnetite is the predominant conductor in the Legris Lake Complex. The majority of the chargeability anomalies are associated with high resistivities, suggesting possible reduction in porosity of rocks by carbonate and/or epidote-albite alteration; but the magnitude of the anomalies does not necessarily correspond to the intensity of the alteration. Caution must be used when interpreting resistivity data as it displays a strong tendency to follow topography, creating lows in swamp areas and highs on bedrock ridges. Leucogabbro (unit 5a*) is commonly associated with high resistivities on the order of 710,000 ohm-m. Variations in resistivity, chargeability, and magnetic anomalies in leucogabbro (unit 5ab) are most likely explained by the different intensities of "hematitic" alteration at the expense of magnetite. All of the Cu-Ni-PGE mineralization discovered to date (*e.g.* the area of the Main Showing) is associated with at least moderate chargeabilities. The Cu-Ni-PGE mineralization in drill-holes DDH L00-04, -08, and -07 is located on the margin of an area with strong magnetic/chargeability anomalies, whereas the drill-holes DDH L00-09, -10, and -11, in the centre of the same magnetic/chargeability anomalies, failed to intersect any significant mineralization. Most chargeability anomalies increase with increasing depth.

DISCUSSION

Cu-Ni-PGE Mineralization

The source for the Cu, Ni, and PGE in the mineralization of the Legris Lake Complex is considered to be the parental magmas to the Complex itself, but the mineralization process is less certain. There are several possible processes that played a role in the mineralization:

1. Late-stage saturation of sulphur in the parental magma;
2. Fractionation of Ni, Cu, and PGE in sulphide liquid in the magma;
3. Transportation of PGE from solidifying magma by aqueous fluids that originated from the parental magmas (*i.e.* deuteric fluids);
4. Leaching of PGE from the solidified intrusions by aqueous fluids that originated from an external source/s as described by Molnar and Watkinson (2002).

Copper, Ni, and PGE are preferentially incorporated into an immiscible sulphur liquid upon saturation of sulphur in a silicate melt. This model (model 1) is considered to be the main cause of the PGE mineralization in Sudbury-type Ni-sulphide ore deposits. Such a magmatic process could also explain the mineralization at Legris Lake. If this is indeed the main process for mineralization at Legris Lake, high contents of Cu and Pd relative to Pt and Ni require the late-stage saturation of sulphur in the parental magmas. Iridium (Ir), osmium (Os), ruthenium (Ru), and Ni are compatible with early crystallizing silicate minerals in comparison to Pd, Pt, Au, and Cu. Therefore, magmas are enriched in Pd, Pt, Au and Cu relative to Ir, Os, Ru and Ni during fractional crystallization (Fig. 10). Since Pd is more incompatible than Pt, the ratios of Pd/Pt increase during fractional crystallization. Sulphur saturation may have been prompted by a volume reduction of the melt by crystallization, and the incorporation of silica and/or sulphide from surrounding metasedimentary rocks. The incorporation of silica and sulphur into the melt from metasedimentary host rocks is supported by the presence of abundant metasedimentary rock fragments in the Northwestern Border area and the earlier mentioned partial melting of metasedimentary roof pendants in the Southeastern Border area of the Legris Lake Complex. Brecciation and multiple magma pulses contributed to the efficient scavenging of PGE from the silicate magmas, causing a very high effective ratio of silicate to sulphide melt (R factor; Theriault et al. 1997) for the sulphide. The resulting PGE- and Cu-rich sulphide melt would thus be concentrated in leucocratic phases of the Complex.

The enrichment of Pd and Cu may also take place within sulphide liquid, since Fe, Ni, Os, Ir and Ru are preferentially incorporated in an early monosulphide solution (Barnes et al. 1997). This latter process (model 2) is discounted as having contributed substantially to the Cu- and Pd-rich mineralization at Legris Lake because sulphide minerals represent only a minor component of the intrusive rocks of the Complex.

Chlorine-rich aqueous fluids can also affect the separation of Pd and Cu from other PGEs and Ni because the former elements are more soluble in aqueous fluids (Jaireth 1992; Meurer et al. 1999; Sassani and Shock 1990). Therefore, the high contents of Cu and Pd in the Complex, relative to the other metals, suggest the possible transport and enrichment of Cu and Pd by aqueous fluids (models 3 and 4). This possibility is supported by the common occurrence of breccias in the Complex, and local PGE mineralization, which is not associated with significant Cu-Ni mineralization (Fig. 9).

There is, however, no evidence for extensive hydrothermal activity involving fluid of external origin. The distribution of breccias and alteration indicates that hydrothermal activity was confined within the Complex. Therefore, the leaching of PGEs by external fluids (model 4) is also discounted. Local transport of PGEs by magmatic (deuteric) fluids (model 3) is supported by the hydrofracturing of the wall rocks surrounding leucogabbro (unit 5a*), and the presence of varitextured leucogabbro. The common occurrence of epidote surrounding sulphide blebs, suggest hydrothermal origins. However the alteration is not interconnected, being confined to discrete halos surrounding disseminated and blebby sulphides and is attributed to the exsolution of volatiles during crystallization of the sulphide melt (Fig. 7).

Comparison with Other Copper-Nickel and Platinum-Group-Element Deposits

The Legris Lake Complex contains a wide range of igneous phases, from leucogabbro to dunite in composition, with high degrees of brecciation associated with multiple magma injection. The breccias, although metasediment-rich, share many similarities in lithology and texture with the heterolithic gabbro described by Lavigne and Michaud (2002), which surrounds the East Gabbro and hosts the Twilight and Roby Zones at the Lac des Iles mine. The Northwestern Boarder area of the Legris Lake Complex is also similar to the Cu-Ni-

PGE-rich breccias lining the western contact of the River Valley intrusion of the East Bull Lake Suite of mafic-ultramafic intrusions near Sudbury, Ontario. However, the restriction of Cu-Ni-PGE mineralization in leucogabbro near the contact with underlying ultramafic rocks shares similarities to stratiform-style mineralization in large layered, mafic-ultramafic complexes

The geochemical characteristics of the Cu-Ni-PGE mineralization of the Legris Lake Complex plot mostly in the lower part of the tholeiitic-hosted deposits field (Fig. 11), close to the mineralized rocks of the Lac des Iles deposit, but in a slightly more Pt-rich part of the diagram near the values for the Rathbun Lake deposit, which is considered to be of hydrothermal origin (Rowell 1984).

Effective Exploration Techniques for this Style of Mineralization

The low to moderate sulphide content of the PGE mineralization in the Legris Lake Complex does not give strong geophysical anomalies. The PGE mineralization occurs in both magnetite-rich and magnetite-poor leucogabbro (unit 5a*). Therefore, it is recommended that geological mapping and trenching should be combined with geophysical surveys before the commencement of diamond drilling. Induced polarization, and ground-based magnetometer surveys were useful in outlining possible areas of mineralization. Chargeability highs associated with Cu-Ni-PGE mineralization at Legris Lake are not very strong and the mineralization typically occurs on the margin, as opposed to the centre, of such magnetic/chargeability highs.

Prospecting remains an effective technique for exploration. In addition, careful investigation of weakly anomalous samples (>10 ppb Pd) is necessary due to the unpredictable distribution of the mineralization and narrow halos associated with the PGE mineralization. This is best exemplified by the occurrence of a 36 ppb Pd sample on surface, whose location became the collar location of DDH L00-07, which subsequently intersected 2.11 metres of 1.6 g/t Pd at depth. Due to the very low combined PGE concentration in weakly mineralized samples, it is important to use only Pd and not Pt+Pd or total PGE, in outlining anomalous areas. This is due to slightly high Pt values in ultramafic rocks compared to gabbroic rocks and local weakly anomalous Au mineralization associated with retrograde alteration.

CONCLUSION

The Legris Lake Complex hosts significant Cu-Ni-PGE mineralization with several long (> 5 m) drill-core intersections containing greater than 1 g/t combined PGE. The mineralization is predominantly Pd and Cu-rich, with lesser amounts of Pt, Au, and Ni. It is considered to be of late magmatic origin, with local enhancement by magmatic-hydrothermal activity. The mineralization is confined to leucogabbro (*i.e.* Main Showing subtype, unit 5a*; and varitextured subtype, unit 5aa) overlying clinopyroxenite. The mineralized leucogabbro occurs within a 2 kilometre long by 600 metre wide breccia zone in the Northwestern Border area of the Legris Lake Complex. This breccia zone is more than sufficient in size to host a Cu-Ni-PGE deposit amenable to economic development *via* open pit mining. The breccia zone continues at depth as is indicated by the results of magnetometer surveys and diamond drilling. Furthermore, the mineralization may extend along the northern contact of the

Complex, in an area covered by thick overburden, where several chargeability anomalies and bodies of leucogabbro (unit 5a*) remain untested by diamond drilling. The centre of the Complex consists of homogeneous leucogabbro (unit 5ab) and does not appear to be a favourable host for Cu-Ni-PGE mineralization. The Northeastern Boarder area has received little exploration and has the potential to host significant Cu-Ni-PGE mineralization as it shows more extensive and stronger magnetic anomalies than the Northwestern Boarder area.

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TABLES

Table 1. Representative Cu, Ni, and PGE concentration in higher-grade drill core samples.

FIGURE CAPTIONS

Figure 1. Location and regional geology map of the Legris Lake Complex. Modified after Pye and Fennwick (1964).

Figure 2. Geological map of the Legris Lake Complex. This map was produced after to the completion of the 2001 exploration program on the Legris Lake Complex.

Figure 3. (A) Foliated granodiorite country rock, from the western side of the Legris Lake Complex. (B) Quartz arenite country rocks, located in the Northwestern Border area, displaying strongly folded quartz veins.

Figure 4. (A) Leucogabbro (unit 5a*) with late crosscutting mafic dike, from the northwestern border area. (B) Leucogabbro (unit 5ab), with late crosscutting mafic dike, from the centre of the Legris Lake Complex. (C) Melanogabbro (unit 5c) from the eastern border area. (D) Heterolithic breccia (unit 4a) from the northwestern border area. (E) Leucogabbro (unit 5a*) brecciated by fine grain magnetite-rich leucogabbro near DDH L00-07. (F) Clinopyroxenite breccia (unit 5d) from the northwestern border area.

Figure 5. Geological grid map of western part of the Legris Lake Complex. This map was produced after to the completion of the 2001 exploration program on the Legris Lake Complex, however only holes mentioned in this manuscript are shown for simplicity.

Figure 6. Diamond drill hole cross section across the Northwestern Border area of the Legris Lake Complex. This cross section was produced after to the completion of the 2001

exploration program on the Legris Lake Complex. All holes labels L01-## were drilled during 2001.

Figure 7. (A) Hand sample of mineralized leucogabbro (unit 5a*) displaying dark green epidote alteration surrounding Cu-Ni sulphides. (B) Reflected light photomicrograph of chalcopyrite surrounded by epidote in leucogabbro (unit 5a*) from DDH L00-01. plag=plagioclase, cpx=clinopyroxene, epd=epidote, cpy=chalcopyrite.

Figure 8. (A) Histogram of the Pt:Pd ratios of Cu-Ni-PGE mineralization in the Legris Lake Complex. (B) Histogram of the Cu:Ni ratios of Cu-Ni-PGE mineralization in the Legris Lake Complex. (C) Plot of Cu vs. Pd of Cu-Ni-PGE mineralization in the Legris Lake Complex. (D) Plot of Cu vs Ni of Cu-Ni-PGE mineralization in the Legris Lake Complex. (E) Plot of Pt+Pd vs Cu+Ni of Cu-Ni-PGE mineralization in the Legris Lake Complex. (F) Plot of Au vs Pt+Pd of Cu-Ni-PGE mineralization in the Legris Lake Complex.

Figure 9. Magnetite-rich leucograbbro sample from DDH L00-03 containing high Rh, and low Cu. plag=Plagioclase, cpx=clinopyroxene, mag=magnetite.

Figure 10. Diagram illustrating the effects of a fractionating magma before and after sulphur saturation on Cu-Ni-PGE partition coefficients modified after Lightfoot and Keays (1995).

Figure 11. Plot of Cu/(Cu+Ni) vs Pt/(Pt+Pd) of Cu-Ni-PGE mineralization in the Legris Lake Complex compared to other Cu-Ni-PGE deposits. Modified after MacTavish (1999) and Michaude (1998).

Table 1. Representative Cu, Ni, and PGE concentration in higher-grade drill core samples

Hole	Grid Location		Core Length (m)	Interval Length (m)	PGE (Pd+Pt+Au) g/t	Pd g/t	Pt g/t	Au g/t	Cu %	Ni %
	North	East								
L00-01	95+55 N	94+85 E	35.75 – 42.00	6.25	0.88	632	171	75	0.17	0.09
and			51.30 – 63.30	12.00	0.86	609	157	99	0.22	0.10
Including			51.30 – 56.60	5.30	1.10	797	176	132	0.34	0.15
and			60.55 – 61.80	1.25	1.78	1170	412	201	0.35	0.11
L00-02	95+55 N	95+10 E	51.60 – 62.30	10.70	1.62	1217	237	171	0.32	0.09
Including			52.70 – 56.10	3.40	1.93	1543	260	130	0.34	0.13
Including			54.25 – 54.70	0.45	3.75	3150	386	214	0.75	0.27
and			56.90 – 62.30	5.40	1.82	1315	283	222	0.33	0.09
Including			56.90 – 60.00	3.10	2.66	1947	404	312	0.47	0.14
L00-04	95+50 N	98+00 E	3.70 – 8.40	4.70	0.87	187	161	519	0.27	0.07
Including			6.90 – 8.40	1.50	1.15	655	260	238	0.41	0.10
L00-07	10100	9550	43.92 – 48.84	4.92	1.21	0.957	0.152	0.097	0.13	0.04
Including			46.73 – 48.84	2.11	2.04	1.599	0.246	0.193	0.26	0.06
L00-08	9550	9900	18.74 – 28.69	9.95	3.16	2.037	0.410	0.712	0.42	0.13
Included			25.33 – 26.69	1.36	3.40	2.550	0.460	0.394	0.46	0.15
and			57.24 – 61.04	3.80	2.92	1.938	0.342	0.643	0.29	0.11
and			72.26 – 75.26	3.00	1.88	1.322	0.272	0.289	0.33	0.10
L00-03ext	9550	9975	223.92 – 228.60	4.68	0.248	0.191	0.046	0.011	0.021	0.013
and			227.20 – 282.22	4.63	0.344	0.272	0.047	0.025	0.072	0.045
and			284.37 – 287.82	3.45	0.331	0.227	0.046	0.06	0.010	0.030
Including			285.18 – 285.95	0.77	1.113	0.910	0.185	0.018	0.010	0.070

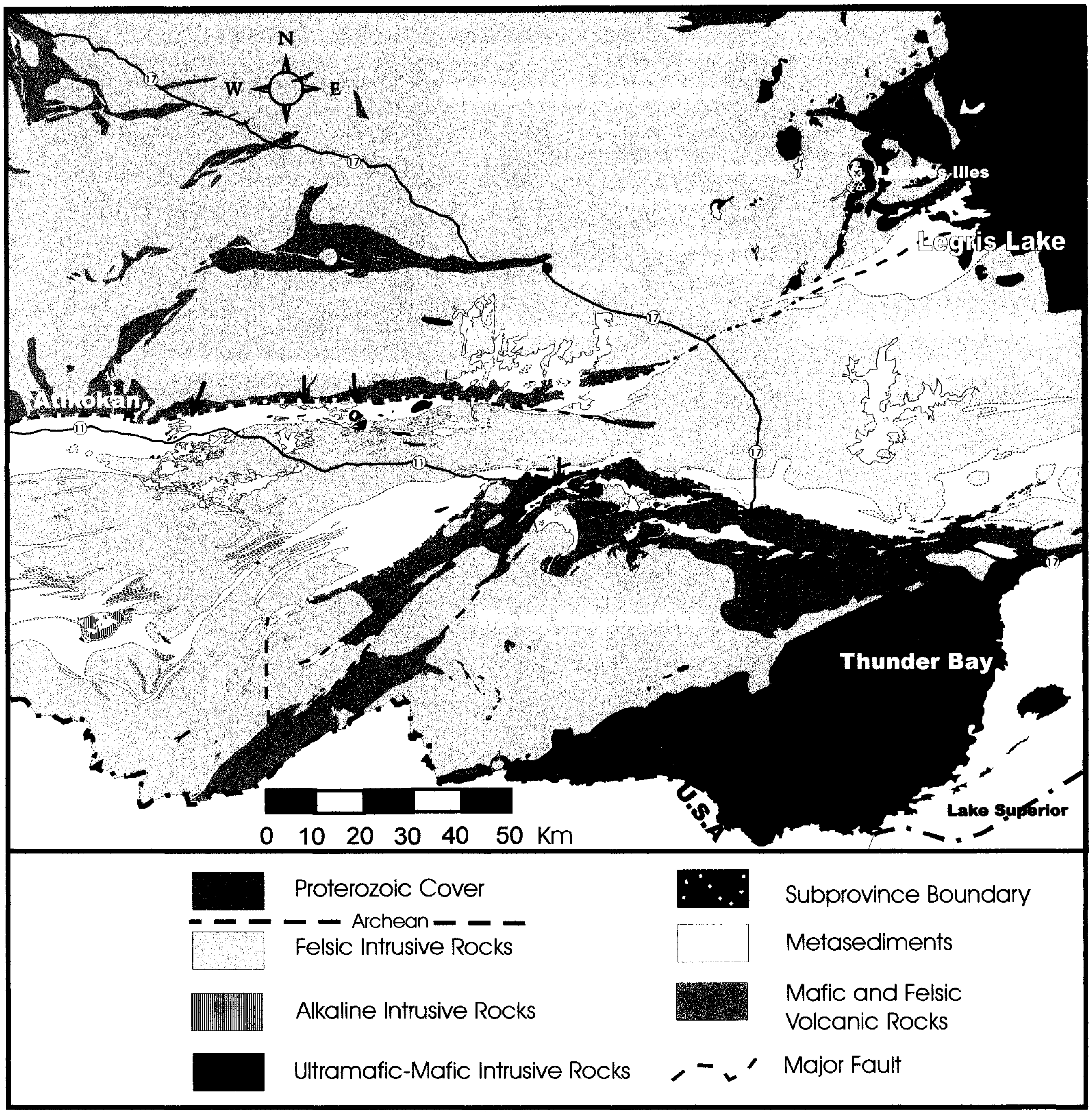
N
W
E
17
11
Atikokan
s Illes
Legris Lake
Thunder Bay
U.S.A
Lake Superior
0 10 20 30 40 50 Km
Proterozoic Cover
Archean
Felsic Intrusive Rocks
Alkaline Intrusive Rocks
Ultramafic-Mafic Intrusive Rocks
Subprovince Boundary
Metasediments
Mafic and Felsic Volcanic Rocks
Major Fault

Figure 1.

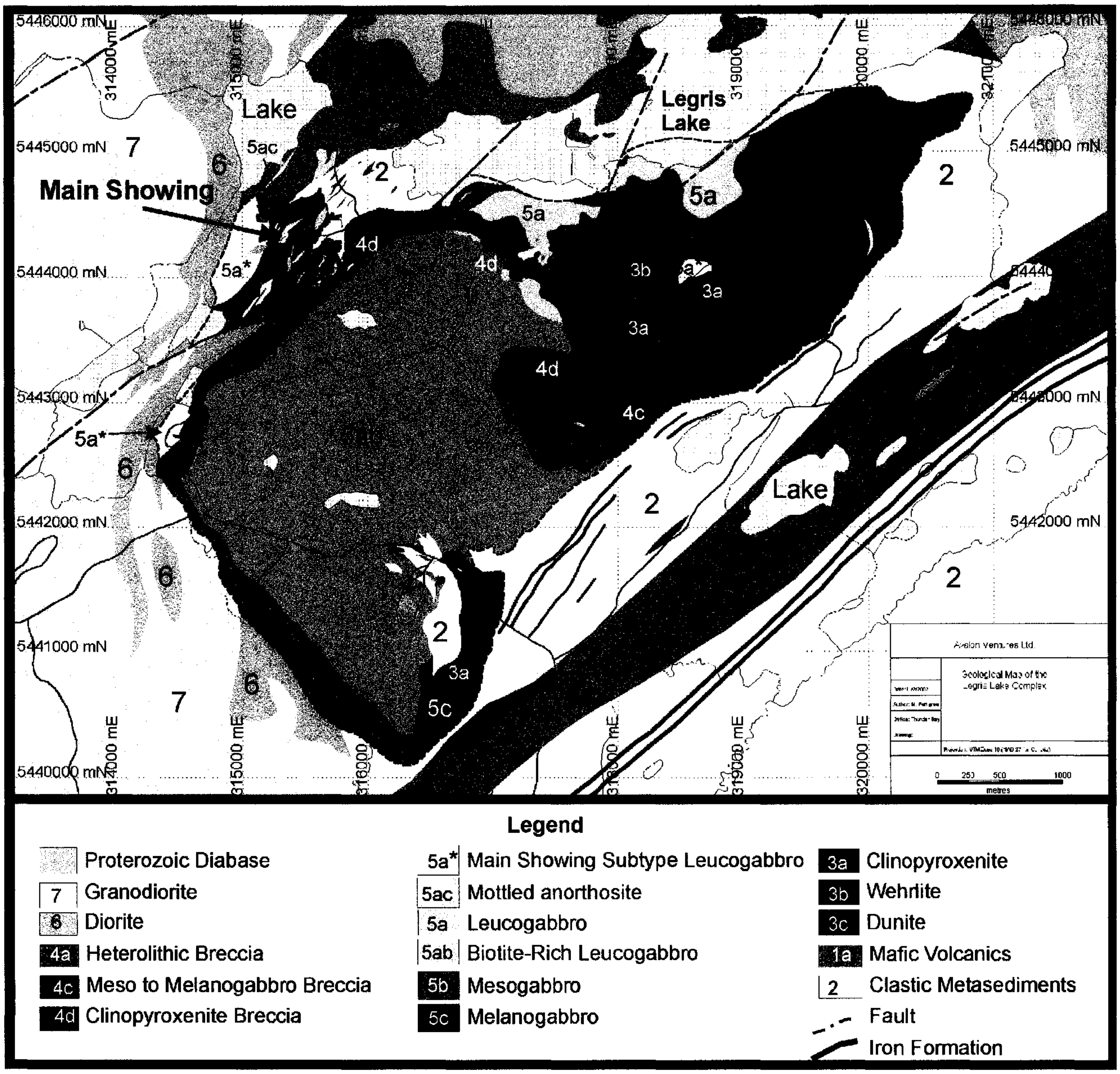
5446000 mN
5445000 mN
5444000 mN
5443000 mN
5442000 mN
5441000 mN
5440000 mN
314000 mE
315000 mE
316000
319000
320000 mE
Lake
Legris Lake
Main Showing
5ac
5a
5a*
4d
4c
3a
3b
5c
2
6
7
Lake
Avalon Ventures Ltd.
Geological Map of the Legris Lake Complex
Author: M. Pettigrew
Office: Thunder Bay
Drawing:
0
250
500
1000
metres
Legend
Proterozoic Diabase
7 Granodiorite
6 Diorite
4a Heterolithic Breccia
4c Meso to Melanogabbro Breccia
4d Clinopyroxenite Breccia
5a* Main Showing Subtype Leucogabbro
5ac Mottled anorthosite
5a Leucogabbro
5ab Biotite-Rich Leucogabbro
5b Mesogabbro
5c Melanogabbro
3a Clinopyroxenite
3b Wehrlite
3c Dunite
1a Mafic Volcanics
2 Clastic Metasediments
Fault
Iron Formation

Figure 2.

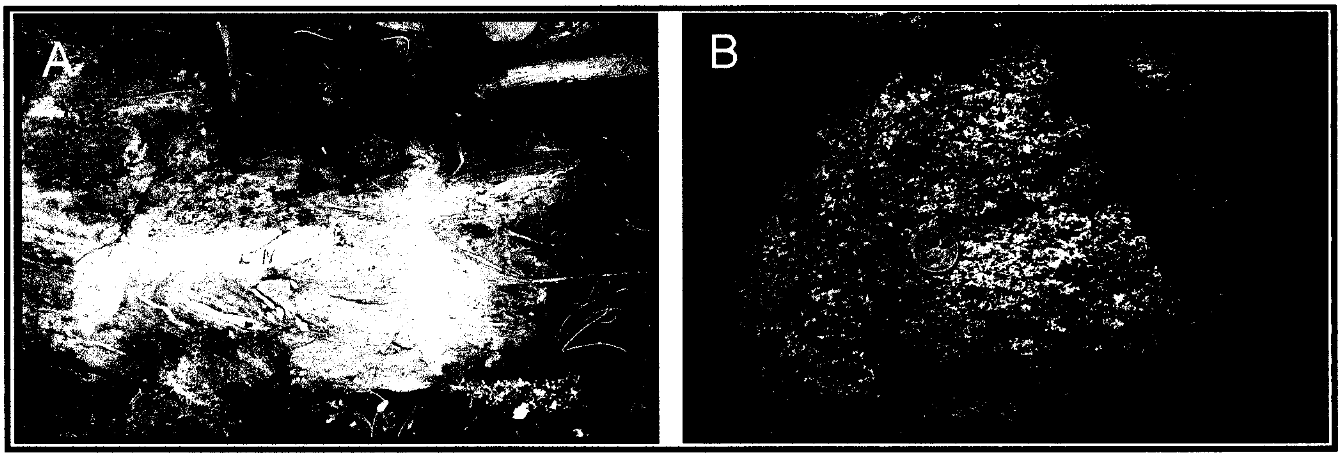

Figure 3.

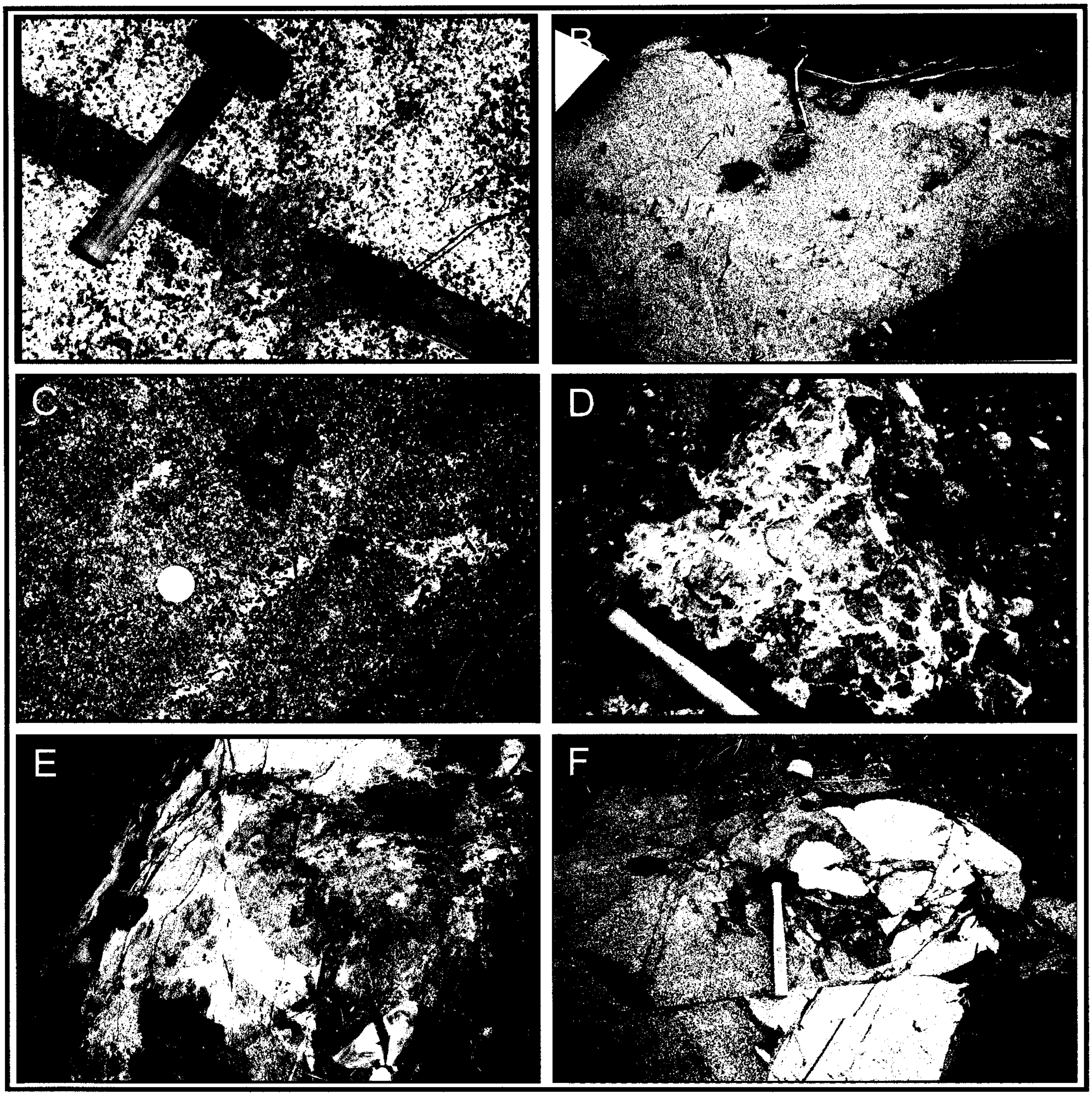

Figure 4.

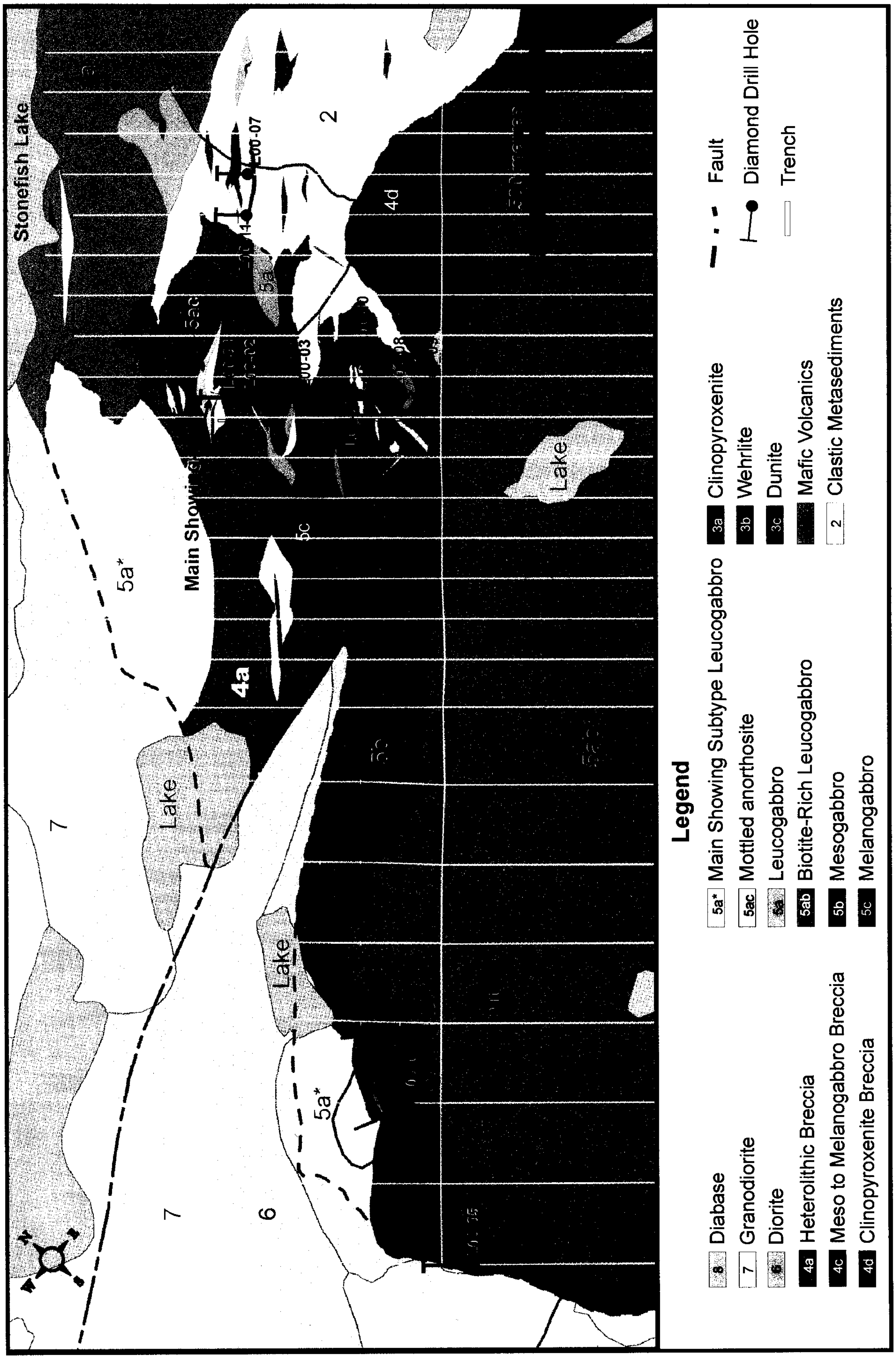
Stonefish Lake
Main Showing
5a*
4a
5c
5ac
4d
2
7
6
Lake
00-07
00-14
00-03
00-02
Legend
8 Diabase
7 Granodiorite
6 Diorite
4a Heterolithic Breccia
4c Meso to Melanogabbro Breccia
4d Clinopyroxenite Breccia
5a* Main Showing Subtype Leucogabbro
5ac Mottled anorthosite
5a Leucogabbro
5ab Biotite-Rich Leucogabbro
5b Mesogabbro
5c Melanogabbro
3a Clinopyroxenite
3b Wehrlite
3c Dunite
Mafic Volcanics
2 Clastic Metasediments
Fault
Diamond Drill Hole
Trench

Figure 5.

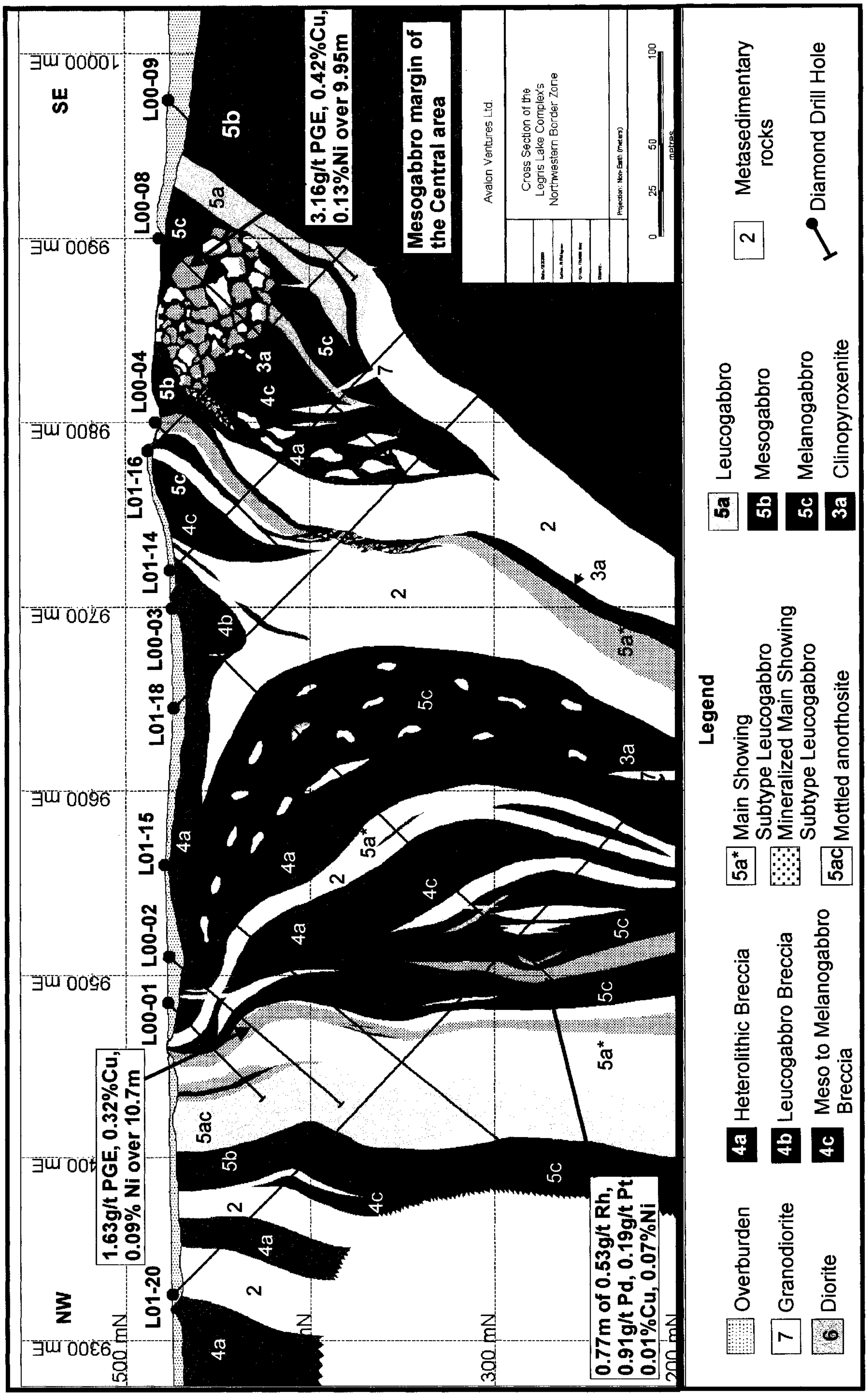
NW
SE
9300 mE
9400 mE
9500 mE
9600 mE
9700 mE
9800 mE
9900 mE
10000 mE
500 mN
400 mN
300 mN
200 mN
L01-20
L00-01
L00-02
L01-15
L01-18
L00-03
L01-14
L01-16
L00-04
L00-08
L00-09
1.63g/t PGE, 0.32%Cu, 0.09% Ni over 10.7m
0.77m of 0.53g/t Rh, 0.91g/t Pd, 0.19g/t Pt 0.01%Cu, 0.07%Ni
3.16g/t PGE, 0.42%Cu, 0.13%Ni over 9.95m
Mesogabbro margin of the Central area
Avalon Ventures Ltd.
Cross Section of the Legris Lake Complex's Northwestern Border Zone
Projection: Non-Earth (meters)
0
25
50
100
metres
4a
2
5b
4c
5ac
5c
5a*
4b
5a
3a
7
Legend
Overburden
7 Granodiorite
6 Diorite
4a Heterolithic Breccia
4b Leucogabbro Breccia
4c Meso to Melanogabbro Breccia
5a* Main Showing Subtype Leucogabbro
Mineralized Main Showing Subtype Leucogabbro
5ac Mottled anorthosite
5a Leucogabbro
5b Mesogabbro
5c Melanogabbro
3a Clinopyroxenite
2 Metasedimentary rocks
Diamond Drill Hole

Figure 6.

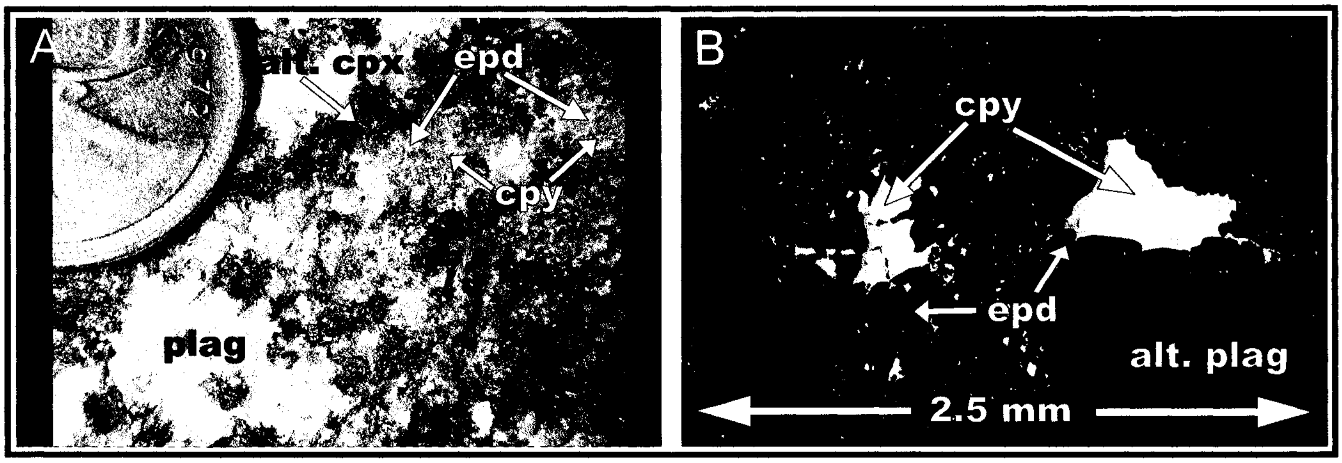

Figure 7.

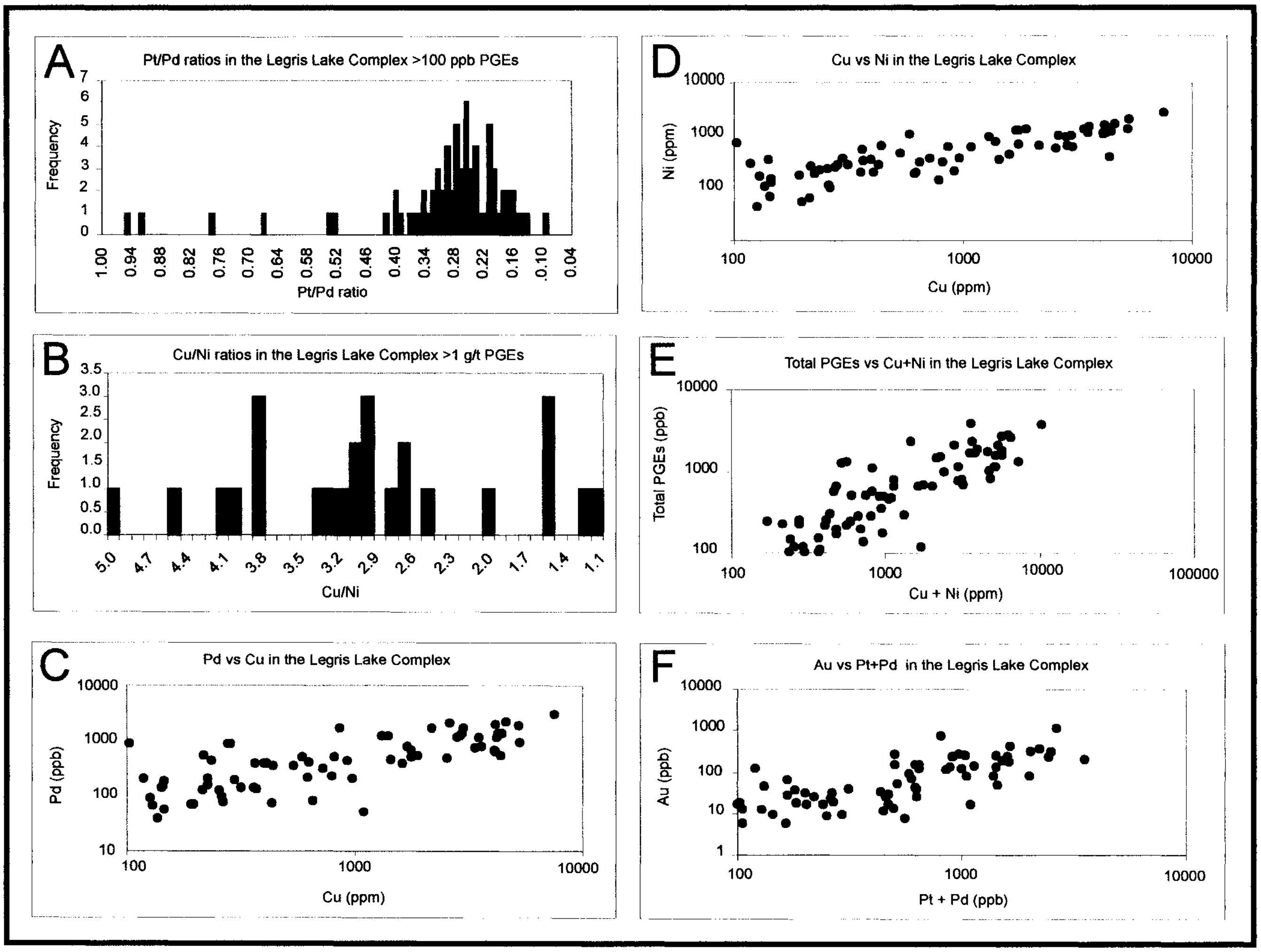
A
Pt/Pd ratios in the Legris Lake Complex >100 ppb PGEs
Frequency
7
6
5
4
3
2
1
0
1.00
0.94
0.88
0.82
0.76
0.70
0.64
0.58
0.52
0.46
0.40
0.34
0.28
0.22
0.16
0.10
0.04
Pt/Pd ratio
D
Cu vs Ni in the Legris Lake Complex
Ni (ppm)
10000
1000
100
Cu (ppm)
100
1000
10000
B
Cu/Ni ratios in the Legris Lake Complex >1 g/t PGEs
Frequency
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
5.0
4.7
4.4
4.1
3.8
3.5
3.2
2.9
2.6
2.3
2.0
1.7
1.4
1.1
Cu/Ni
E
Total PGEs vs Cu+Ni in the Legris Lake Complex
Total PGEs (ppb)
10000
1000
100
100
1000
10000
100000
Cu + Ni (ppm)
C
Pd vs Cu in the Legris Lake Complex
Pd (ppb)
10000
1000
100
10
100
1000
10000
Cu (ppm)
F
Au vs Pt+Pd in the Legris Lake Complex
Au (ppb)
10000
1000
100
10
1
100
1000
10000
Pt + Pd (ppb)

Figure 8.

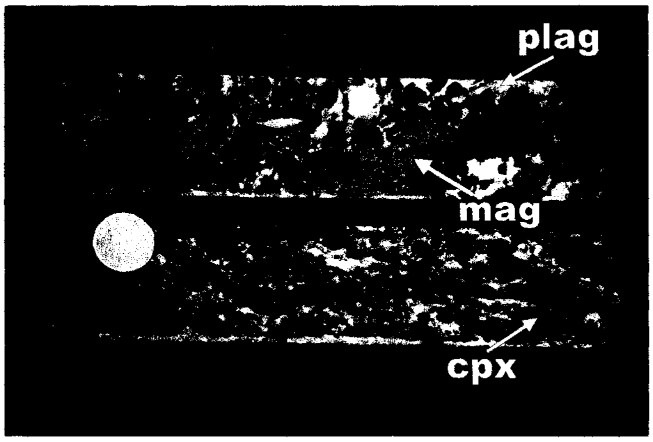

Figure 9.

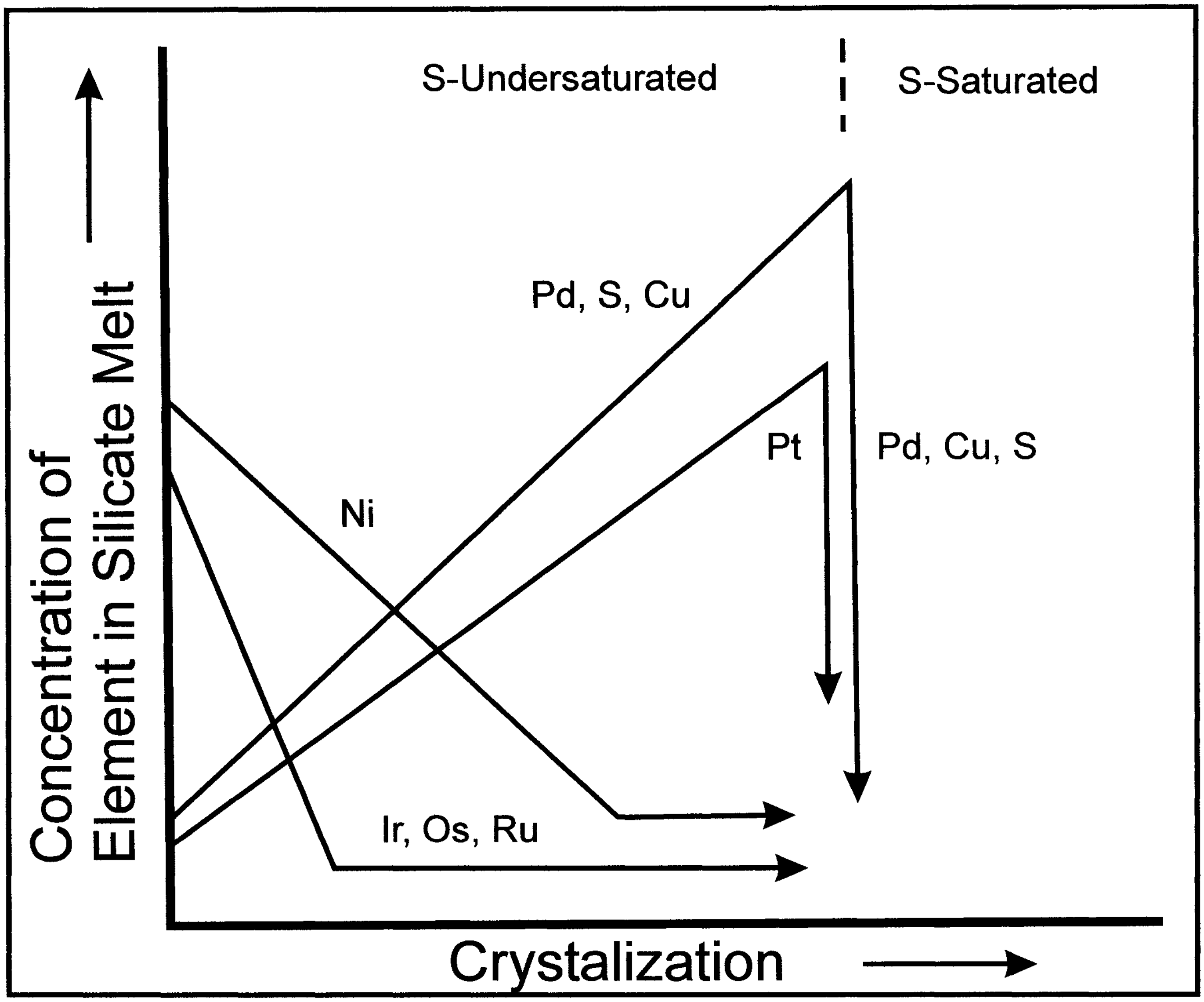
S-Undersaturated
S-Saturated
Concentration of Element in Silicate Melt
Pd, S, Cu
Pt
Pd, Cu, S
Ni
Ir, Os, Ru
Crystalization

Figure 10.

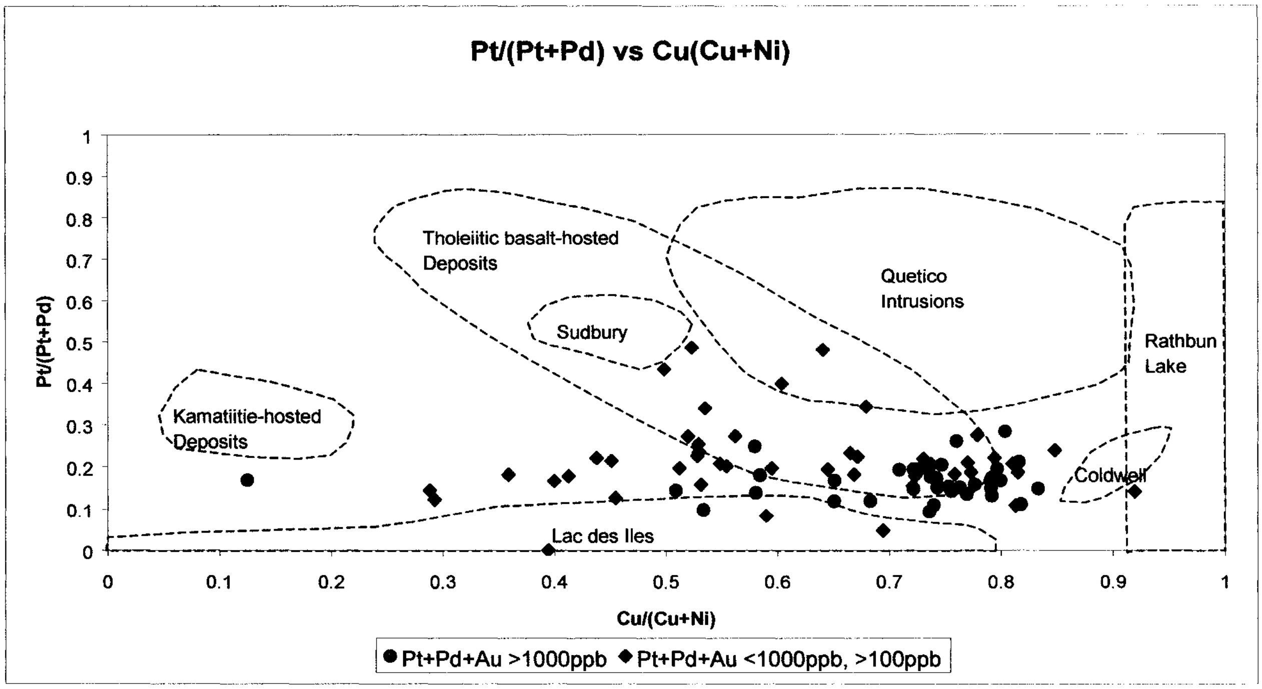
Pt/(Pt+Pd) vs Cu(Cu+Ni)
Pt/(Pt+Pd)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Cu/(Cu+Ni)
Tholeiitic basalt-hosted Deposits
Quetico Intrusions
Sudbury
Kamatiitie-hosted Deposits
Rathbun Lake
Coldwell
Lac des Iles
● Pt+Pd+Au >1000ppb ◆ Pt+Pd+Au <1000ppb, >100ppb

Figure 11.

Palladium-Copper-Rich PGE Mineralization in the Legris Lake Mafic-Ultramafic Complex, Western Superior Province of Canada

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SYNOPSIS

The Legris Lake Complex is a northeast-trending 7.3 by 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, ~7 km northwest of the Legris Lake Complex, the former hosting the Lac des Iles palladium mine. Four phases of exploration have been conducted on the Legris Lake Complex property since the fall of 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 by 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 characteristics of the PGE mineralization in the Legris Lake Complex are distinctly different from many PGE deposits where the ore occurs in sulphide-rich bodies at the base of mafic and ultramafic rocks, such as the Sudbury contact ores and Noril'sk. PGE enrichment in the Legris Lake Complex occurs in sulphide-poor (1-10 vol%, less than 5 vol% in most cases), medium- to coarse-grained, porphyritic leucogabbro (termed 'Main Showing-type') hosted within zones of intense magmatic brecciation. The mineralized leucogabbro is highly mineralogically evolved and exhibits a sill-like form near the stratigraphic top of the complex. 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 (~0.2) and high Cu/Ni ratios (~3). PGE contents display a positive correlation with those of Cu and Ni. The origin of the mineralization is best explained by preferential partition of PGEs 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. The 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 likely reflecting a high oxidation state and volatile-rich nature of the parental magmas. This primary magmatic PGE mineralization was followed by minor redistribution of PGEs by deuteric hydrothermal fluids released from the parental magma.

INTRODUCTION

The Legris Lake Complex, located approximately 90 km north of Thunder Bay, Ontario, Canada, is a 7.3 by 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 145.6 million tonnes grading 1.57 g/t Pd and 0.17 g/t Pt, 0.12 g/t Au, 0.06% Cu, and 0.05% Ni[21]. 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 has been described by several researchers,[12,16,30,31,3] but little documentation is available for the Legris Lake Complex and its mineralization. This paper presents details of the recently discovered mineralization in the Complex.

Title to the Legris Lake Complex property is currently held 50/50 by Avalon Ventures Ltd. and Starcore Resources Ltd., with Avalon as the Operator. Placer Dome (CLA) Limited has 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 the fall of 1999 resulted in 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, 0.42 wt.% Cu over 9.95 m (DDH L00-08) and 4.50 g/t Pd, 0.62 g/t Pt, 0.20 g/t Au, 0.50 wt.% and Cu over 0.97 m (DDH L01-14)[22]. A detailed exploration history of the complex appears in report by Pettigrew[22].

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 which form a circular surface expression approximately 30 km in diameter.[9,30] These include the PGE-bearing Lac des Iles Complex (2692 $^{+4}/_{-2}$ Ma[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 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 northeast-trending space cleavage, parallel to the subprovince boundary (Fig. 2). Similar textures, common in the southern Wabigoon province, were probably developed during the accretion of the Quetico Subprovince onto the Wabigoon Subprovince.[39] The lack of this space cleavage in the Legris Lake Complex indicates that it postdates or is possibly contemporaneous with this metamorphic/deformational event. However, the Complex and surrounding rocks are overprinted by a local greenschist facies alteration associated with late granitic intrusions. All rocks in the Legris Lake area also exhibit a north-south fracture set and were intruded by diabase sills during the Mid-continent Rift at 1.1 Ga[19] (Figs. 2 and 3).

GEOLOGY OF THE LEGRIS LAKE COMPLEX

The Legris Lake Complex formed through multiple injections of volatile-rich mafic magmas and extensive assimilation of sedimentary rocks. This resulted in the Complex consisting of various gabbroic rocks with minor anorthosite and ultramafic rocks such as wehrlite. Of particular interest is a plagioclase (70 to 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 is hosts the majority of the known platinum group element (PGE) mineralization. This Main Showing-type is less evolved, with low SiO_2 (~50-53 wt%) and moderately high MgO (4 to 6 wt%) compared to other leucogabbro, which contain 58-61 wt% SiO_2 and 4-5 wt% MgO. The Main Showing-type leucogabbro shows overall low concentrations of large ion lithophile elements, displaying trace element patterns distinctly different from other leucogabbros (Fig. 4).

The Complex also contains numerous dykes, sills, and breccias containing fragments of cognate phases and metasedimentary country rocks. The interaction between the parental magmas and country rocks is so extensive that the boundary 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 resulted in significant deuteric alteration in earlier solidified phases. The alteration is particularly abundant in the Northwestern Border area where complex textures are developed in 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.

Based on the lithological associations and textures, the Complex is divided into four areas: Central, Northeastern Border, Southwestern Border and Northwestern Border areas.

Central Area

This area has a surface exposure of several square km and consists almost entirely of medium-grained, massive, biotite-rich leucogabbro with moderate magnetic susceptibilities. There are several large tongue-shaped blocks of metasedimentary rocks extending up to 600 m from the contact with sedimentary rocks into the Complex, which are interpreted to be roof pendants (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

This area consists of mostly mesogabbro and clinopyroxenite with many other minor phases including leucogabbro and wehrlite. This area is very poorly exposed and much of the interpretation is based on geophysical and limited drill core data. This 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 (500 by 200 m) zone of clinopyroxenite breccia along the boundary with the Central area, termed the Cross Zone, is characterized by abundant anorthosite to melanogabbro breccias in a strongly magnetic matrix of clinopyroxenite to melanogabbro. Anomalous contents of PGEs (up to 300 ppb) occur in the matrix of this breccia.

Southwestern Border Area

This area consists of mostly mesogabbro and coarse-grained leucogabbro (Main Showing-type) and is homogeneous in comparison to 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 (~ 10 m) lherzolite - dunite core with abundant magnetite.

Northwestern Border Area

This area is extremely heterogeneous in texture and composition, consisting of predominant sediment-rich heterolithic breccias, and a wide variety of igneous rocks ranging from anorthosite to clinopyroxenite, yet 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 near complete disaggregation of conglomerates and transformation of cobbles into rounded xenoliths in gabbroic matrix. Furthermore, fluids expelled by dehydration of sedimentary rocks and solidifying magmas caused extensive brecciation of rocks.

Sedimentary rocks generally contain pyrite (up to 1 vol%), and the assimilation of such rocks likely contributed to the saturation of sulphur in the magma and formation of Cu-Ni-PGE mineralization in this area.

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 zones: 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, which is characterized by low Cu and Ni and high Rh and Pd was found only in the hole (DDH: L00-03) at depth near the Main Showing Zone.

Copper-Palladium-Rich Mineralization

This style of mineralization occurs in sill-like structures (200 m long x 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 is disturbed by the injection of crystal mushes from underlying phases into overlying phases. For example, the earlier crystallized clinopyroxenite unit was 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 leucogabbro 'sill' is best illustrated in DDH 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, with the highest grades 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 commonly possess coarse epidote halos and are often accompanied by apatite crystals (Figs. 10 and 11). The epidote alteration changes the colour of the mineralized leucogabbro (Fig. 10) from white to dark green in hand sample. Plagioclase (An_{51} -An_{58}) is saussuritized (fine-grained sericite-epidote-carbonate alteration) and locally altered to pure epidote; clinopyroxene in the matrix is altered to hornblende, chlorite, and actinolite.

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

The mineralized rocks display consistent Pt/Pd ratios of ~ 0.2 with slightly more variable Cu/Ni ratio of ~3, and an erratic Au/(Pt+Pd) ratio of ~0.1 (Figs. 13A, 13B, 13C). Palladium contents are positively correlated with those of Cu, Ni, and total PGEs (Figs. 13D, 13E, 13F).

This style of mineralization also occurs in the Vande, Stinger, and Powder Hill Zones to the south (~15 km from Poplar to Powder Hill Zone) of the Legris Lake Complex, which are located along the boundary between the Towle Lake Intrusion and country metasedimentary and pyroclastic volcanic rocks.

Copper-Nickel-Poor, Palladium-Rich Mineralization

This style of mineralization is best exhibited in the Stonefish Lake Zone that protrudes into the metasedimentary rocks from the Northwestern Border area (Fig. 3). The host rock for this style of mineralization is heterolithic, leucogabbro and leucogabbro breccia. The leucogabbro described here as varitextured display a highly variable composition (clots of altered clinopyroxene and plagioclase-rich zones) and range of grain sizes. 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 varitextured leucogabbro breccia locally grades 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.

The enrichment of PGEs occurs erratically in the varitextured leucogabbro breccia and mottled anorthosite. Copper-Ni sulphides are not common and they are not correlated with the enrichment of PGEs (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 Mineralization

This style of mineralization was only intersected near the bottom of DDH L00-03 (Fig. 6), with grades up to 0.52 g/t Rh and 0.91 g/t Pd. This style occurs within a coarse grained mesogabbro with relatively unaltered plagioclase but with strongly actinolite altered clinopyroxene. The mesogabbro, which commonly contains disseminated to locally abundant magnetite (up to ~15 vol%). The mineralized rocks are rich in vanadium (0.11 wt.%) and TiO_2 (1.86 wt.%), and low in Cr_2O_3 (<0.01 wt.%), suggesting that this coarse gabbro represents a pegmatitic phase. Several Pd-Bi-tellurides and Pd-Hg-arsenides were identified using an electron microprobe. All PGMs are enclosed by actinolite in close proximity to finely disseminated sulphides of pyrite + millerite + chalcopyrite.

DISCUSSION

Many mantle-derived, mafic melt contains high Pd compared to other PGEs. This enrichment of Pd appears to be due to the apparent more incompatible nature of Pd compared to Pt in mantle minerals.[36,21,24] Similar to many other mafic magmas, the parental magmas for the Legris Lake Complex likely contained high Pd compared to other PGEs. Before the parental magmas were injected into the site, they most likely underwent fractional crystallization of olivine at depth, leading to the overall depletion of Ni and elevated REE within the Legris Lake Complex. The magmas were apparently undersaturated with S, and incompatible metals, such as Pd and Cu,[8,21,32,25] were enriched in the parental magmas. Palladium was more enriched than Pt during this fractional crystallization due to more incompatible nature of Pd compared to Pt.[36,24] The Cu-Pd enriched magmas 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). The continuing crystallization caused a volume reduction of silicate melt, which led the sulphur saturation of the magma and the immiscible separation of sulphide melt. The sulphur saturation was aided by assimilation of clastic metasedimentary rocks that commonly contain pyrite (up to 1 vol%). This was assisted by high SiO_2 contents of assimilating metasedimentary rocks as increasing SiO_2 lowers the solubility of sulphur in mafic melt.[38,15] The assimilation of sedimentary rocks also promoted the evolution of the parental magmas to leucocratic composition.

PGEs in the melt preferentially partitioned to the sulphide melt[5] (Fig. 13F), 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 Subtype leuocogabbro. The later, more voluminous sulphide has a lower (Pt+Pd)/(Cu+Ni) ratio since much of the PGEs 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.[35,1]

The common occurrence of magnetite in the Complex suggest that the parental magmas had high fO_2. Furthermore, abundant magnetite grains within and near sulphide blebs suggests that the sulphide melt had high oxygen/(oxygen+sulphur) ratios. Magmatic sulphides formed in basalts are known to contain high oxygen, up to 0.5 in oxygen /(oxygen+sulphur) ratios.[6] Experimental studies confirm high oxygen contents in sulphide melt formed in oxidizing silicate melt.[7] The High magnetite contents in the Legris Lake Complex indicates a high oxygen content in sulphide melt and oxidizing condition in the parental magmas.

The occurrence of hydrous alteration halo surrounding sulphide blebs suggests that the sulphide melt was rich in volatiles. These volatile elements were likely exsolved from solidifying sulphide melt, producing the hydrous alteration halo, just like 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 PGEs by aqueous fluids discharged from sulphide melt during the solidification. Such magmatic fluids would have been high in Cl[2]. Saline fluids are known to dissolved significant PGEs especially at elevated temperatures.[29,40] Thus, PGEs were expelled from sulphide minerals during the solidification of sulphide melt and deposited in the hydrous alteration halo.

The highly evolved nature of the Cu-Pd rich style of mineralization is illustrated by the trends on the Cu/(Cu+Ni) vs. Pt/(Pt+Pd) diagram in which the bulk of the data from the Legris Lake Complex clusters 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 while those formed by evolved magmas plot in the lower right corner.[18] 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] were also operating, possibly contributed to the enrichment of magmatically concentrated PGEs at the Legris Lake Complex.

The Stonefish Lake Zone is quite distinct from the rest of mineralization in the Complex. The Zone contains very low sulphide contents, less than 0.2 vol %, and show erratically distributed, anomalous to moderate PGE contents, up to 1.46 g/t, in varitextured leucogabbro breccia and along narrow (< 0.5 m) ductile shears. We consider that the mineralization is a result of hydrothermal mobilization by deuteric fluids of PGEs. Magmatic fluids are highly saline[2] and PGEs, especially Pd, are soluble in hot saline fluids.[28,40] Such magmatic fluids derived from the parental magmas likely focused along distal pegmatitic sills, breccias, and shear zones where they precipitated PGEs. The small size of this type of mineralization suggests limited hydrothermal activity in the Legris Lake Complex.

Comparison To Other PGE Deposits

The Legris Lake Complex and the nearby Lac des Iles Complex (Fig. 2) are considered to be co-genetic[9, 13] and share many geological features, such as abundant igneous breccias, a wide variety of lithologies, multiple injections of magmas, 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 opinions have proposed on the genesis of PGE mineralization. They include the Pd enrichment by "constitutional zone refining" (i.e. metal zonation caused by the redistribution of primary magmatic Cu-Ni-PGE mineralization, or the deposition of externally scavenged Cu-Ni-PGE by upward moving volatile fluids) of earlier gabbroic rocks,[3] magma mixing between PGE-rich magmas and volatile-rich magmas,[13] immiscible separation of sulphide melt followed by hydrothermal enrichment of Pd.[17, 33] A major expansion of the Lac des Iles Mine in 1999 involved extensive stripping of large areas and diamond drilling, which led better understanding of the relationships between the mineralization and lithologies and 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 exsolved from a PGE-volatile-rich gabbroic magmas which 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 focused fluid flow due to 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 Ma[20]) is part of a suite of gabbro-anorthitic complexes, the East Bull Lake intrusive suite, which 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 to pyrrhotite and pentlandite.[10,20] In addition, the mineralization is confined within several hundred metres of the contact with country rocks and displays evidence of deuteric alteration.[10,20]

Although the geological setting of the mineralization at the Legris Lake Complex is similar to Lac des Iles Mine and East Bull Lake Suite, the style of mineralization differs substantially from the two. The bulk of Lac des Iles Mine's mineralization is hosted within the matrix of igneous breccias[11] and displays little correlation between Pd and base metal sulphides. In the River Valley intrusion, which is one of East Bull Lake Suite intrusions, the contact-type mineralization is mostly confined to the boundaries of the intrusion and country rocks. Mineralization also appears to be independent of lithological type, occurring in both breccia clasts and matrixes. Contrarily, the bulk of the mineralization at Legris Lake Complex 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 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,[23] the J-M Reef of the Stillwater Complex[27,35] 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 the crystallization through 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 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 Pt/Pd ratio of ~0.2 and Cu/Ni ratio of ~3, and bulk rock samples show a positive correlation between PGEs and base metals. The mineralization is explained by sulphur saturation in the parental magmas due to volume reduction of 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 likely 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.[20] However, the occurrence of mineralization in leucogabbro near the contact with underlying ultramafic rocks shares similarities to stratiform-style mineralization in large layered, mafic-ultramafic complexes.

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FIGURE CAPTIONS

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

Figure 2. Location of the Legris Lake Complex and a suite of cogenetic mafic-ultramafic complexes in the southwestern Wabigoon Subprovince.

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

Figure 4. Rare earth element concentrations of leucogabbros normalized to chondrite values. The normalizing values are those of MacDonough and Sun.[16] The Main Showing-type leucogabbro (solid lines) show low concentrations of large ion lithophile elements compared to biotite-rich leucogabbro (dashed lines).

Figure 5. Schematic diagrams showing the origin of the Northwestern Border area. 1) Intrusion of gabbroic sills. 2) Partial melting and assimilation of intervening metasedimentary lenses between intrusions caused them to fail, producing textures and structures akin to those produced by the sedimentary processes of slumping and soft-sediment deformation. Cu-Ni-PGE mineralization most likely 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 the Northwestern Border area. 4) Intrusion of granodiorite dykes branching out from nearby granodioritic plutons.

Figure 6. Simplified vertical cross section across the Northwestern Border area based on diamond drill core and geophysical data. Mottled anorthosite refers to highly altered anorthosite with poikilitic interstitial clinopyroxene.

Figure 7. Schematic diagram showing the Cu-Ni-PGE mineralization in a sill-shaped intrusion hosted by a breccia zone.

Figure 8. Detailed geological map of a trench in the northwestern portion of the Poplar Zone showing Pt and Pd contents of channel samples and the sample locations. The numbers besides the sampling locations are the sum of Pt+ Pd in ppb.

Figure 9. Down hole profile of total PGEs and (Cu+Ni) vs. depth in DDH L01-16, passing through the Poplar Zone.

Figure 10. (A) Unmineralized leucogabbro (Main Showing-type) from Main Showing Zone (DDH L00-01). (B) Mineralized leucogabbro (Main Showing-type) from Main Showing Zone displaying epidote alteration (grey in the photo) surrounding finely disseminated Cu-Ni sulphides.

Figure 11. Photomicrograph showing a composite bleb of sulphide minerals surrounded by epidote (Ep) in leucogabbro (DDH; L00-01). Field of view is 2.5 mm. (A) transmitted light microscopy (B) reflected light microscopy, showing the distribution of chalcopyrite (Cpy) and pyrite (Py).

Figure 12. Backscattered electron image of braggite grains (PdS) enclosed in a portion of an epidote alteration halo surrounding a large sulphide bleb, which is out of the field of view. The sample was collected from Main Showing-type leucogabbro in the Main Showing Zone. Abbreviations; Ep=epidote, Cpy=chalcopyrite, Hb = hornblende, Mil=millerite, Pl=plagioclase.

Figure 13. Metal ratios of the Cu-Pd-rich style of Cu-Ni-PGE mineralization. (A) Histogram of the Pt/Pd ratios of Cu-Ni-PGE mineralization in the Legris Lake Complex. (B) Histogram of the Cu/Ni ratio of Cu-Ni-PGE mineralization in the Legris Lake Complex. (C) Histogram of the ratios of Au/(Pt+Pd) of the Legris Lake Complex. (D) Pd vs. Cu in the mineralized rocks in the Legris Lake Complex. (E) (Pt+Pd) vs. (Cu+Ni) in the mineralized rocks in the Legris Lake Complex. (F) Cu vs. Ni in the mineralized rocks in the Legris Lake Complex. Values compiled from drill core assay data.

Figure 14. (Pt+Pd+Au) vs (Cu+Ni). Note that the Cu-Ni-poor, Pd-rich Stonefish Lake Zone differs from the Cu-Pd-rich Poplar Zone. Values compiled from channel sample assay data.

Figure 15. Cu/(Cu+Ni) vs Pt/(Pt+Pd). Note that the mineralized rocks at Legris Lake Complex cluster in the lower right corner of the tholeiitic field and display a weaker trend parallel to the

Lac des Iles deposit. Modified after Naldrett and Cabri[18] with additional data from Quetico intrusions by MacTavish[14] and from Lac des Iles Complex by Michaud.[17]

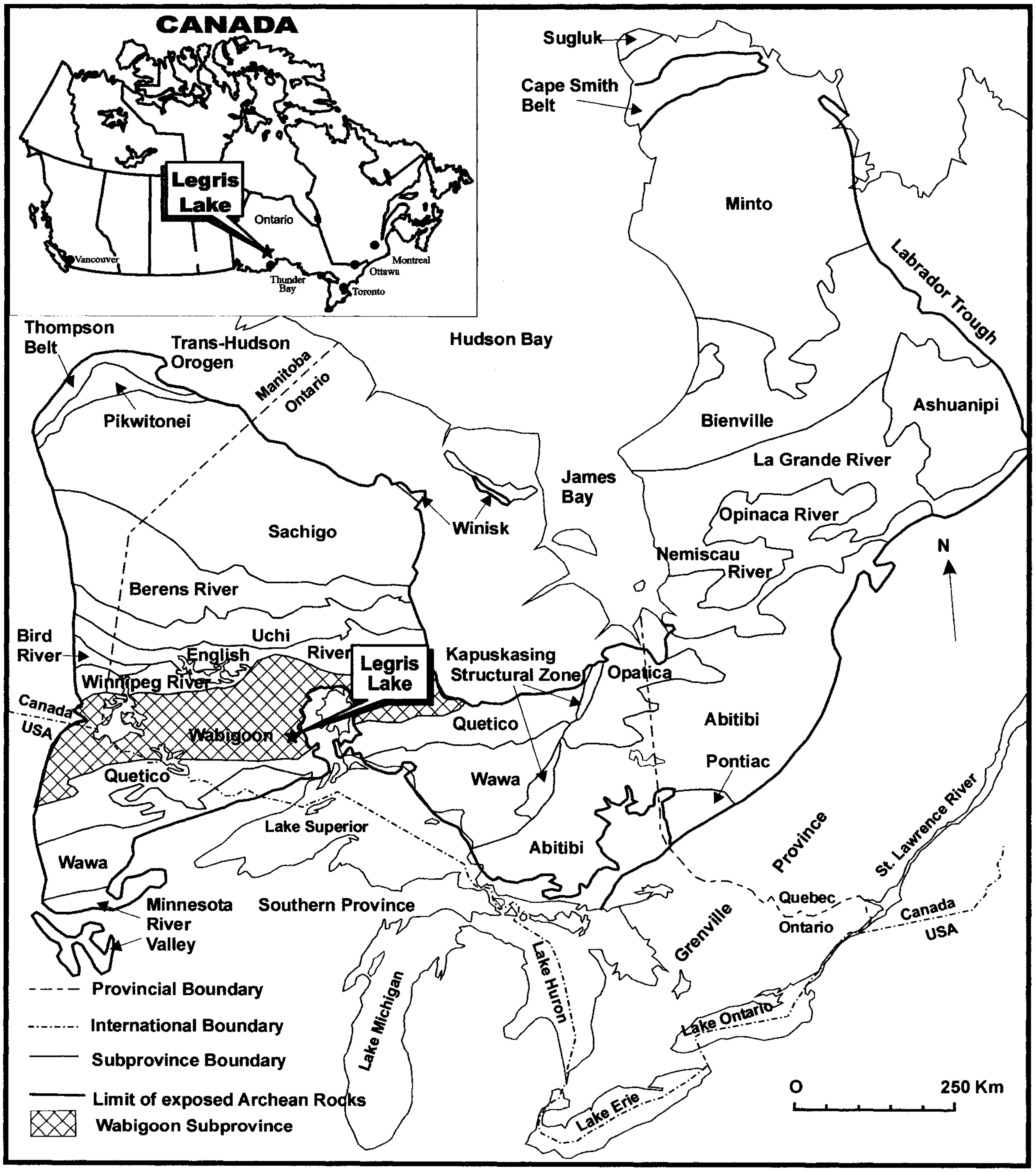
CANADA
Legris Lake
Ontario
Vancouver
Thunder Bay
Toronto
Ottawa
Montreal
Sugluk
Cape Smith Belt
Minto
Labrador Trough
Hudson Bay
Thompson Belt
Trans-Hudson Orogen
Manitoba
Ontario
Pikwitonei
Bienville
Ashuanipi
La Grande River
James Bay
Winisk
Sachigo
Opinaca River
Nemiscau River
N
Berens River
Bird River
Uchi
English
River
Legris Lake
Kapuskasing Structural Zone
Opatica
Winnipeg River
Canada
USA
Wabigoon
Quetico
Abitibi
Quetico
Wawa
Pontiac
Lake Superior
Abitibi
Province
St. Lawrence River
Wawa
Minnesota River Valley
Southern Province
Grenville
Quebec
Ontario
Canada
USA
Lake Michigan
Lake Huron
Lake Ontario
Lake Erie
0
250 Km
Provincial Boundary
International Boundary
Subprovince Boundary
Limit of exposed Archean Rocks
Wabigoon Subprovince

Figure 1.

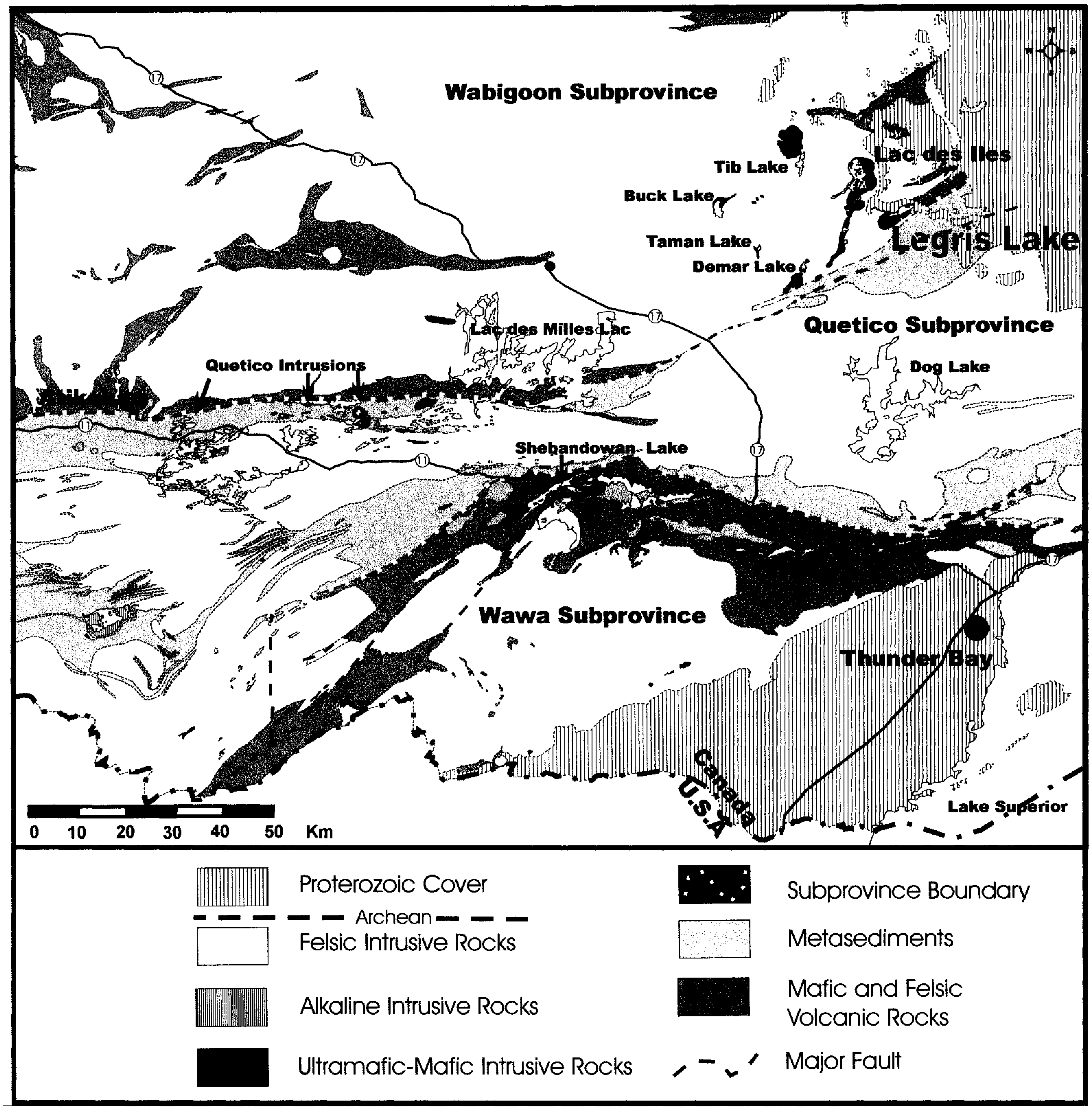
Wabigoon Subprovince
17
Tib Lake
Lac des Iles
Buck Lake
Legris Lake
Taman Lake
Demar Lake
Lac des Milles Lac
Quetico Subprovince
Quetico Intrusions
Dog Lake
11
Shebandowan Lake
Wawa Subprovince
Thunder Bay
Canada
U.S.A
Lake Superior
0 10 20 30 40 50 Km
Proterozoic Cover
Archean
Felsic Intrusive Rocks
Alkaline Intrusive Rocks
Ultramafic-Mafic Intrusive Rocks
Subprovince Boundary
Metasediments
Mafic and Felsic Volcanic Rocks
Major Fault

Figure 2.

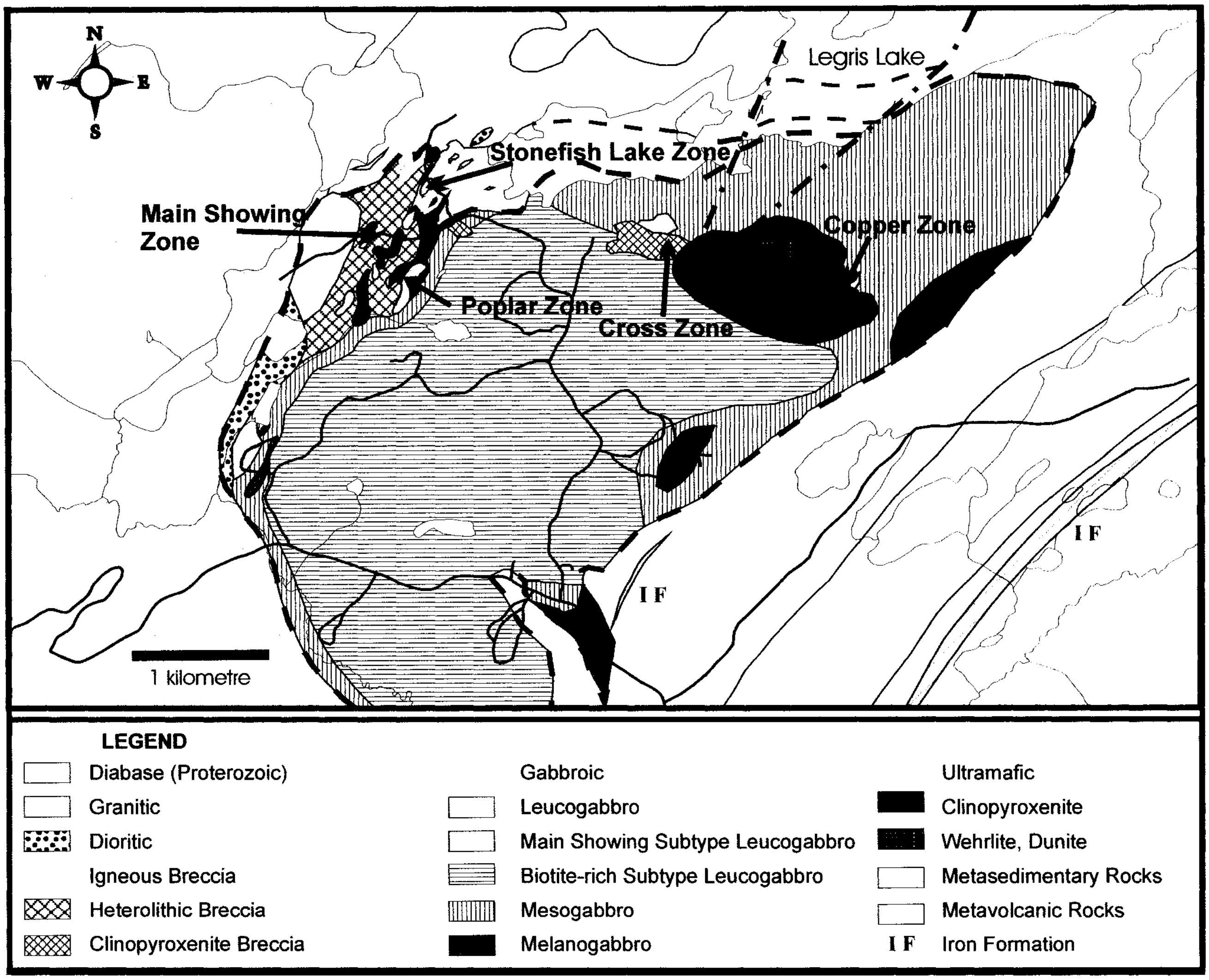
N
W
E
S
Legris Lake
Stonefish Lake Zone
Main Showing Zone
Copper Zone
Poplar Zone
Cross Zone
I F
I F
1 kilometre
LEGEND
Diabase (Proterozoic)
Granitic
Dioritic
Igneous Breccia
Heterolithic Breccia
Clinopyroxenite Breccia
Gabbroic
Leucogabbro
Main Showing Subtype Leucogabbro
Biotite-rich Subtype Leucogabbro
Mesogabbro
Melanogabbro
Ultramafic
Clinopyroxenite
Wehrlite, Dunite
Metasedimentary Rocks
Metavolcanic Rocks
I F Iron Formation

Figure 3.

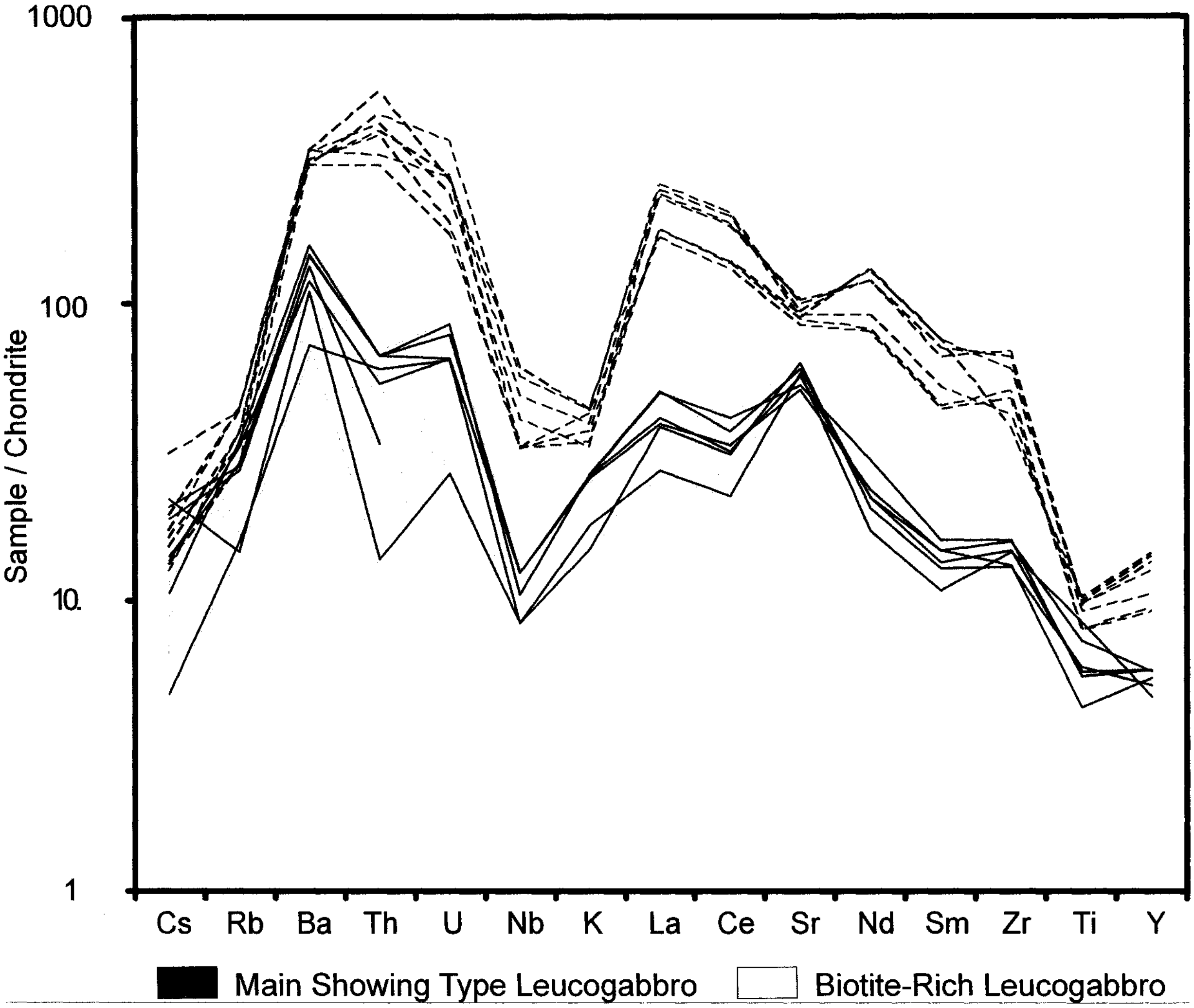
1000
100
10
1
Sample / Chondrite
Cs
Rb
Ba
Th
U
Nb
K
La
Ce
Sr
Nd
Sm
Zr
Ti
Y
Main Showing Type Leucogabbro
Biotite-Rich Leucogabbro

Figure 4.

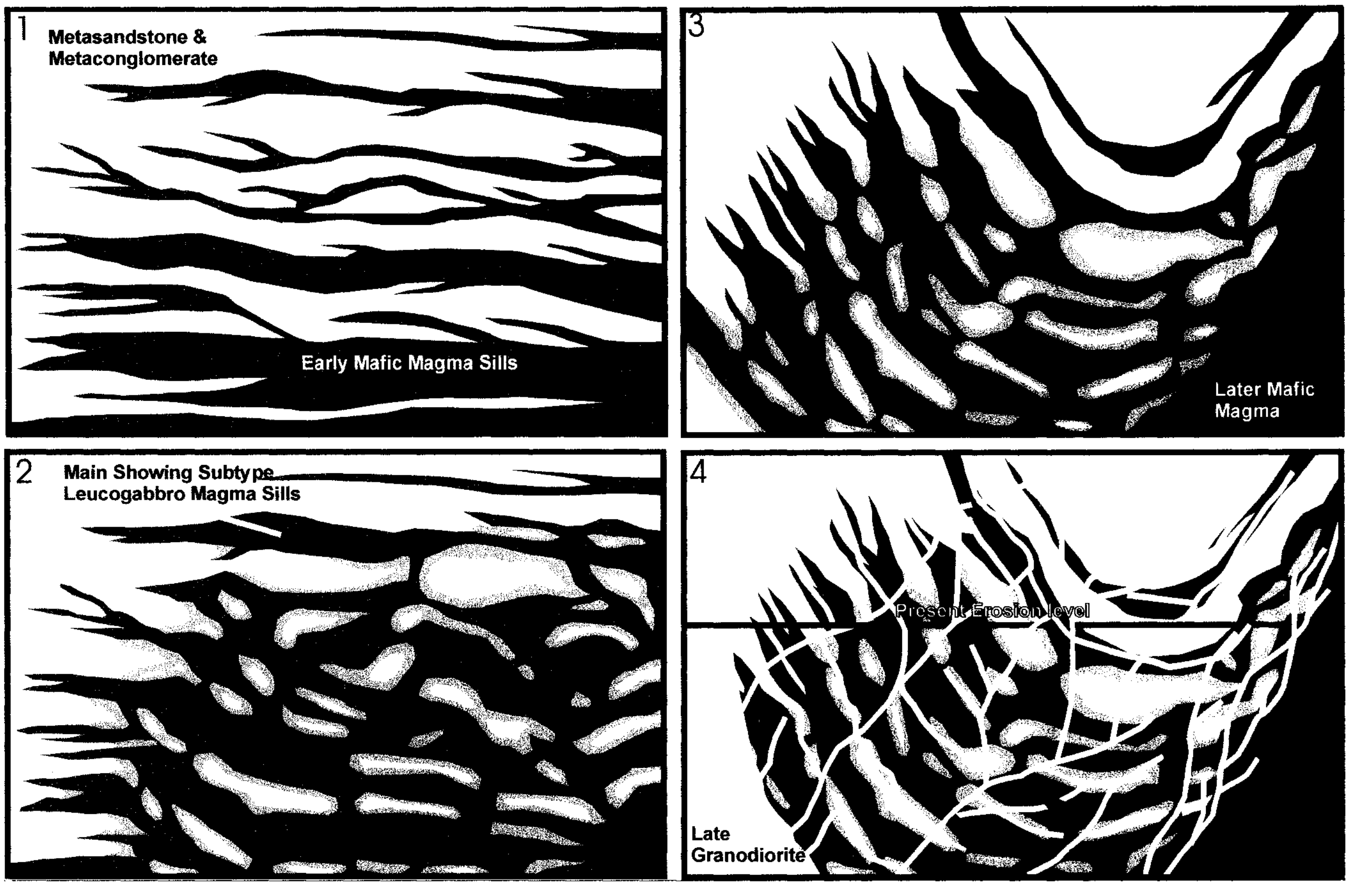
1
Metasandstone &
Metaconglomerate
Early Mafic Magma Sills
2
Main Showing Subtype
Leucogabbro Magma Sills
3
Later Mafic
Magma
4
Present Erosion level
Late
Granodiorite

Figure 5.

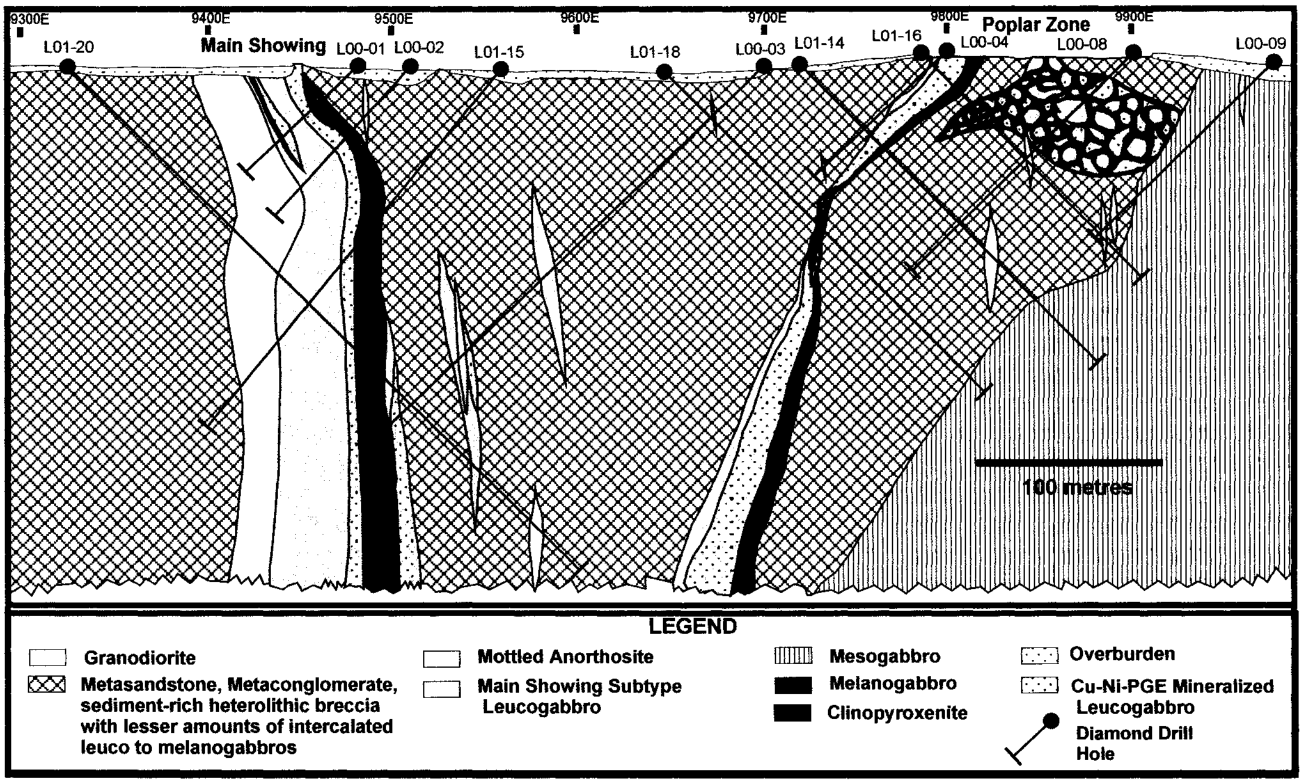
9300E
9400E
9500E
9600E
9700E
9800E
9900E
Main Showing
Poplar Zone
L01-20
L00-01
L00-02
L01-15
L01-18
L00-03
L01-14
L01-16
L00-04
L00-08
L00-09
100 metres
LEGEND
Granodiorite
Metasandstone, Metaconglomerate, sediment-rich heterolithic breccia with lesser amounts of intercalated leuco to melanogabbros
Mottled Anorthosite
Main Showing Subtype Leucogabbro
Mesogabbro
Melanogabbro
Clinopyroxenite
Overburden
Cu-Ni-PGE Mineralized Leucogabbro
Diamond Drill Hole

Figure 6.

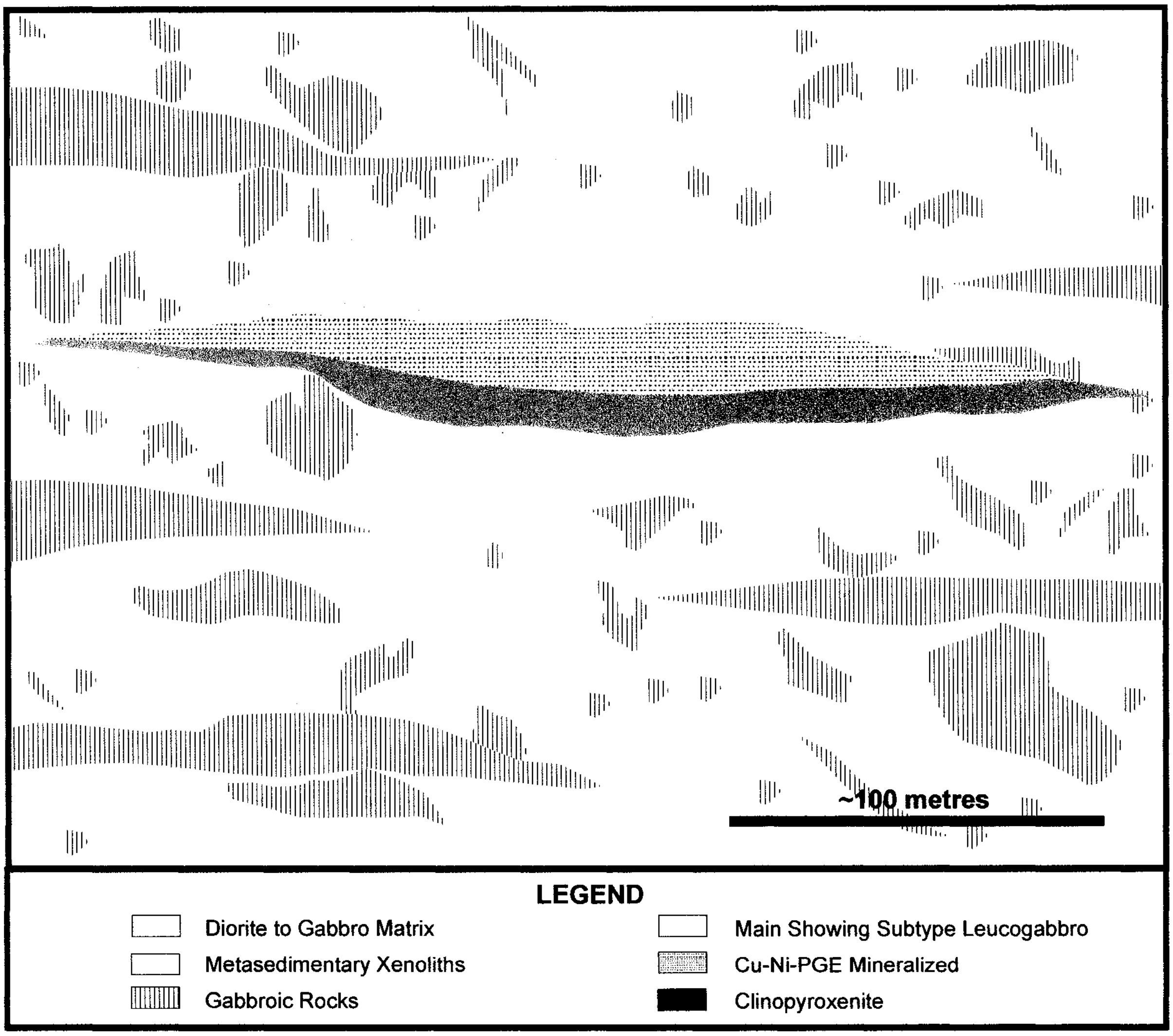
~100 metres
LEGEND
Diorite to Gabbro Matrix
Metasedimentary Xenoliths
Gabbroic Rocks
Main Showing Subtype Leucogabbro
Cu-Ni-PGE Mineralized
Clinopyroxenite

Figure 7.

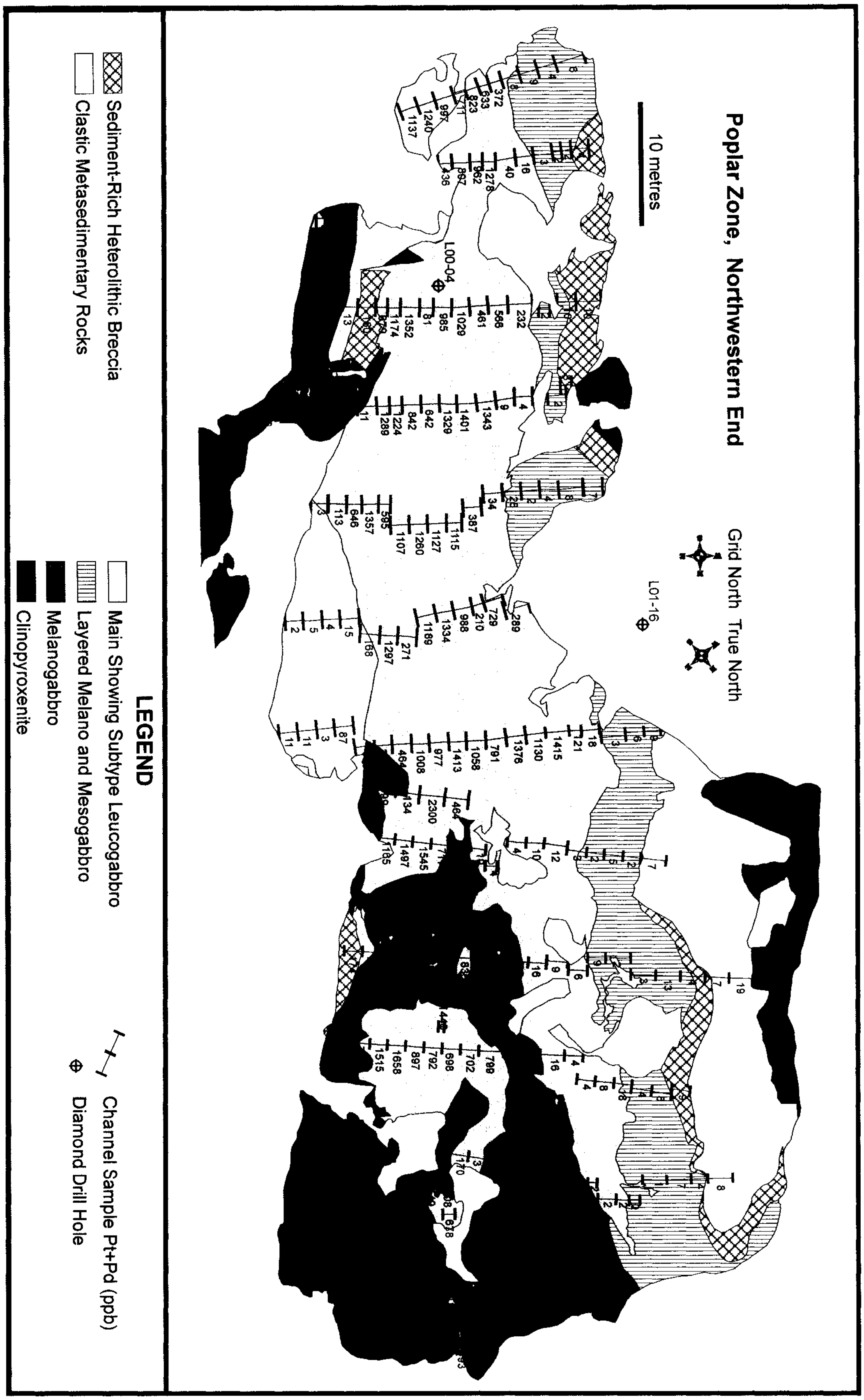
Poplar Zone, Northwestern End
10 metres
Grid North
True North
L01-16
L00-04
LEGEND
Main Showing Subtype Leucogabbro
Layered Melano and Mesogabbro
Melanogabbro
Clinopyroxenite
Sediment-Rich Heterolithic Breccia
Clastic Metasedimentary Rocks
Channel Sample Pt+Pd (ppb)
Diamond Drill Hole

Figure 8.

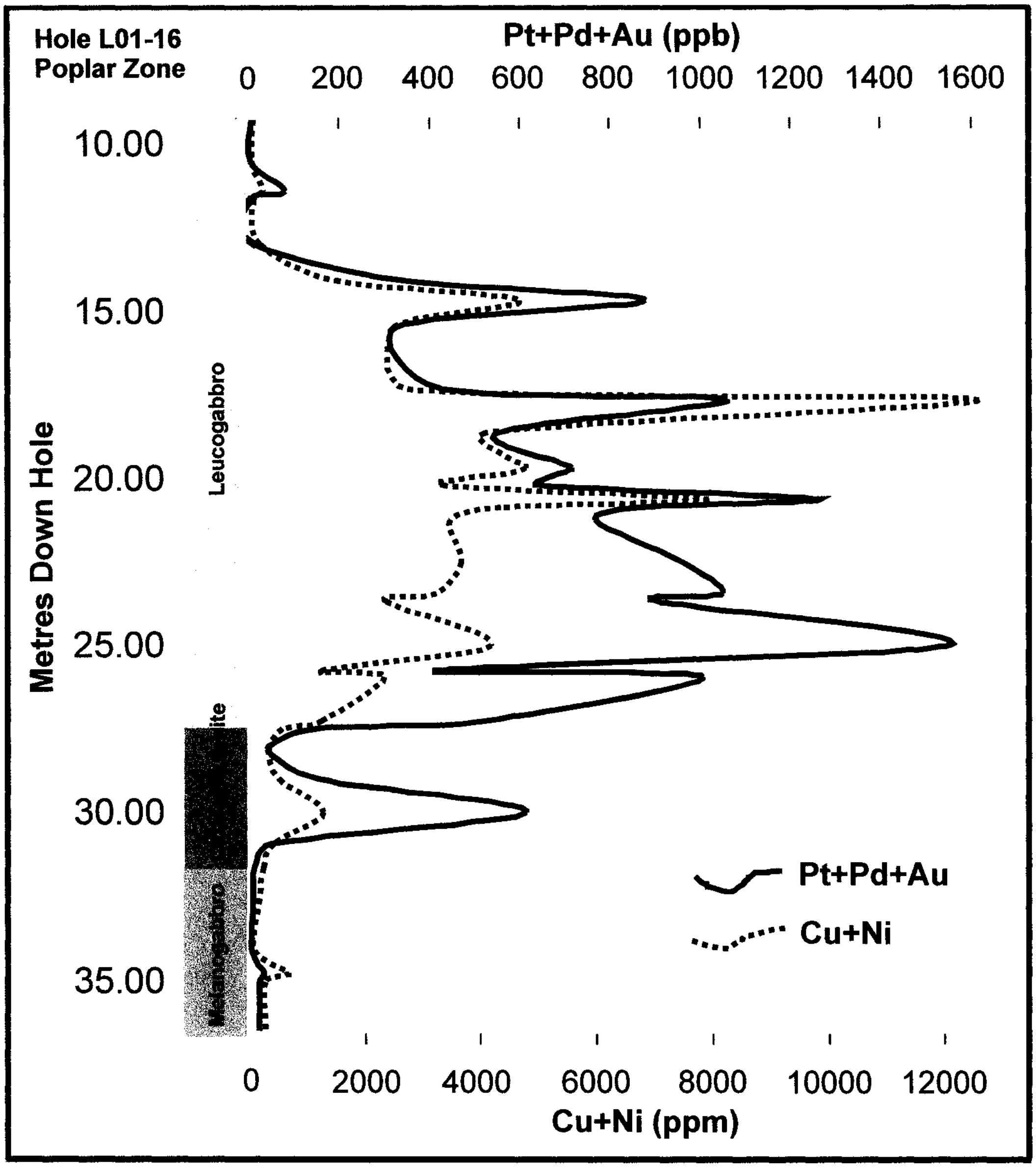
Hole L01-16
Poplar Zone
Pt+Pd+Au (ppb)
0
200
400
600
800
1000
1200
1400
1600
Metres Down Hole
10.00
15.00
20.00
25.00
30.00
35.00
Leucogabbro
ite
Melanogabbro
Pt+Pd+Au
Cu+Ni
0
2000
4000
6000
8000
10000
12000
Cu+Ni (ppm)

Figure 9.

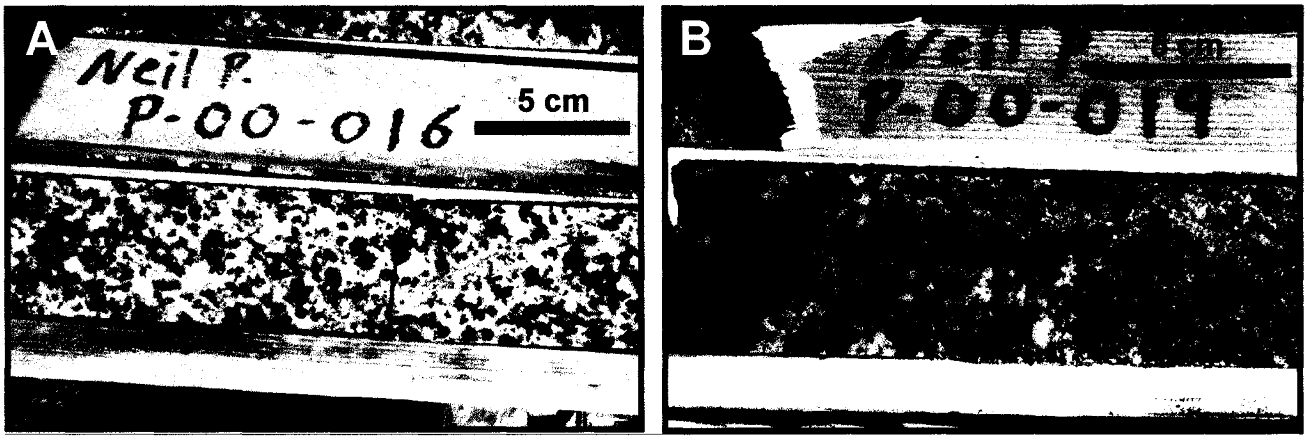

Figure 10.

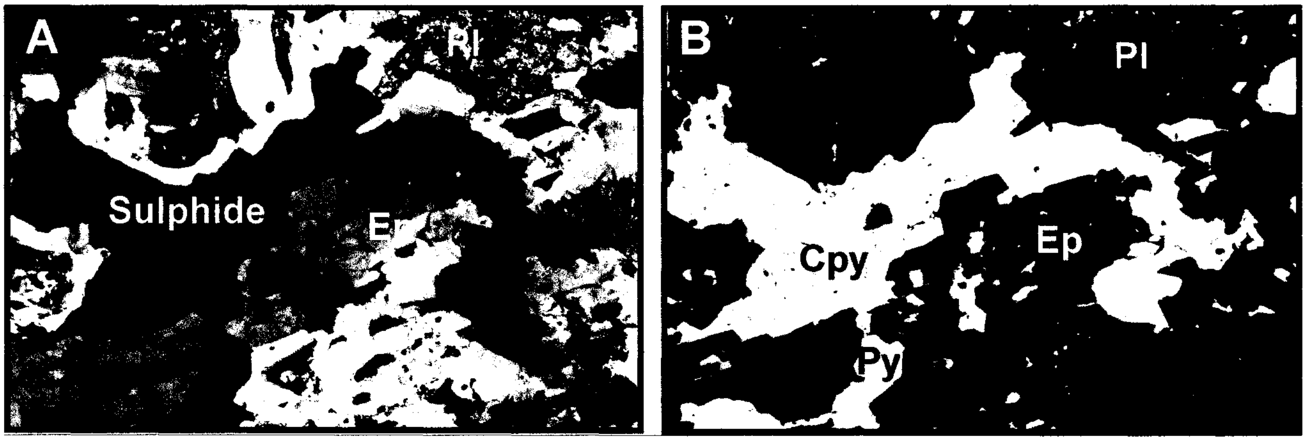

Figure 11.

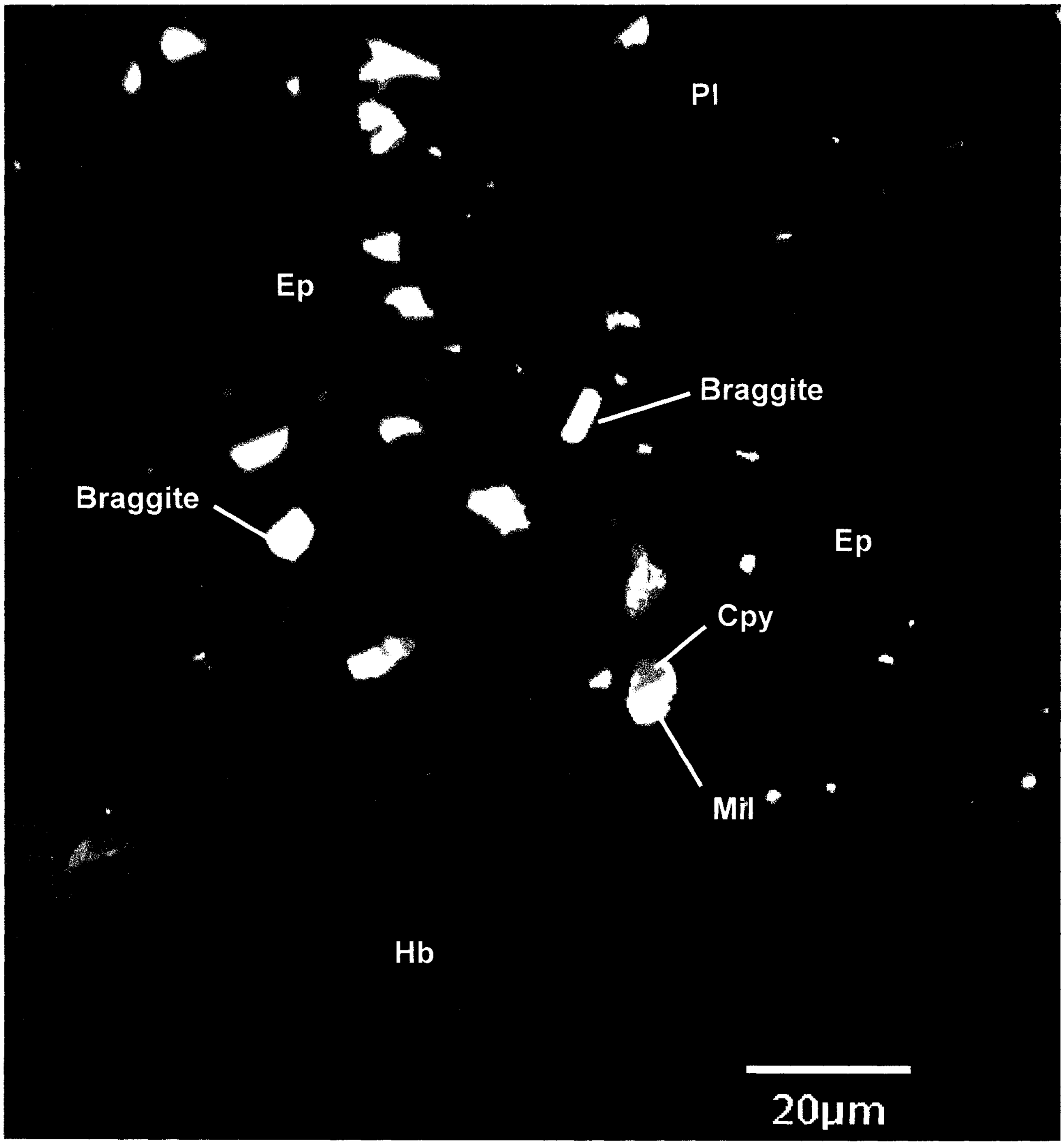

Figure 12.

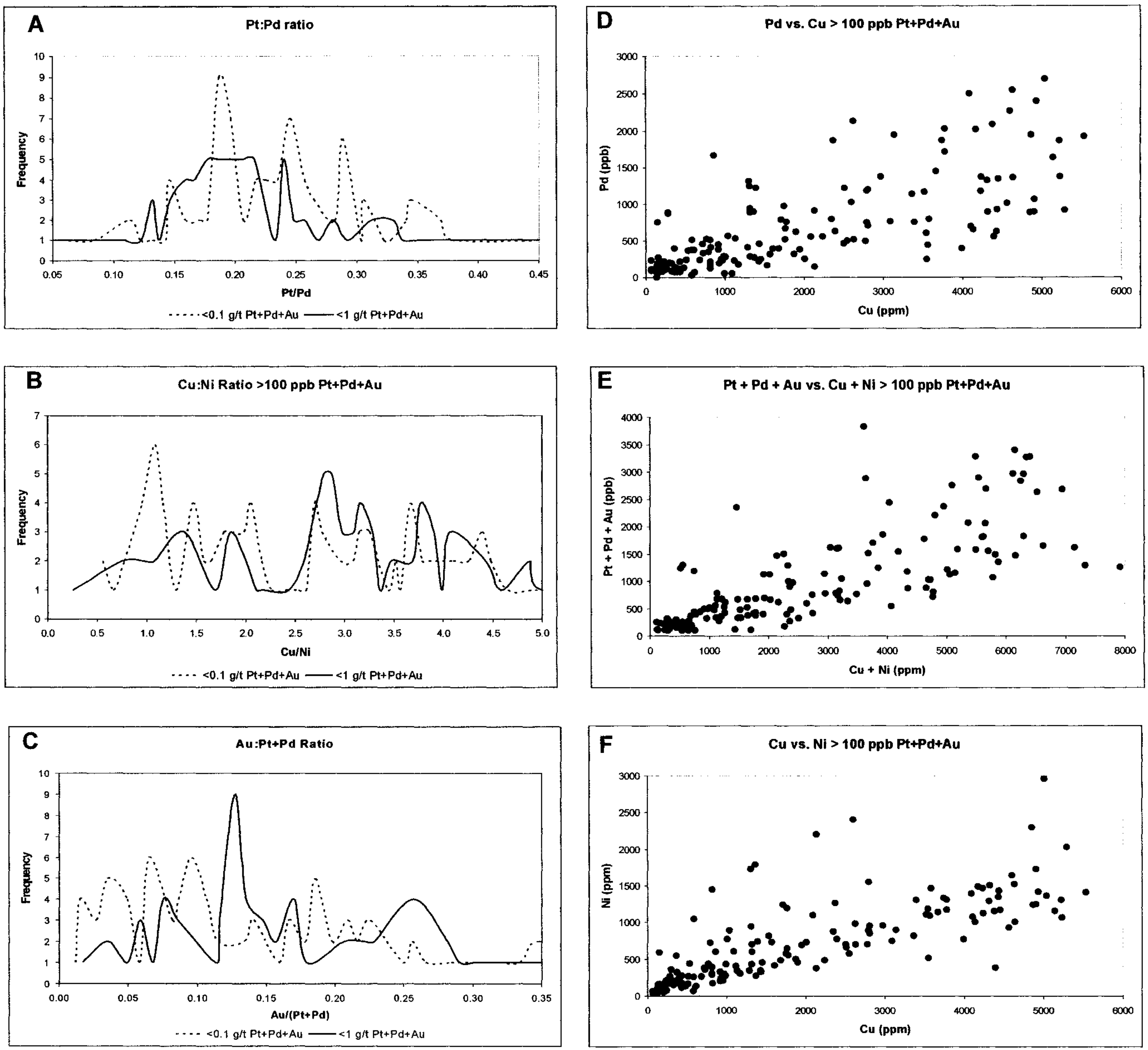
A
Pt:Pd ratio
Frequency
Pt/Pd
0.05 0.10 0.15 0.20 0.25 0.30 0.35 0.40 0.45
0 1 2 3 4 5 6 7 8 9 10
<0.1 g/t Pt+Pd+Au
<1 g/t Pt+Pd+Au
D
Pd vs. Cu > 100 ppb Pt+Pd+Au
Pd (ppb)
0 500 1000 1500 2000 2500 3000
Cu (ppm)
0 1000 2000 3000 4000 5000 6000
B
Cu:Ni Ratio >100 ppb Pt+Pd+Au
Frequency
0 1 2 3 4 5 6 7
Cu/Ni
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5 4.0 4.5 5.0
<0.1 g/t Pt+Pd+Au
<1 g/t Pt+Pd+Au
E
Pt + Pd + Au vs. Cu + Ni > 100 ppb Pt+Pd+Au
Pt + Pd + Au (ppb)
0 500 1000 1500 2000 2500 3000 3500 4000
Cu + Ni (ppm)
0 1000 2000 3000 4000 5000 6000 7000 8000
C
Au:Pt+Pd Ratio
Frequency
0 1 2 3 4 5 6 7 8 9 10
Au/(Pt+Pd)
0.00 0.05 0.10 0.15 0.20 0.25 0.30 0.35
<0.1 g/t Pt+Pd+Au
<1 g/t Pt+Pd+Au
F
Cu vs. Ni > 100 ppb Pt+Pd+Au
Ni (ppm)
0 500 1000 1500 2000 2500 3000
Cu (ppm)
0 1000 2000 3000 4000 5000 6000

Figure 13.

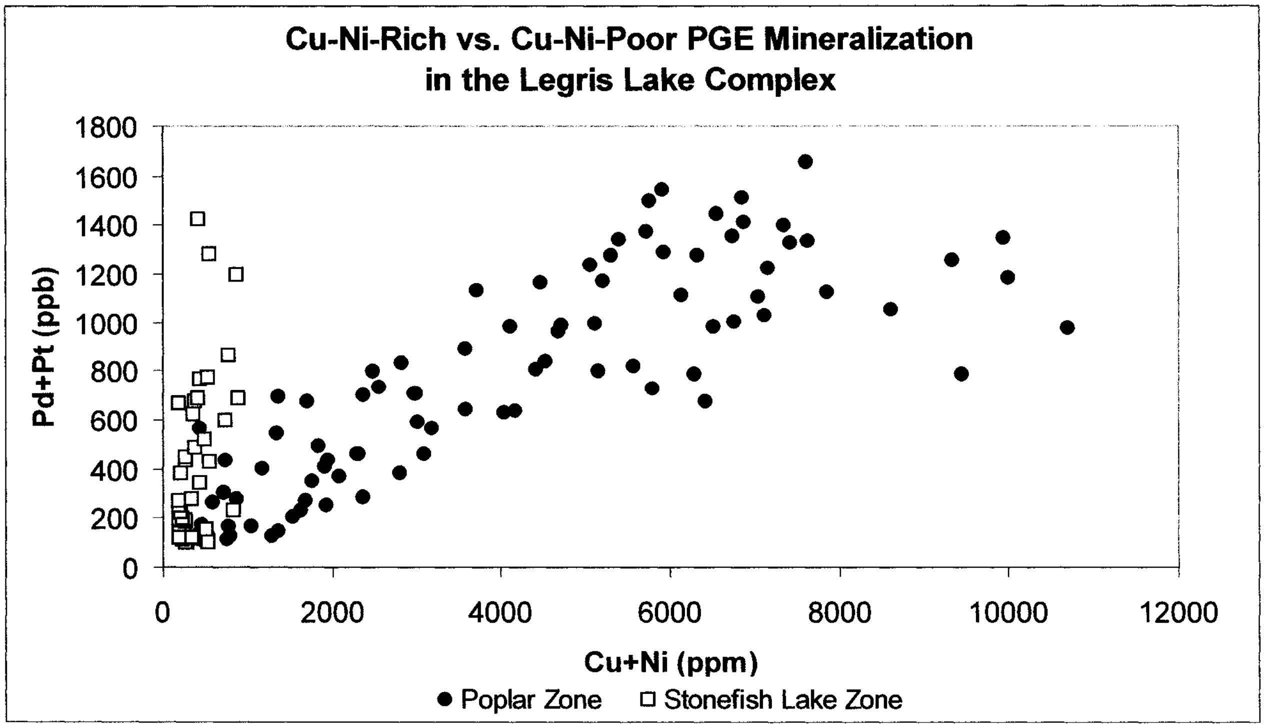
Cu-Ni-Rich vs. Cu-Ni-Poor PGE Mineralization
in the Legris Lake Complex
Pd+Pt (ppb)
1800
1600
1400
1200
1000
800
600
400
200
0
0
2000
4000
6000
8000
10000
12000
Cu+Ni (ppm)
● Poplar Zone
□ Stonefish Lake Zone

Figure 14.

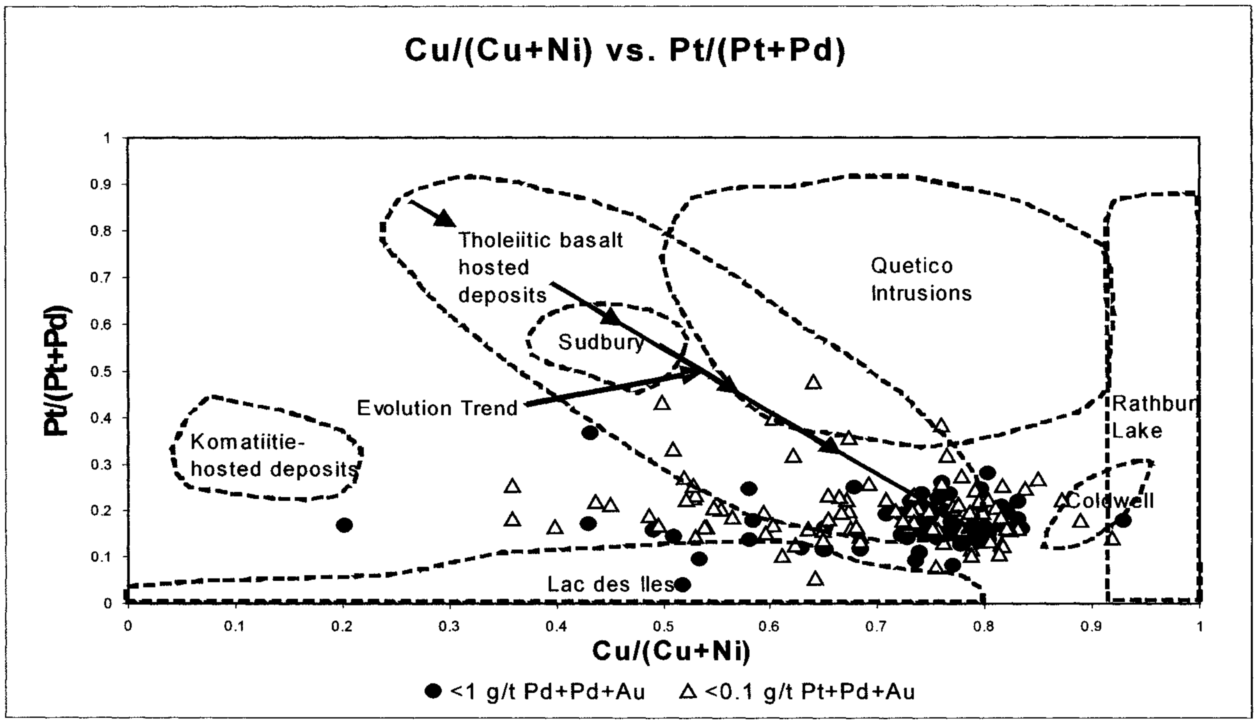
Cu/(Cu+Ni) vs. Pt/(Pt+Pd)
Pt/(Pt+Pd)
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Cu/(Cu+Ni)
Tholeiitic basalt hosted deposits
Quetico Intrusions
Sudbury
Evolution Trend
Komatiitie-hosted deposits
Rathburn Lake
Coldwell
Lac des Iles
● <1 g/t Pd+Pd+Au
△ <0.1 g/t Pt+Pd+Au

Figure 15.

The Quetico Intrusions of the Western Superior Province: Neo-Archean Examples of Alaskan/Ural-Type Mafic-Ultramafic Intrusions

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Precambrian Research

Abstract

The Quetico Intrusions have traditionally referred to an east-west striking, 45 km long array of mafic-ultramafic intrusions along the northern Quetico Subprovince boundary. Our examination of ultramafic-mafic intrusions in the interior of the Quetico Subprovince indicates that this array extends an additional 80 km to southwest including the Stawson Lake, Samuels Lake, and Red Horse intrusions. Among them, we conducted a detailed study of the Samuels Lake intrusion that shows the minimum age of 2688 +6/-5 Ma.

The Quetico Intrusions are commonly zoned with olivine-bearing clinopyroxenite cores surrounded by hornblendite and accompanied by Cu-Ni-platinum group elements (PGE) mineralization. Large intrusions contain wehrlite cores surrounded by clinopyroxenite, hornblendite and gabbro with minor diorite along their rims. Small intrusions show the lithological zoning, but lack one or two units. All intruded during the

D2 deformation before or during M2 regional metamorphism, suggesting their contemporaneous intrusion at ~ 2690 Ma.

All intrusions share not only common lithology and lithological textures but also similar mineralogy and mineral chemistry. The parental magmas for the Quetico Intrusions are hydrous as evident by abundant primary hornblende and biotite, early crystallization of clinopyroxene, the occurrence of pegmatite, and myrmekitic textures in late dioritic phases. The bulk chemical compositions show “arc geochemical signatures”, high concentration of large ion lithophile elements and low concentrations of high field strength elements, such as Nb, Ta and Ti. This is further consistent with the mineral compositions of pyroxene and hornblende that plot in the field for arc rocks.

The Archean Quetico intrusions display many similarities with Alaskan/Ural-type zoned mafic-ultramafic intrusions in Phanerozoic orogenic belts. Common features include lithological zoning, hornblende-rich lithologies, lack of orthopyroxene, and common PGE mineralization. The compositions of olivine, pyroxene, and hornblende from the Quetico intrusions are also similar to the available data from the Alaskan/Ural-type intrusions.

1.0 Introduction

Several mafic-ultramafic intrusions, collectively known as the Quetico Intrusions occur along the northern boundary of the Quetico Subprovince (Fig. 1). These intrusions range in size from 3-5 m thick dykes of limited length to elliptical stocks up to 3300 m by 1800 m and intrude metaturbidites. The Quetico Intrusions commonly contain clinopyroxenite cores and hornblendite rims. Larger intrusions contain wehrlite cores surrounded by clinopyroxenite, gabbro, diorite and syenite with gradational boundaries. They are characterized by the presence a pegmatite phase containing plagioclase-cored hornblende in a plagioclase matrix, which is referred to as "appinite" by previous workers (e.g., MacTavish, 1992; 1999). These intrusions are also commonly accompanied by Cu-Ni-PGE mineralization, however none of the known mineralization has yet to prove economic.

Apart from the array of mafic-ultramafic intrusions along the northern Subprovince boundary, there are several mafic-ultramafic intrusions in the centre of the Quetico Subprovince. We examined these intrusions as they have not been documented and compared them with the intrusions along the northern boundary. Among them, we selected the Samuels Lake intrusion for a detailed study due to availability of extensive drill core, and lack of intense deformation in the intrusion. We collected and examined a total of 50 representative samples from the intrusion. Additional, 32 representative samples were examined from 10 other Quetico Intrusions. This paper documents the lithology, geochemistry, mineral chemistry, and sulphide mineralization of the mafic-ultramafic intrusions in the Quetico Subprovince, discusses the origin of the Quetico

Intrusions, and compares them with the zoned Alaskan/Ural-type mafic-ultramafic complexes found in Phanerozoic orogenic belts.

2.0 Regional Geology

2.1 The Quetico Subprovince

The Quetico Subprovince consists of predominantly metamorphosed graywackes and siltstones. Although its origin remains in debate, it is considered to be a fore arc accretionary prism (Williams 1990). The Quetico metasedimentary belt was accreted to the Wabigoon Subprovince to the north and later the Wawa greenstone belt accreted to the Quetico belt to the south (Fig. 1). The proposed depositional setting is consistent with a short time interval, less than 20 Ma, between the sedimentation and subsequent deformation and metamorphism in the Quetico belt (Valli *et al.*, in press).

Five plutonic suits are recognized in the Quetico belt (Williams 1991) (Fig. 2); Suite 1) early mafic-ultramafic intrusions (Quetico Intrusions); Suite 2) foliated tonalite and diorite ca 2688-2687 Ma (Percival and Sullivan 1988; Davis et al. 1989, 1990); Suite 3) syenitic rocks of 2680 +/-1 Ma (Hattori and Percival, 1999), Suite 4) voluminous, peraluminous granitic rocks ca 2670-2653 Ma (Percival and Sullivan 1988); and Suite 5) late mafic sills. Suite 2 is similar to arc-related plutons of the Onaman-Tashota Terrane of the Wabigoon Subprovince (Percival 1989).

Four deformation events are recognized in the vicinity of the Quetico Intrusions (Williams 1991). D1 includes soft sediment deformation, minor isoclinal folding, and development of a planar fabric parallel to the original bedding (S1). D2 is accompanied by isoclinal folding and development of regional axial planar fabrics (S2). D3 produced upright, open to tight folding and D4 local scale shear zones cutting earlier fabrics.

The regional metamorphism, M1 peaked shortly after the sedimentation (Valli *et al.*, in press) whereas M2 metamorphism is local, related to the late suite 3 and 4 granitoids (up to granulite facies) and peaked during the waning stages of D2-D3 deformation (Sawyer 1983) overprinting regional metamorphic fabrics.

2.2. Quetico Intrusions

The term Quetico Intrusions was first employed by Watkinson and Irvine (1964) to describe a group of small, mafic-ultramafic intrusions forming stocks, plugs, sills and dykes along the northern boundary of the Quetico Subprovince (Fig. 2). They are mostly small (less than 3 km in diameter), and composed of a variety of hornblende-rich lithologies. They commonly display concentric lithological zoning, and posses little or no orthopyroxene. A detailed description of these intrusions appears in MacTavish (1992, 1999). The Quetico Intrusions differ from older (ca 2.73 Ga) mafic-ultramafic intrusions in Wabigoon and Wawa greenstone belts such as the Bad Vermilion Lake, Grassy Portage, and Shebandowan complexes, which are associated with komatiities and anorthosites.

We examined numerous mafic-ultramafic intrusions in the Quetico belt and found three intrusions in the center of the belt similar to those along the northern boundary. They are the Stawson Lake, Samuels Lake, and Red Horse intrusions (Fig. 2). All three intrusions are small in size (less than 1 km in diameter) and have similar mineralogy, textures, rock-types, bulk rock compositions, and mineral chemistry, the details of which are described later. They also have similar characteristic features, such as the occurrence of hornblende-plagioclase pegmatite, late hornblende-diorite phases, poikilitic-textured hornblende in clinopyroxene-rich rocks, and disseminated Cu-Ni-PGE-rich sulphides. These findings expand the array of Quetico Intrusions a further 80 km to the southwest.

3.0 Samuels Lake intrusion

Samuels Lake intrusion has a NE-SW elliptical (500 x 250 m) shape and show steeply dipping sharp boundaries with the host metasedimentary rocks (Pettigrew *et al.* 2000). The intrusion is conformable with regional fabrics of the host metasedimentary rocks. The interior has very little deformation, mostly in the form of narrow, conjugate brittle-ductile shears, and a local, poorly developed fracture set is recorded within the Intrusion.

The intrusion has the minimum U-Pb zircon age of 2688 +6/-5 Ma (V. McNicoll, unpublished data), which represents the age a late diorite phase. It has weak concentric zoning with a wehrlite core surrounded by clinopyroxenite (Fig. 3). These units were subsequently intruded by hornblendite, and small diorite dikes and plugs (Fig. 3). The intrusion has undergone three phases of alteration/metamorphism, deuteric alteration, amphibolite facies (M2) metamorphism, and a late greenschist facies alteration. Deuteric alteration refers here to the hydrothermal alteration products due to magmatic fluids released from the parental magmas during the crystallization of the Samuels Lake Intrusion. This alteration event resulted in the partial to complete, pervasive replacement of clinopyroxene by hornblende +/- actinolite-tremolite and serpentinization of olivine. Local minor carbonate alteration and minor redistribution of chalcopyrite also appears to be associated with this event. Subsequent regional metamorphism of amphibolite grade had little effect on the pre-existing mineral assemblage of hornblende + clinopyroxene + actinolite + olivine + serpentine + plagioclase. Secondary titanite (Fig. 4A) gives the U-Pb age of this event at 2668+/- 6 Ma (V. McNicoll, unpublished data). Late greenschist facies metamorphism resulted in minor chloritization of hornblende and biotite, saussuritization of plagioclase, and minor quartz-carbonate veinlets along fractures.

3.1 Petrology of the Samuels Lake intrusion

3.1.1 Wehrlite

This unit forms the core of the intrusion (Fig.3) and grades into the clinopyroxenite unit. The majority of this unit lies beneath Samuels Lake and its distribution is based primarily on diamond drill cores. This unit is composed of olivine and clinopyroxene(Mg#=atomic ratio of $Mg/(Mg+Fe^{2+})$= 0.85-0.92), with interstitial hornblende(Mg#= 0.84) and minor phlogopite(Mg# = 0.91), magnetite and sulphides (Fig. 4B and 5A). Both clinopyroxene and olivine are subhedral to euheral in a matrix of fine to medium grained anhedral hornblende and phlogopite ± sulphide. The subhedral to euhedral textures of the olivine and clinopyroxene indicate a cumulus origin of the unit. Olivine is generally the earliest crystallizing phase, however some olivine grains contain clinopyroxene inclusions. Early crystallization of clinopyroxene and late crystallization of plagioclase suggest high water contents in the parental magmas (e.g., Sisson and Grove, 1993).

The sulphides display blebby to net-textures surrounding olivine and clinopyroxene grains. The occurrence of exsolved pentlandite and chalcopyrite in pyrrhotite confirm their magmatic origin. These sulphides may comprise up to 40 vol.% of the unit. Sulphide-rich rocks contain aggregates of medium to fine grained clinopyroxene and hornblende, which are now altered to a mixture of hornblende + actinolite-tremolite ± chlorite. These aggregates form grey globular patches, which in conjunction with nearly black serpentinized olivine, give the unit a distinct appearance (Fig. 5A).

Olivine grains enclosed by sulphides commonly display deep embayment of sulphides (almost skeletal in texture), suggesting that the crystallization of olivine took place during the immiscible separation of sulphide melt (Fig. 4C). All olivine grains in the wehrlite unit are serpentinized, whereas those in the sulphide-poor clinopyroxenite unit are largely unaltered. It is likely that the sulphide melt was volatile-rich, and if so aqueous fluids driven off during the solidification of sulphides may have been responsible for the serpentinization of olivine grains.

3.1.2 Clinopyroxenite

Clinopyroxenite is the most voluminous unit of the intrusion and is well exposed on surface (Fig. 3). This unit displays cumulate textures and is comprised of coarse-grained (commonly greater than 2 cm) clinopyroxene (Mg# = 0.83-0.87) with minor interstitial hornblende(Mg#= 0.68-0.88), phlogopite(Mg#= 0.90), magnetite, ± olivine(Mg#= 0.76-0.78) ± plagioclase. It commonly displays poikilitic textures produced by fine to medium-grained clinopyroxene enclosed by intercumulus hornblende or clinopyroxene (Fig. 4D and 5B). This unit contains only trace amounts of pyrrhotite and erratic Cu-PGE-rich mineralization. This unit commonly grades into plagioclase-bearing clinopyroxenite, and less commonly melanogabbro near the contacts of the intrusion with the sedimentary rocks.

Identification of primary and secondary hornblende in this unit is impeded by the similar compositions of the two types of hornblende. Much of the hornblende is secondary, replacing coarse clinopyroxene grains during deuteric alteration, however primary interstitial hornblende is identified in less altered samples.

3.1.3 Hornblendite

This unit intruded semi-solidified wehrlite and clinopyroxenite producing the texture of magma mingling and local brecciation. This unit is typically medium grained and composed almost entirely of subhedral, elongate hornblende(Mg# =0.67-0.70) crystals with interstitial plagioclase, phlogopite(Mg#= 0.72), titanite, and trace K-feldspar, ilmenite, pyrrhotite and pyrite (Fig. 4E and 5C). The monomineralic nature of the unit along with it subhedral hornblende crystals and fine-grained matrix of plagioclase-phlogopite suggest that this unit is also of cumulate origin. This unit formed by multiple pulses of intrusions indicated by fragments of earlier hornblendite, with different grain sizes and plagioclase contents. The unit intruded as a crystal mush based on alignment of hornblende crystals parallel to the intrusive contacts.

3.1.4 Pegmatite

This unit forms dykes and pods and occurs in all rock types. It is composed of large (2-10 cm) euhedral to subhedral hornblende(Mg# =0.73) crystals containing plagioclase cores with a plagioclase matrix (Fig. 5D). It also contains significant amounts of phlogopite(Mg# = 0.64), K-feldspar, titanite, apatite, +/- quartz and carbonate.

3.1.5 Hornblende Diorite

This is the youngest unit, forming dykes and plugs with abundant angular fragments of wehrlite and clinopyroxenite (Fig. 5E). It is volumetrically minor in comparison to other units and often intrudes along the contact of the intrusion with the surrounding metasedimentary rocks. This unit locally grades into hornblende gabbro, quartz-diorite, monzodiorite, and quartz monzodiorite. This unit is typically medium grained (~2 mm) and composed primarily of plagioclase, hornblende(Mg# = 0.54-0.63), quartz, microcline and biotite(Mg# = 0.53) with trace ilmenite, pyrrhotite, apatite, titanite, monazite and zircon. It displays well-developed myrmekitic textures (Fig. 4F) and commonly brecciates earlier ultramafic rocks on a mineral grain-scale (Fig. 5F), suggesting that the melt was volatile-rich. The angular fragments suggest that it intruded after the complete solidification of earlier units. Local potassic and epidote alteration is developed in and immediately adjacent to the dykes probably due to the release of aqueous fluid during the solidification of the unit.

3.2 Geochemistry of the Samuels Lake intrusion

3.2.1 Effects of Deuteric Alteration

The Samuels Lake intrusion shows the evidence of deuteric alteration, which is primarily expressed as an addition of volatile elements, such as CO_2 and H_2O, to the rocks as indicated by minor carbonate alteration and extensive replacement of clinopyroxene by hornblende. This alteration, although pervasive, is not interpreted to have been intense as evident by the presence of abundant relict clinopyroxene, absence of widespread hydrothermal veining and/or intense alteration of the surrounding country rock, however it must be addressed when interpreting geochemical data.

Large ion lithophile elements (LILE), especially alkalis and alkali-earth elements, are soluble in aqueous fluids. However, high field strength elements (HFSE), such as Ta, Nb, Zr, and Ti most likely remained immobile during deuteric alteration and regional metamorphism (Polat and Hofmann 2003). This is supported by minor scatter shown by LILE and tight clusters of patterns shown by HFSE in the Samuels Lake Intrusion (Fig. 6). Rare earth elements (REE) also display consistent patterns except for minor scatters in light REE (Fig. 7), which is attributed to minor mobility of light REE in hydrothermal fluids (Seifert *et al.* 1985; Polat and Hofmann 2003).

3.2.2 Lithology and Geochemistry

The wehrlite and clinopyroxenite units display similar patterns of chondrite-normalized trace elements and REE (Fig. 6 and 7) and follow the same evolutionary trend on the diagram of MgO/(MgO+FeO) vs. SiO_2 (Fig. 8) suggesting they likely crystallized from the same magma. The diorite dykes and plugs follow similar evolutionary trends (Figs. 6, 7, and 8), suggesting that they too are likely formed from the same magma, which crystallized the wehrlite and clinopyroxenite units.

3.2.3 Mineral Composition

A total of 87 crystals of olivine, clinopyroxene, hornblende, and biotite were analyzed from 9 representative samples from the Samuels Lake intrusion. Olivine is Mg-rich ($Fo_{75.6-77.4}$), and displays low Ni contents (0.07 to 0.09 wt% NiO), suggesting sulphur saturation before or during crystallization of olivine. This is consistent with the interpretation based on the texture of olivine and sulphides (Fig. 4C). Clinopyroxene is predominantly diopside (Fig. 9) and plots in the sub-alkaline field defined by Lebas (1962) (Fig. 10). The clinopyroxene compositions are similar to those from arc igneous rocks (Fig. 9 and 10). Hornblende compositions vary greatly, and display considerable overlap between primary and secondary hornblende. However, their range of compositions is also similar to the range displayed by hornblende in arc igneous rocks (Fig. 11). Although the intrusion contains significantly high Cr (up to 0.16wt% Cr) in the bulk rocks, it is devoid of chromite. The lack of chromite is explained by the elevated Cr_2O_3 in clinopyroxene (up to 0.63 wt%), hornblende (up to 1.15 wt%) and phlogopite (up to 0.42wt%).

3.2.4 Parental Magma Geochemistry

Due to the lack of chilled margins the nature of the parental magma can only be inferred from consideration of cumulate and fractionate lithologies. Cumulate minerals such as olivine and clinopyroxene do not significantly fractionate Ta, Nb, Ti and LREE (Rollinson 1996), therefore although the concentrations of these trace elements in the bulk rocks may not represent those of the parental magmas, their ratios and patterns should reflect those of the original parental magmas. Trace element compositions show "arc" geochemical signatures (Pettigrew *et al.* 2001a, 2001b) (Fig. 6) characterized by low Nb, Ta, and Ti contents (Fig. 6). Similarly the La-Y-Nb element discrimination diagram of the bulk rocks also point to arc-related magmas (Fig. 12).

These arc geochemical signatures of the bulk rock compositions are consistent with clinopyroxene and hornblende compositions (Fig. 9, 10, and 11). The parental magma was also clearly hydrous and rich in alkalis, as indicated by abundant hornblende and biotite. The hydrous nature of the parental magma is further supported by early crystallization of clinopyroxene (Sisson and Grove, 1993), occurrence of pegmatites, and myrmekitic texture in late dioritic phases (Dymek and Schiffries 1987).

3.3 Cu-Ni-PGE Mineralization in the Samuels Lake Intrusion

Cu-Ni-PGE mineralization is restricted to the wehrlite and clinopyroxenite units. The sulphide-rich portions of wehrlite contain high Cu (up to 2.63 wt.%), Ni (up to 0.68 wt.%) and Co (up to 0.08 wt.%) with PGE contents of up to 940 ppb Pt, 900 ppb Pd, and 330 ppb Au. However, metal contents in the ~180 ppb Pt, ~230 ppb Pd, ~100ppb Au, ~0.50% Cu, ~0.45% Ni, and ~0.04% Co range are more typical.

Copper-Ni-PGE mineralization in the clinopyroxenite is much more sporadic with contents of up to 1500 ppb Pt, 1270 ppb Pd, 0.29 wt.% Cu, 0.06wt.% Ni, and 0.01wt.% Co in grab samples. The mineralization is much more Pt-Pd-Cu-rich, and sulphide-poor than that found in the wehrlite unit.

4.0 Discussion

4.1 Comparison between the Samuels Lake intrusion and other mafic-ultramafic intrusions along the northern Quetico Subprovince boundary.

This comparison uses our bulk rock data from 32 representative samples from 10 intrusions and 30 samples from 7 intrusions determined by McTavish (1992, 1999) along the northern Subprovince boundary. We determined the mineral compositions of 24 clinopyroxene, olivine and hornblende grains from the Kawene and North Elbow Lake intrusions along the northern boundary. Our data is combined with 48 clinopyroxene mineral analyses from Kawene and Abiwin intrusions performed by MacTavish (1992, 1999), which brings the mineral analysis database to 72 analyses from 3 different intrusions excluding the Samuels Lake intrusion.

The composition of the Samuels Lake intrusion is very similar to those from other Quetico Intrusions as illustrated by a plot of MgO/(MgO+FeO) vs. SiO_2 (Fig. 8). They all show fractionated REE with elevated light REE with little or no Eu anomalies (Fig. 7), elevated LILE and depletion of Nb, Ta and Ti (Fig. 6).

Both Samuels Lake intrusion and Quetico Intrusions have not only similar mineralogy but also similar mineral compositions. Furthermore, the compositional variations of clinopyroxene and hornblende are similar among the intrusions (Fig. 9, 10 and 11).

The three intrusions in the interior and the intrusions along the northern boundary of the Quetico Subprovince display similar relationships with the host sedimentary rocks. Metasedimentary country rocks contain numerous M2 quartz segregation veins and several veins cut the margin of the mafic-ultramafic intrusions along the northern subprovince boundary, suggesting that they intruded prior to or during the early stages of M2 metamorphism. The Samuels Lake intrusion also shows the evidence of M2 amphibolite grade regional metamorphism. The remarkable similarities between the three intrusions in the interior and intrusions along the northern subprovince boundary suggest they are most likely contemporaneous.

4.2 Timing of the Quetico Intrusions

The intrusions along the northern boundary are considered to be ~2688±4 Ma (Davies *et al.* 1990). This is consistent with the minimum age of the Samuels Lake intrusion, U-Pb zircon age of 2688 Ma +6/-5 Ma (V. McNicoll, unpublished data) from diorite. Furthermore, it is also in accord with the metamorphic age of 2668 ±6 Ma (V. McNicoll, unpublished data) obtained from metamorphic titanite in hornblendite from the Samuels Lake intrusion. This age is also contemporaneous with the age of regional peak metamorphism in the area, and the late voluminous peraluminous plutonic event at 2670-2653 Ma (Percival and Sullivan 1988).

4.3 Origin of the intrusions

Numerous opinions have been proposed for the origin of the Quetico Intrusions. Williams (1989) suggested that some of the Intrusions are the remnants of mantle diapirs emplaced during the early sedimentation of the Quetico turbidites based on the presence of fine-grained chloritic sediments in the Quetico Subprovince. Williams (1989) also proposed that the small dyke-like bodies were a tectonically emplaced dismembered ophiolite sequence. MacTavish (1992, 1999) suggested that these intrusions represent

Archean examples of the Appinite suite of intrusions in the British Iles, which are closely associated with granitic plutons, as described by Pitcher and Berger (1972). MacTavish (1999) also suggested the Quetico Intrusions were produced by mixing between mafic and felsic magmas during the formation of the granitic Quetico Batholithic Complex. Pirie (1978), and Watkinson and Irvine (1964) argued that they were cumulates of tholeiitic olivine-basalt magmas, which intruded into deeply buried sedimentary rocks.

Although some intrusions along the northern boundary of the Quetico Subprovince where deformation is intense have fault contacts, the majority of intrusions show igneous contacts with thermal aureoles in their host sedimentary rocks, indicating their emplacement by magmas. The intrusions are generally coarse or medium grained at their contacts without apparent chill zones (Fig. 13A and 13B), suggesting their intrusion into hot metasedimentary rocks and/or re-absorption of their outer chill zones by later upward flowing magmas.

Clinopyroxene and hornblende grains from all intrusions have similar compositions to those from igneous rocks in modern arcs (Fig. 9) and trace element composition of the bulk rock compositions of the intrusions have clear arc geochemical signatures (Fig. 6, 12). The arc-related geochemical signatures suggest that their parental magmas were originated from a mantle source that had undergone metasomatism during subduction. This does not necessarily suggest active subduction during the magmatism.

4.4.0 Comparison between the Alaskan/Ural-type and Quetico Intrusions

The Samuels Lake intrusion, and thereby the Quetico Intrusions, display many similarities with Phanerozoic Alaskan/Ural-type intrusions (Table 1.). Alaskan/Ural-type intrusions, are also referred to as zoned ultramafic–(mafic) complexes due to distinct lithological zoning. Well documented examples include the Goodnews Bay, Union Bay and Salt Chuck complexes in Alaska; the Tulameen Complex in British Columbia, Canada; the Alto Condoto Complex in Colombia; the Nizhni Tagil and Inagli complexes in Urals, Russia; and the Owendale Complex of New South Wales Australia. Similarities between the Quetico Intrusions and Alaskan/Ural-type intrusions include the intrusion morphology, lithology, textures, mineralogy, bulk rock compositions, mineral compositions, and PGE mineralization.

Alaskan/Ural-type intrusions were first described in southeastern Alaska and the Ural Mountains of Russia (Taylor, 1967; Taylor and Nobel 1969). They are restricted to Phanerozoic mobile belts such as those in the Cordillera in North and South America, Urals, and New South Wales in Australia (Taylor 1967; Tistl 1994; Fershtater *et al.*, 1997; Johan 2002). These intrusions together with similar intrusions in the area form linear arrays along major tectonic sutures (Garuti *et al.* 1997). These intrusions share several structural, petrological and genetic characteristics, which distinguish them from other types of mafic-ultramafic intrusions (Taylor 1967; Johan, 2002). Notable features include their relatively small size (generally 4 to 7 km), pipe-like shape, concentrically zoned lithologies consisting of a dunite core surrounded successively by clinopyroxenite, hornblendite and mozonite-grabbro rims, lack of orthopyroxene, diopsidic composition of clinopyroxene, pegmatite facies of clinopyroxene and hornblendite units, and common occurrence of PGE mineralization.

Although the Alaskan/Ural-type intrusions are recognized as a distinct type of mafic-ultramafic intrusion, their genesis remains in debate (Murray 1972; Tistl 1994;

Johan 2002). Proposed emplacement mechanism varies from dome-like diapiric injection of semi-solidified magma (Tislt 1994) to the feeder pipes of overlying andesitic volcanoes (Murray, 1972; Conrad and Kay, 1984). Proposed parental magmas include high-Ca, high-Mg alkaline ultrabasic magmas (Irvine 1967, 1974) and high-Mg basaltic magmas with arc tholeiite affinities (Murray 1972; Conrad and Kay 1984; Himmelber *et al.* 1986; Debari *et al.* 1987; Loucks 1990; Tislt 1994). Although debate remains over the magma type, most workers agree that the magmas were hydrous, and oxidizing compared to oceanic ridge basalts (Loucks 1990; Loney and Himmelberg 1992).

4.4.1. Lithological comparison

The Alaskan/Ural-type intrusions are characterized by their concentric zoning of lithologies with a gabbroic outer rim grading inward through clinopyroxenite to wehrlite and finally to a dunite core (Murray 1972; Irvine 1967; Findlay 1969; Rublee 1994; Nixon 1996; Foley *et al.* 1997). The Quetico Intrusions also commonly display crude concentric zoning, as well displayed in the Kawene, Chief Peter, Plateau Lake, North Elbow Lake, and Samuels lake Intrusions. They consist of an outer rim of hornblende-gabbro, hornblendite or clinopyroxenite with a clinopyroxenite to wehrlite core.

The Alaskan/Ural-type intrusions are predominantly composed of dunite, wehrlite, olivine clinopyroxenite, clinopyroxenite, hornblende clinopyroxenite, clinopyroxene hornblendite, hornblende- and/or clinopyroxene-bearing gabbro/diorite (Nixon 1996; Foley *et al.* 1997). Feldspar-bearing lithologies include gabbro/diorite, monzonite, monzodiorite and minor alkali-feldspar syenite and hornblende feldspar ± quartz ± biotite pegmatite (Nixon 1996; Foley *et al.* 1997). The latter lithologies are volumetrically minor, commonly form crosscutting dykes, such as hornblende gabbro dykes of the Owendale Complex of New South Wales Australia (Supple and Barron 1986; Johan *et al.* 1989), the coarse-grained hornblende gabbro dykes of the El Chacao and Cerro Pelon Intrusions of northern Venezuela (Murray 1972,) and the hornblende-plagioclase pegmatites of the Judd Harbor Complex in Alaska (Irvine 1974), respectively. The Quetico Intrusions are composed of similar lithologies, such as clinopyroxenite, olivine clinopyroxenite, wehrlite, hornblendite, and hornblende gabbro. The Quetico Intrusions also contain, late volumetrically minor feldspar-rich lithologies, which occur as dykes and plugs ranging from diorite to monzonite and pegmatitic hornblende + plagioclase + minor biotite +/- quartz "appinite" patches and dykes.

4.4.2. Intrusion Morphology

Although the Alaskan/Ural-type intrusions possess igneous contacts they rarely preserve outer chill zones nor produce wide metamorphic aureoles, their margins are also often faulted and display ductile deformation due to later deformation (Nixon 1996) similar to the Quetico Intrusions (Larsen 1964, MacTavish 1992, 1999 Pettigrew *et al.* 2000).

The Alaskan/Ural-type intrusions are generally small, less than 7 km, in comparison to other mafic ultramafic complexes (Foley *et al.* 1997) similar to the Quetico Intrusions, which range from less than 100 m up to 3 km in diameter.

The Alaskan/Ural-type intrusions occur as arrays or groups of intrusion within long, linear orogenic belts parallel to major regional structures (Murray 1972; Taylor and Noble 1969; Irvine 1974, 1976; Fershtater *et al.,* 1997). For example, zoned, mafic-ultramafic intrusions in Urals form a Platinum Belt (Fershtater et al., 1997). The distribution of intrusions is comparable with the array of intrusions along the boundary between Quetico and Wabigoon Subprovinces, with the Quetico Fault representing the major regional structure.

4.4.3. Textural similarities

Layering is rare although locally developed in both Alaskan/Ural-type (Irvine 1967; Irvine 1974) and Quetico Intrusions (Larsen 1964, MacTavish 1992, 1999). Cumulus textures are common in both Alaskan/Ural-type (Nixon 1996) and the Quetico Intrusions (Watkinson and Irvine 1964 Larsen 1974, MacTavish 1992, 1999, Pettigrew *et al.* 2000, 2001a) and poikilitic textures predominant, especially in hornblende-rich lithologies (Nixon 1996). This consists mostly of poikilitic hornblende enclosing and/or replacing clinopyroxene +/- olivine in Alaskan/Ural-type Intrusions (Murray 1972). Large (up to 5cm) poikilytic hornblende and clinopyroxene enclosing clinopyroxene +/- olivine is also characteristic of the Quetico Intrusions giving them a distinctive appearance in the field (Fig. 5B). Coarse grain to pegmatitic hornblende-plagioclase dykes and veins are also characteristic of both the Alaskan/Ural-type (Irvine 1974; Tistl et al. 1994; Murray 1972) and the Quetico Intrusions (MacTavish 1992, 1999, Pettigrew *et al.* 2000, 2001a)

4.4.4. Bulk rock compositions

Akaskan/Ural-type Intrusions display arc geochemical signatures (Johan 2002; Tistl *et al.* 1994), such as distinct lows at Nb,Ta and Ti and elevated LILE (Fig. 6) similar to the Quetico Intrusions. Both intrusion types also display high concentrations of light REE compared to heavy REE (Fig. 7)

4.4.5. Mineralogical Similarities

Both Alaskan/Ural-type intrusions and Quetico Intrusions contain abundant clinopyroxene, olivine, hornblende and magnetite with essentially no orthopyroxene (Nixon 1996; Foley *et al.* 1997; Irvine 1967; Larsen 1974, MacTavish 1992, 1999, Pettigrew *et al.* 2000, 2001a). The compositions of olivine (Fig. 14), clinopyroxene (Fig. 9 and 10), and amphibole (Fig. 11) from the Quetico Intrusions are also similar to those available from the Alaskan/Ural-type intrusions.

Alaskan/Ural-type intrusions commonly contain chromite in dunite, whereas Cr in Quetico Intrusions is bound in silicate minerals, mostly in clinopyroxene. This may reflect less oxidizing conditions of parental magmas for Archean Quetico Intrusions than Phanerozoic Alaskan/Ural type intrusion. However, both types of intrusions also contain abundant magnetite.

4.4.6. Cu-Ni-PGE Mineralization

Alaskan/Ural-type intrusions and associated placers have been historically been an important source of PGEs. PGE mineralization in the Alaskan/Ural type intrusions typically occurs in the central dunite unit (Nixon et al. 1990; Johan 2002). This is comparable to the wehrlite in the core of the Quetico Intrusions, which host the bulk of the PGE mineralization.

The PGE ratios of the two types of intrusions are similar. The Alaskan-Ural type intrusions are characteristically Pt and Ir-rich (Pt/Pd ratios >1) and depleted in Ru (Ru/Ir ratios <1) (Johan 2002). The Quetico Intrusions show an average Pt/Pd ratio close to 1 but display considerable variability. Limited number of Ru and Ir data from the Samuels Lake intrusion also show low Ru with Ru/Ir ratios range from 0.12 to 0.81 with the lowest value from the sample containing high Pt+Pd contents in excess of 1 ppm. Other Quetico Intrusions contain Ru contents below detection limits (less than 5 ppb; MacTavish 1992, 1999). A primitive mantle normalized PGE pattern of the Quetico Intrusions is similar to those of several Alaskan/Ural-type intrusions (Fig. 15). Major differences include less fractionation between Ir-group (Os, Ir, and Ru) and Pd-group (Rh, Pd, Pt, and Au) elements and higher Pt/Pd_{PM} values for Alaskan/Ural type intrusions than those for Quetico intrusions. The difference in PGE patterns is likely related to the occurrence of PGE mineralization. The mineralization in the Alaskan/Ural-type intrusions is commonly hosted by chromite-rich dunite with little sulphides, whereas the mineralization in the Quetico Intrusions lacks chromite. Chromite has a high affinity with Ru and Os, forming laurite (Sattari et al., 2002). Earlier removal of chromite would lower the concentrations of Ru and Ir in the parental magmas. This is consistent with high Pd/Ru in sulphide-rich Salt Chuck intrusion (Loney and Himmelberg 1992).

4.4.7. Similarities in Parental Magmas

Geochemical data presented in this study has shown the Quetico Intrusion to possess arc-like geochemical signatures with sub alkaline affinities. The parental magmas of the Quetico Intrusions were also likely to be hydrous (Watkinson and Irvine 1964;

Larsen 1974; MacTavish 1992, 1999; Pettigrew *et al.* 2000, 2001a). Similar features are also documented for the parental magmas of Alaskan/Ural-type Complexes. For example, island arc-like geochemical signatures (Himmelberg *et al.* 1986; Conrad and Kay 1984 DeBari *et al.* 1987; Loucks 1990) and the hydrous nature of parental magmas (Loucks 1990; Loney and Himmelberg 1992).

The Alaskan/Ural type intrusions have been interpreted to be the feeders of andesitic volcanism (Murray 1972; Conrad and Kay 1984). Tistl *et al.* (1994) also concluded that the Alto Condoto mafic-ultramafic Complex, a well-known Alaskan-type intrusion in northern Colombia, represents the feeder for overlying high Mg basalts. The Quetico Intrusions may also represent the feeders of overlying Mg-rich basalts, which have subsequently been eroded. This interpretation would account for the lack of chilled margins, as they would be reabsorbed by new magma flowing up the feeder pipes.

5.0 Summary

The identification of the Stawson Lake, Samuels Lake and Red Horse Intrusion as Quetico-type Intrusions has extended the distribution of the Quetico Intrusions 80 km further to the southwest. The Intrusions are now known to form an array of over 125 km long starting along the northern subprovince boundary and ending in the southwest of the Quetico Subprovince.

The Samuels Lake intrusion is roughly concentrically zoned with a wehrlite core surrounded by clinopyroxenite, which has been intruded by hornblendite and volumetrically minor late diorite dykes and plugs, and hosts two style of Cu-Ni-PGE mineralization. It intruded ca. 2688+6/-5 Ma, most likely during the early stages of D2 and before or during the early stages of M2 as indicated by metamorphic age of ca. 2668+/- 6 in metamorphic titanite. The Samuels Lake Intrusion formed by the fractionation of a sub-alkaline magma with arc geochemical signatures.

The Quetico Intrusions display many similarities with the Phanerozoic Alaskan/Ural-type complexes. These include, relatively small size of the intrusions, linear distribution of the intrusions near major regional structures, concentric zonation of lithologies with olivine-rich cores and gabbroic rims, arc geochemical signatures, similar mineralogy, the lack of orthopyroxene, poikilitic textures, and PGE mineralization. Although the PGE mineralization in Alaskan/Ural-type intrusions commonly occur in chromite-rich dunite, PGE mineralization associated with Cu-Ni sulphides is also reported in the Duke Island Complex and Salt Chuck intrusion. Therefore, the Quetico Intrusions most likely represent sulphide-bearing Neo-Archean examples of Phanerozoic, Alaskan/Ural-type mafic-ultramafic Intrusions.

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Figure Captions

Figure 1. Locations map of the Quetico Subprovince (modified from Card and Ciesielski 1986)

Figure 2. Location map of the Quetico Intrusions. The Quetico Intrusions array is outlined by a finely dotted gray line.

Figure 3. Geological map of the Samuels Lake intrusion.

Figure 4. Photomicrograph and back-scattered electron image of representative units of the Samuels Lake intrusion; (**A**) secondary titanite (Ti) in hornblende (Hb) in pegmatite. (**B**) typical appearance of wehrlite containing unaltered diopside (Cp) and serpentinized olivine (Ol) surrounded by sulphide (Sulph) (**C**) serpentinized olivine (Serp alt. Ol) in sulphide matrix in wehrlite, D) clinopyroxenite where the core of diopside is altered to hornblende (Hb alt. Cp) and rim is altered to actinolite (Ac alt. Cp), (**E**) hornblendite showing euhedral hornblende (Hb) and phlogopitic biotite (Bt), (**F**) back scattered electron image of diorite exhibiting myrmekitic intergrowth of quartz (Qz) in plagioclase (Pl). Field of view in all photomicrographs is 2.5 mm.

Figure 5. Photographs of representative lithological units of the Samuels Lake intrusion; A) werhlite with minor Cu-Ni-PGE mineralization, B) clinopyroxenite showing the crystal faces of coarse diopside, C) hornblendite with abundant pits due to erosion of biotite, D) plagioclase-cored hornblende-plagioclase pegmatite “appinite”, E) late diorite

containing an angular fragment of clinopyroxenite, F) diorite (white matrix) brecciating clinopyroxenite (dark fragments).

Figure 6. Chondrite normalized trace element plots of the Samuels Lake intrusion and Quetico Intrusions. A) hornblende-diorite; B) hornblendite; C) clinopyroxenite; D) wehrlite. The grey shaded area represents the compositional range of the Quetico Intrusions (this study and MacTavish, 1992; 1999). The black lines represent analysis from the Samuels Lake intrusion (this study). The dashed black lines and filled symbols represent analysis from the Owendale, Alaskan-type intrusion, New South Wales, Australia (Johan, 2002). Isolated data points not connected by lines represent the data which did not contain all the elements used in the diagram, therefore when an element is missing a line was not drawn across the area in which it should have been plotted. Chondrite values are Thompson (1982).

Figure 7. Chondrite normalized (McDonough and Sun 1995) rare earth elements of the Quetico Intrusions. A) hornblende-diorite; B) hornblendite; C) clinopyroxenite; D) wehrlite. The gray outline represents the compositional range of occupied by the Quetico Intrusions (this study). The black lines represent analysis from the Samuels Lake intrusion (this study). The dashed black lines and filled symbols represent analysis from the Owendale, Alaskan-Ural-type intrusion, New South Wales, Australia (Johan, 2002) and the Ural Platinum Belt (Fershtater *et al.,* 1997). Rock type symbols are the same as those used in figure 6.

Figure 8. Plot of MgO/(MgO+FeO$^{(\text{Total Fe})}$) versus SiO_2 of the Quetico Intrusions illustrating the different evolutionary paths between clinopyroxenite/wehrlite and hornblendite in the Samuels Lake intrusion. Samuels Lake Intrusion data is from this study; other Quetico Intrusions data is from MacTavish (1992; 1999) and this study.

Figure 9. Clinopyroxenes composition of the Quetico Intrusions. Samuels Lake Intrusion data (in black) is from this study; other Quetico Intrusions data (in grey) is from MacTavish (1992; 1999) and this study. Mildly alkaline pyroxene trends (1. Black Jack sill; 2. alkali basalt-trachyte series; Japan, 3. Gough Is.), strongly alkaline (4. Kungnat syenites; 5. Shiant Iles sill), tholeiitic (Skg Skaergaard), arc suites from Gill (1981), Coleman (1997), Conrad and Kay (1984), Gibb (1973) and Rublee (1994). Rock type symbols are the same as those used in figure 8.

Figure 10. Clinopyroxene compositions of the Samuels Lake intrusion (this study) and Quetico Intrusions (this study and MacTavish, 1992; 1999). The discrimination diagrams are modified after Lebas (1962). The steep slope of the pyroxene array in diagram B is characteristic of pyroxenes in hydrous magmas in subduction zones (Loucks 1990). Data for the Alaskan/Ural-type Tulameen Complex is from Rublee (1994). The term "non-alkaline" by LeBas (1962) include tholeiitic, high-alumina and calc-alkaline affinity. Rock type symbols are the same as those used in figure 8.

Figure 11. Amphibole compositions in the Quetico Intrusion versus those of Alaskan/Ural-type (arc-type) intrusions. Arc amphibole field defined by Beard and

Barker (1989), Tulameen Complex amphibole field defined by Rublee (1994). Quetico Intrusion data is from this study. Rock type symbols are the same as those found in the legend present in figure 8.

Figure 12. La-Y-Nb basalt discrimination diagram (after Cabanis and Lecolle 1989) illustrating the sub alkaline (transitional between calc-alkaline and tholeiitic), island-arc affinity of the Quetico Intrusions. This diagram although designed for basalt analysis is used here for cumulates since cumulate minerals such as olivine and clinopyroxene do not significantly fractionate Ta, Nb, Ti and LREE (Rollinson 1996), therefore although the concentrations of these trace elements in the bulk rocks may not represent those of the parental magams, their ratios and patterns should reflect those of the original parental magmas. Field 1 contains island-arc basalts; field 2 continental basalts; and filed 3 oceanic basalts. These field are subdivided into 1A: calc-alkaline basalts; 1C: island-arc tholeiites; 1B area of overlap between 1A and 1C; 2A: continental basalts; 2B: back-arc basin basalts; 3A: alkali basalts from intercontinental rift; 3B, 3C, E-type MORB (3B enriched, 3C weakly enriched); 3D: N-type MORB. Samuels Lake Intrusion data is from this study; other Quetico Intrusions data is from MacTavish (1992; 1999) and this study. Rock type symbols are the same as those used in figure 8.

Figure 13. Photographs of Quetico Intrusions contacts; A) North Elbow Intrusion, B) Mud Lake Intrusion.

Figure 14. Comparison of forsterite component of olivine from the Quetico Intrusion to other mafic-ultramafic complexes. Data sources are from this study, MacTavish (1992, 1999), Wager and Brown (1968), Deer *et al.* 1978), Coleman (1977), Conrad and Kay (1984), Debari *et al.* (1987), Debari and Coleman (1989), Burns (1985), Gray *et al.* (1986), Snoke *et al.* (1981), Snoke *et al.* (1982), Springer (1989), James (1971), Walawender and Smith (1979), Mossman (1973), Irvine 1974, 1976), Clark (1980), Smith *et al.* (1983), and Himmelberg *et al.* (1986).

Figure 15. Precious metal concentrations from the Quetico Intrusions compared to some Alaskan/Ural-type Complexes. Data sources: Samuels Lake Intrusion (this study; black lines), other Quetico Intrusions (MacTavish, 1992; 1999; grey lines), dunites from the Nizhni Tagil (Fominykh and Khvostova 1970; magenta lines) and Konder (Malitch 1996; red lines) Complex. Symbols for Samuels Lake Intrusion and other Quetico intrusions are the same as Fig. 8. The average values for the Alaskan/Ural-type intrusions from Alaska (blue shaded area) and Ural Mountains (green lines) are a composite of several intrusions from both Alaska and the Urals compiled by Crocket (1981). Primitive mantle values are 0.00725 times chondrite values of McDonough and Sun (1995) after Guillot *et al.* (2000).

Table 1. Compassion between Alaskan/Ural-Type and Quetico Intrusions

Characteristic	Alaskan/Ural-Type Intrusions	Quetico Intrusions
Age	Phanerozoic	late Archean
Distribution	form long linear arrays along major tectonic boundaries in orogenic belts	form a linear array parallel to the Quetico-Wabigoon subprovince boundary
Morphology	small size (<3.5 km), rough concentric zonation of lithologies grading from mafic rims to ultramafic cores	small size (<3.0 km), rough concentric zonation of lithologies with mafic rims grading into ultramafic cores
Lithology	dominated by ultramafic phases such as hornblende-clinopryoxenite, clinopyroxenite and dunite with gabbroic and minor dioritic phases	dominated by ultramafic phases such as hornblendite, clinopyroxenite and wehrlite with minor gabbroic and dioritic phases
Textures	poikilitic textures, pegmatitic phases	poikilitic textures, pegmatitic phases
Mineralogy	abundant clinopyroxene, hornblende, and magnetite, common chromite in dunite lack of orthopyroxene	abundant clinopyroxene, hornblende, magnetite essential lack orthopyroxene
Mineral chemistry	high Mg olivine (Fo 72-94), diopsidic clinopyroxene	high Mg Olvine (Fo 76-82), diposidic clinopyroxene
Bulk rock geochemistry	arc related geochemical signatures with high LILE and low HFSE	arc related geochemical signatures with high LILE and low HFSE
PGE mineralization	Pt-Ir-rich, Ru-poor PGE mineralization associated with chromite. Sulphide-rich examples are accompanied by Cu-Ni mineralization	Pt-Ir-rich, Ru-poor Accompanied by Cu-Ni sulphide mineralization
Parental magmas	hydrous, with arc related geochemical signatures	hydrous, with arc related geochemical signatures
Examples	Goodnews Bay, Union Bay and Salt Chuck complexes in Alaska; Tulameen Complex in British Columbia, Canada; Alto Condoto Complex in Colombia; Nizhni Tagil and Inagli complexes in Urals, Russia; Owendale Complex of New South Wales Australia.	Samuels Lake, Kawene Lake, Plateau Lake, Chief Peter, and North Elbow intrusions

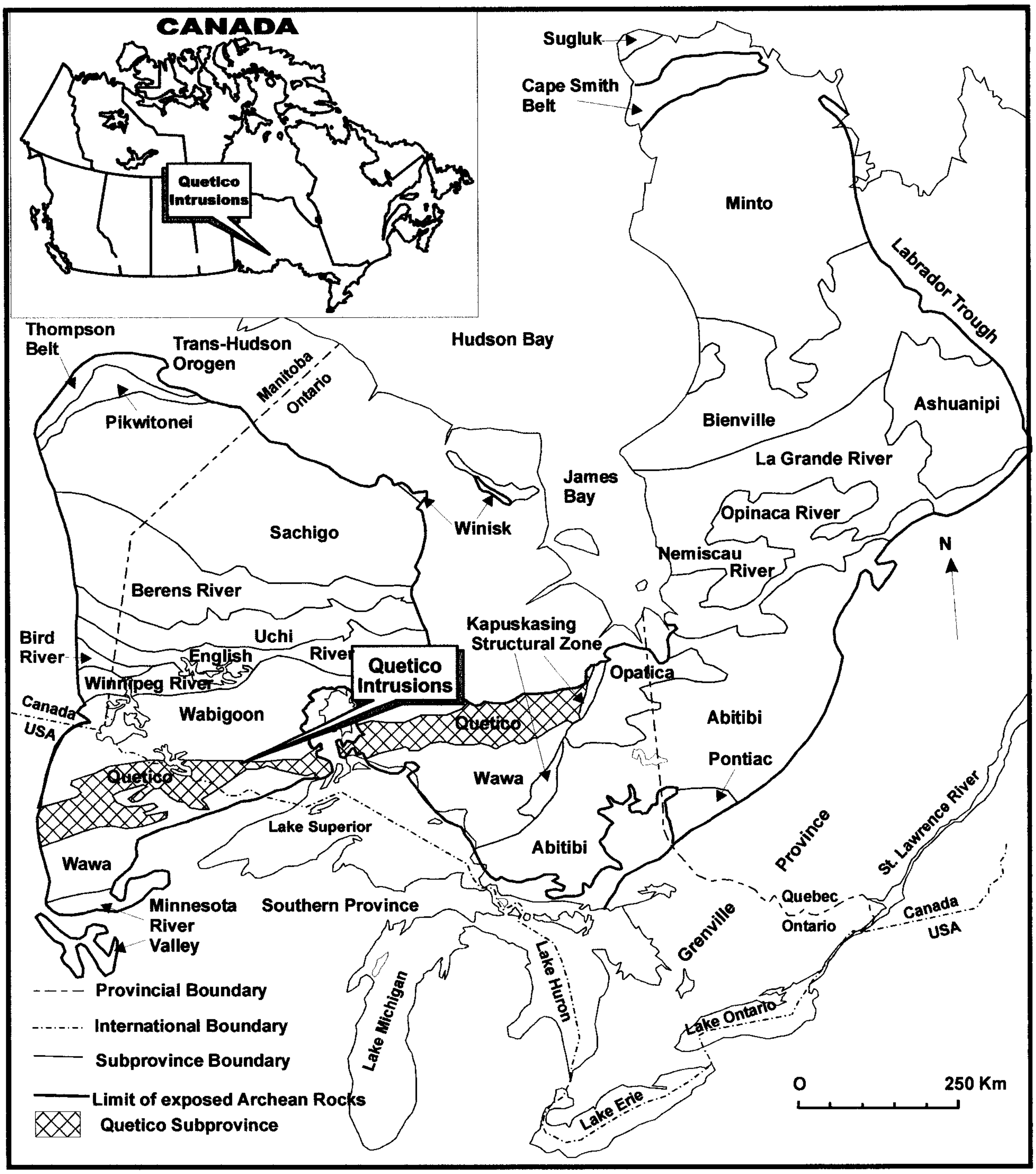

CANADA
Quetico Intrusions
Sugluk
Cape Smith Belt
Minto
Labrador Trough
Thompson Belt
Trans-Hudson Orogen
Hudson Bay
Manitoba
Ontario
Pikwitonei
Bienville
Ashuanipi
La Grande River
James Bay
Opinaca River
Sachigo
Winisk
Nemiscau River
N
Berens River
Kapuskasing Structural Zone
Bird River
Uchi
English River
Quetico Intrusions
Opatica
Winnipeg River
Canada
USA
Wabigoon
Quetico
Abitibi
Quetico
Pontiac
Wawa
Lake Superior
St. Lawrence River
Province
Abitibi
Wawa
Quebec
Ontario
Canada
USA
Minnesota River Valley
Southern Province
Grenville
Lake Huron
Lake Michigan
Lake Ontario
Lake Erie
0
250 Km
Provincial Boundary
International Boundary
Subprovince Boundary
Limit of exposed Archean Rocks
Quetico Subprovince

Figure 1.

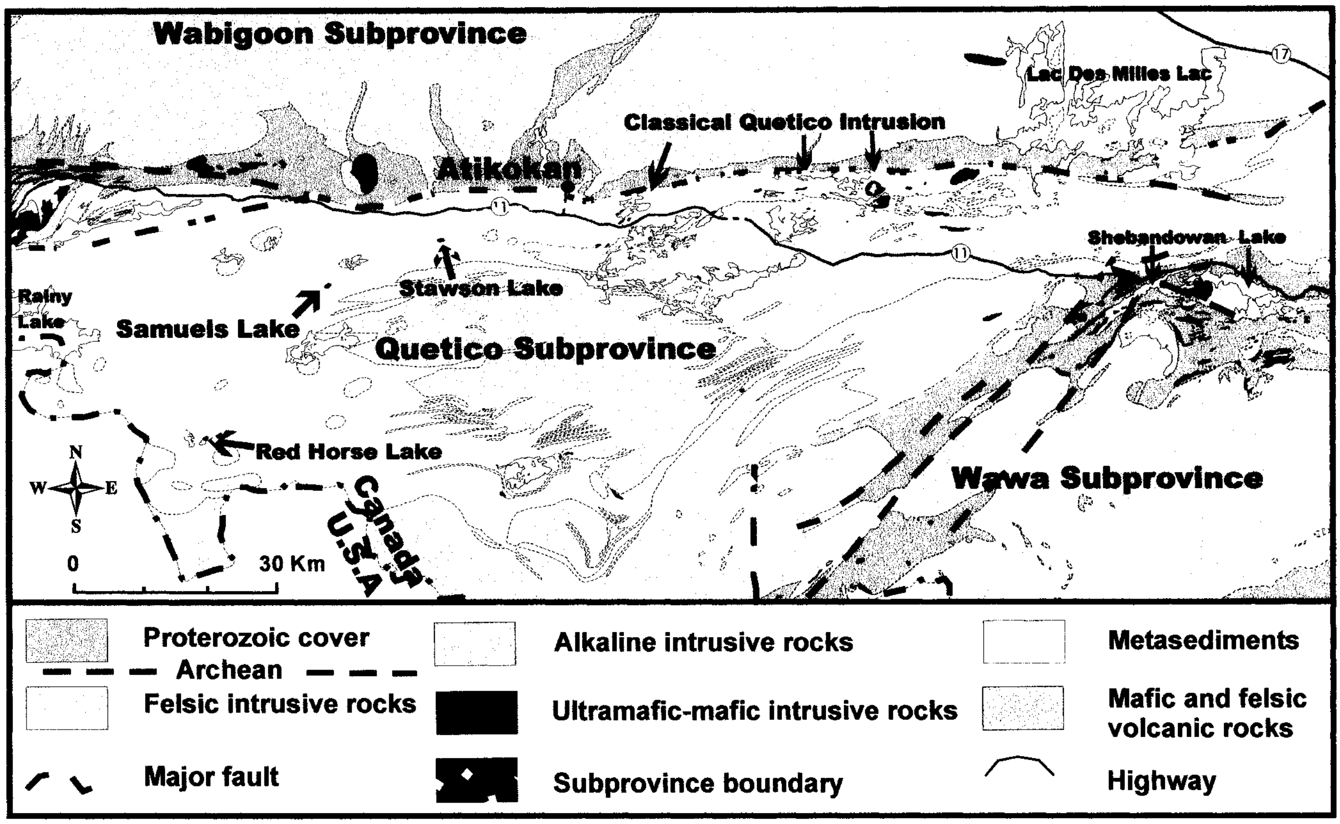
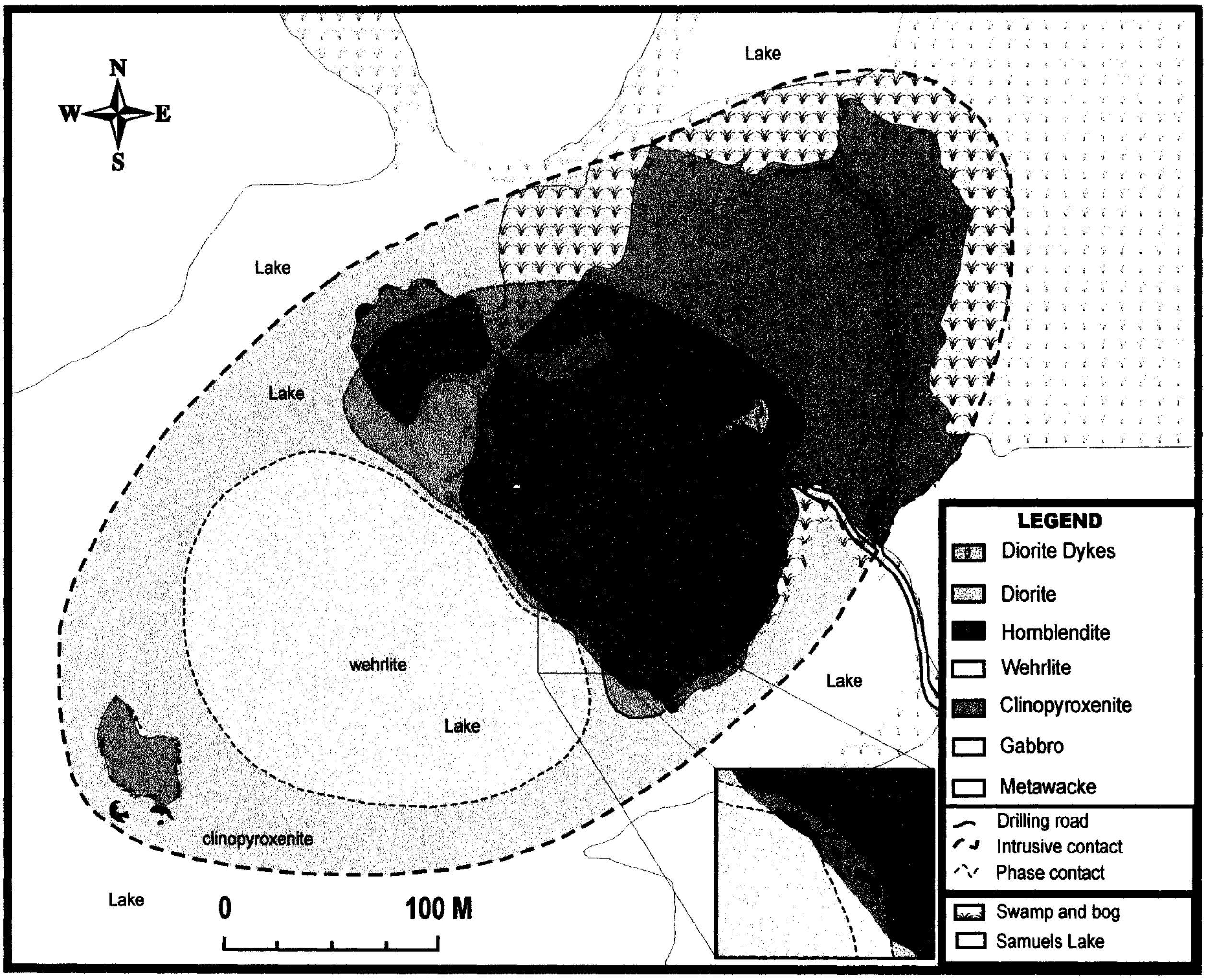

Wabigoon Subprovince
Lac Des Milles Lac
17
Classical Quetico Intrusion
Atikokan
11
Shebandowan Lake
11
Rainy Lake
Stawson Lake
Samuels Lake
Quetico Subprovince
Red Horse Lake
N
W
E
S
0
30 Km
Canada
U.S.A
Wawa Subprovince
Proterozoic cover
Archean
Felsic intrusive rocks
Major fault
Alkaline intrusive rocks
Ultramafic-mafic intrusive rocks
Subprovince boundary
Metasediments
Mafic and felsic volcanic rocks
Highway

Figure 2.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wehrlite
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clinopyroxenite
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LEGEND
Diorite Dykes
Diorite
Hornblendite
Wehrlite
Clinopyroxenite
Gabbro
Metawacke
Drilling road
Intrusive contact
Phase contact
Swamp and bog
Samuels Lake

Figure 3.

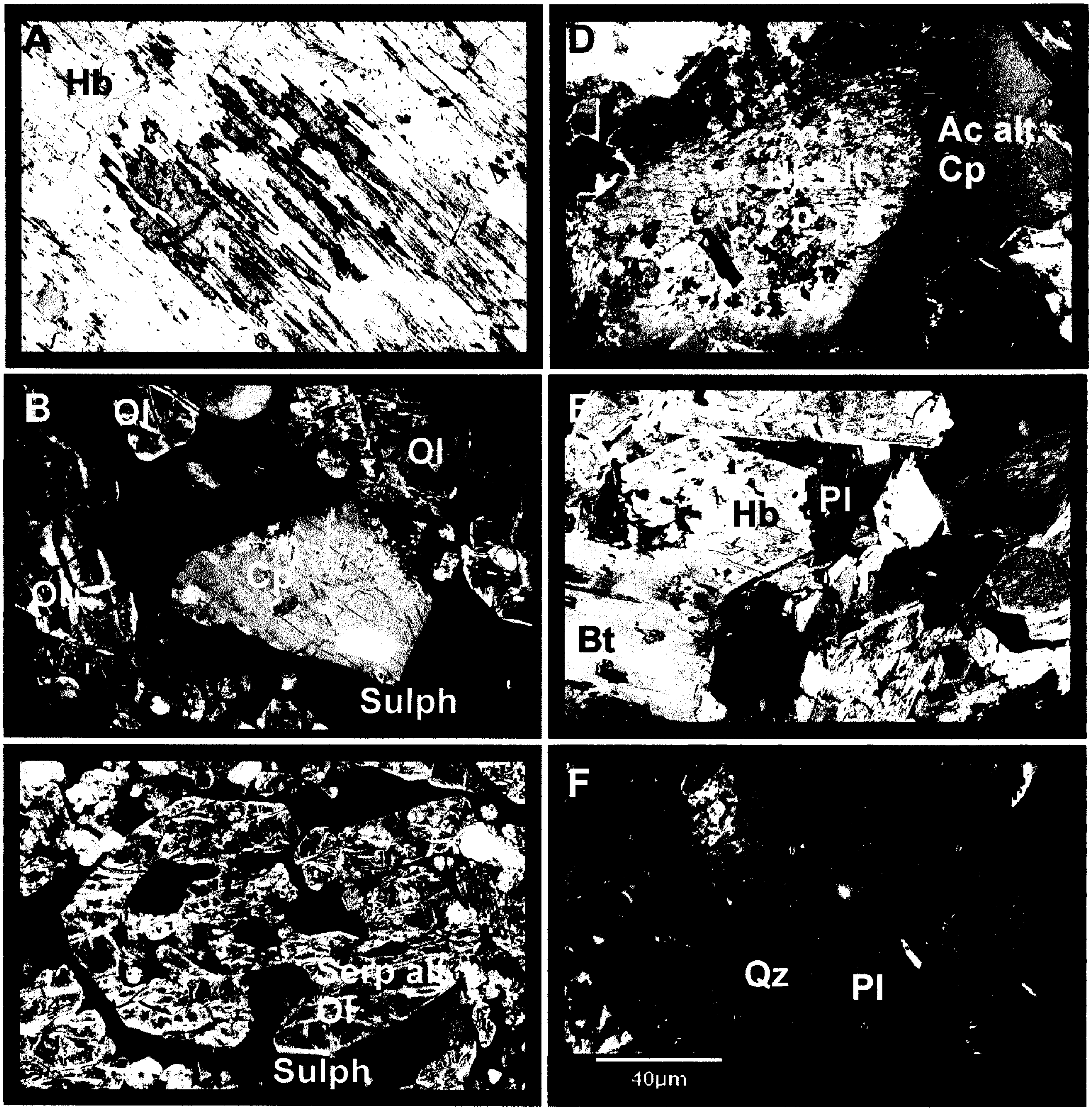

A
Hb
D
Ac alt.
Cp
B
Ol
Ol
Ol
Cp
Sulph
E
Hb
Pl
Bt
Serp alt.
Ol
Sulph
F
Qz
Pl
40μm

Figure 4

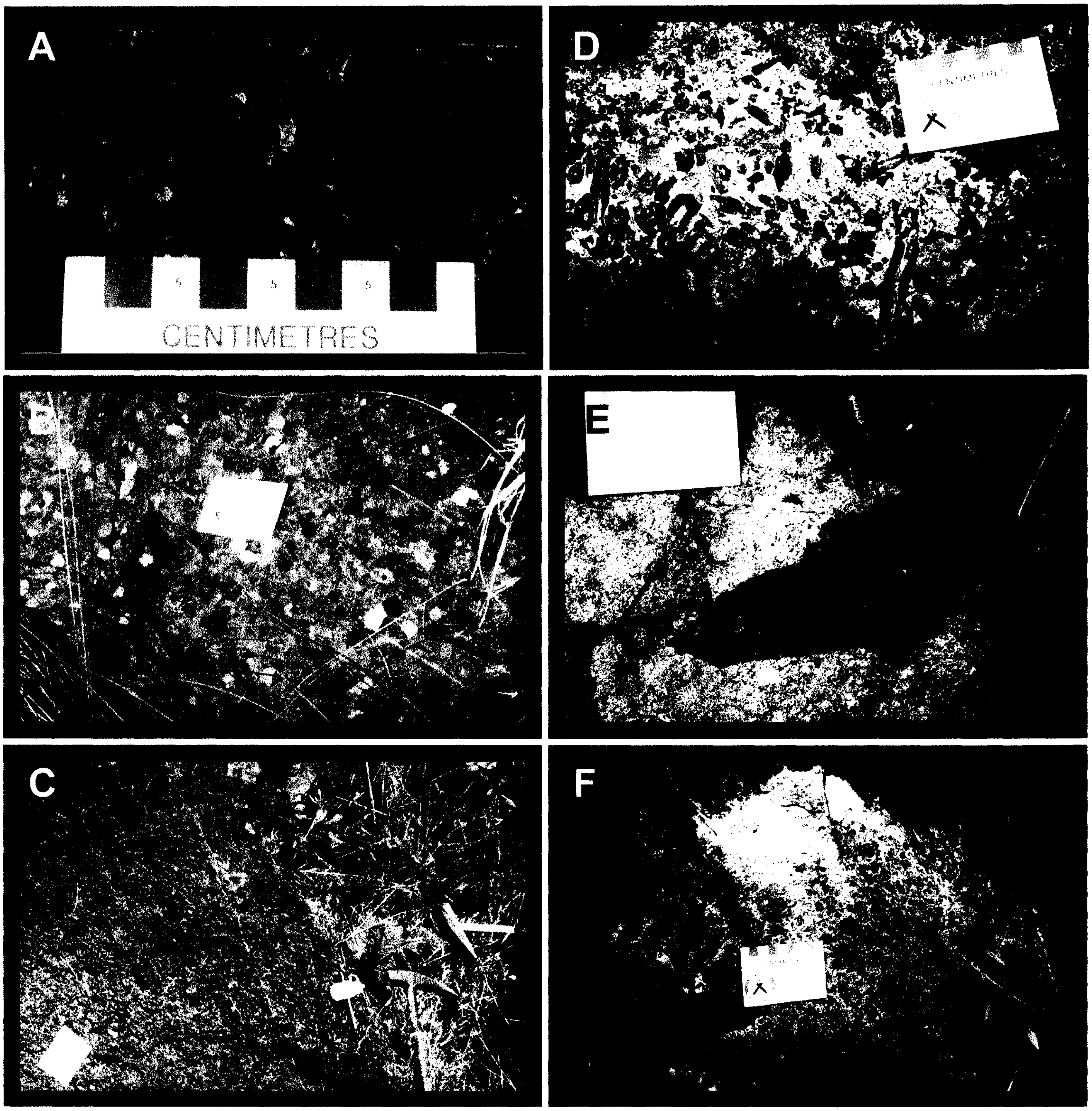
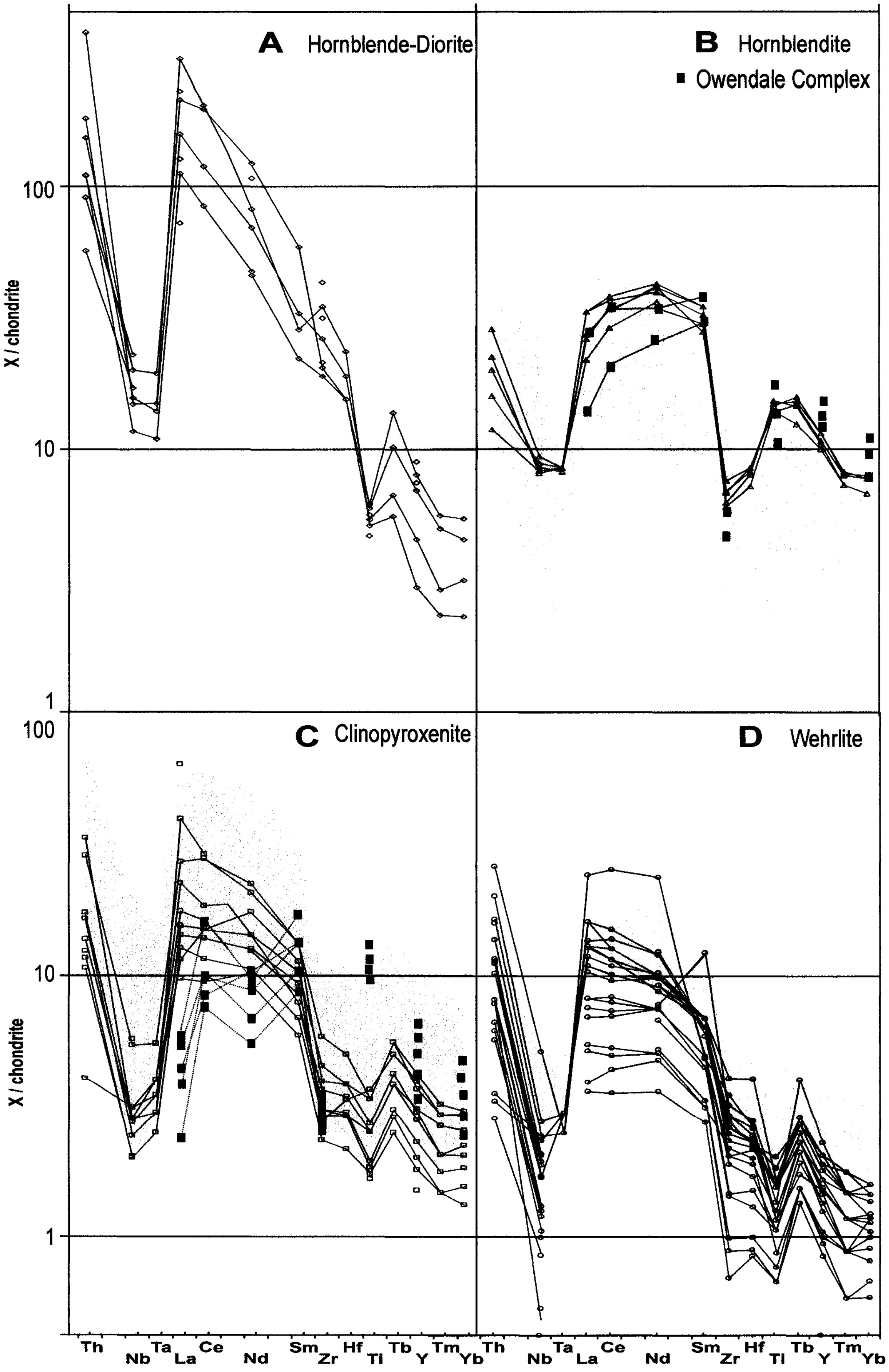


Figure 5


A Hornblende-Diorite
B Hornblendite
■ Owendale Complex
C Clinopyroxenite
D Wehrlite
X / chondrite
X / chondrite
100
10
1
100
10
1
Th
Nb
Ta
La
Ce
Nd
Sm
Zr
Hf
Ti
Tb
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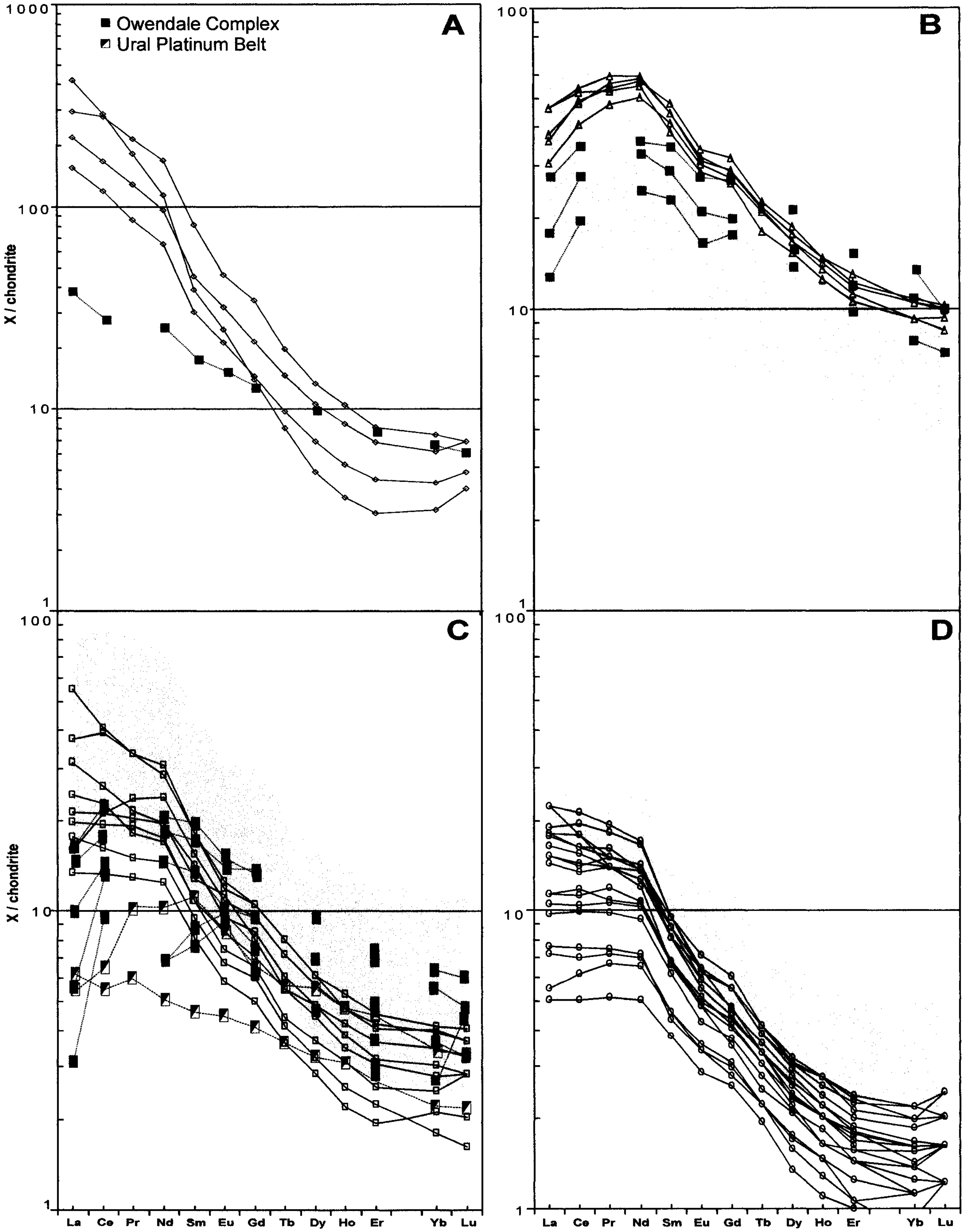
Yb


■ Owendale Complex
◪ Ural Platinum Belt
A
B
C
D
X / chondrite
X / chondrite
1000
100
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Yb
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Figure 7.

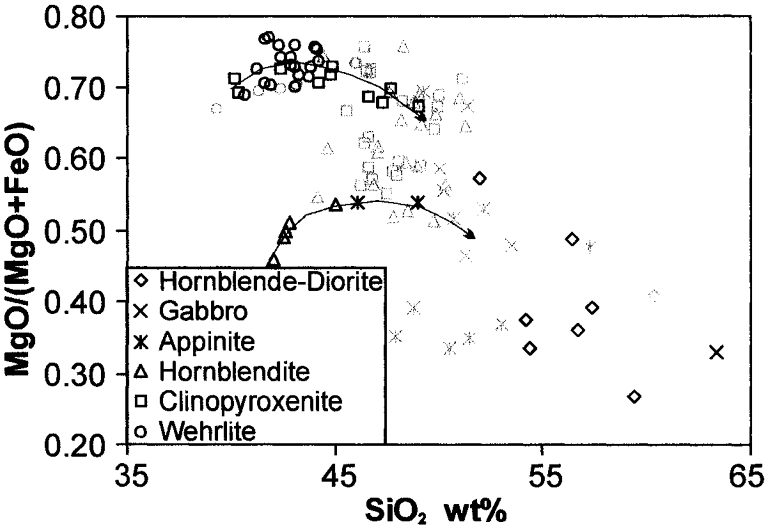
0.80
0.70
0.60
0.50
0.40
0.30
0.20
MgO/(MgO+FeO)
35
45
55
65
SiO₂ wt%
◇ Hornblende-Diorite
× Gabbro
⋇ Appinite
△ Hornblendite
□ Clinopyroxenite
○ Wehrlite

Figure 8.

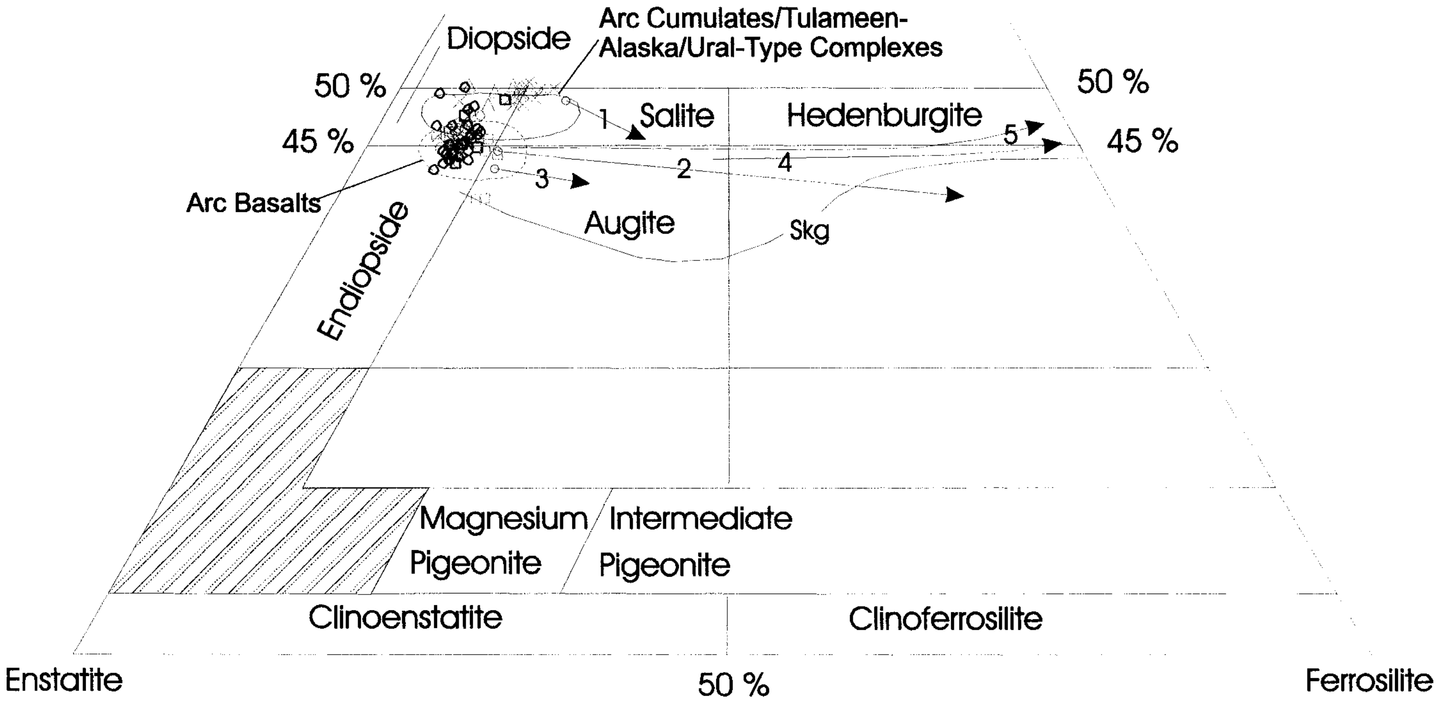
Diopside
Arc Cumulates/Tulameen-
Alaska/Ural-Type Complexes
50 %
45 %
Arc Basalts
Endiopside
1
Salite
Hedenburgite
5
50 %
45 %
2
3
4
Augite
Skg
Magnesium
Pigeonite
Intermediate
Pigeonite
Clinoenstatite
Clinoferrosilite
Enstatite
50 %
Ferrosilite

Figure 9.

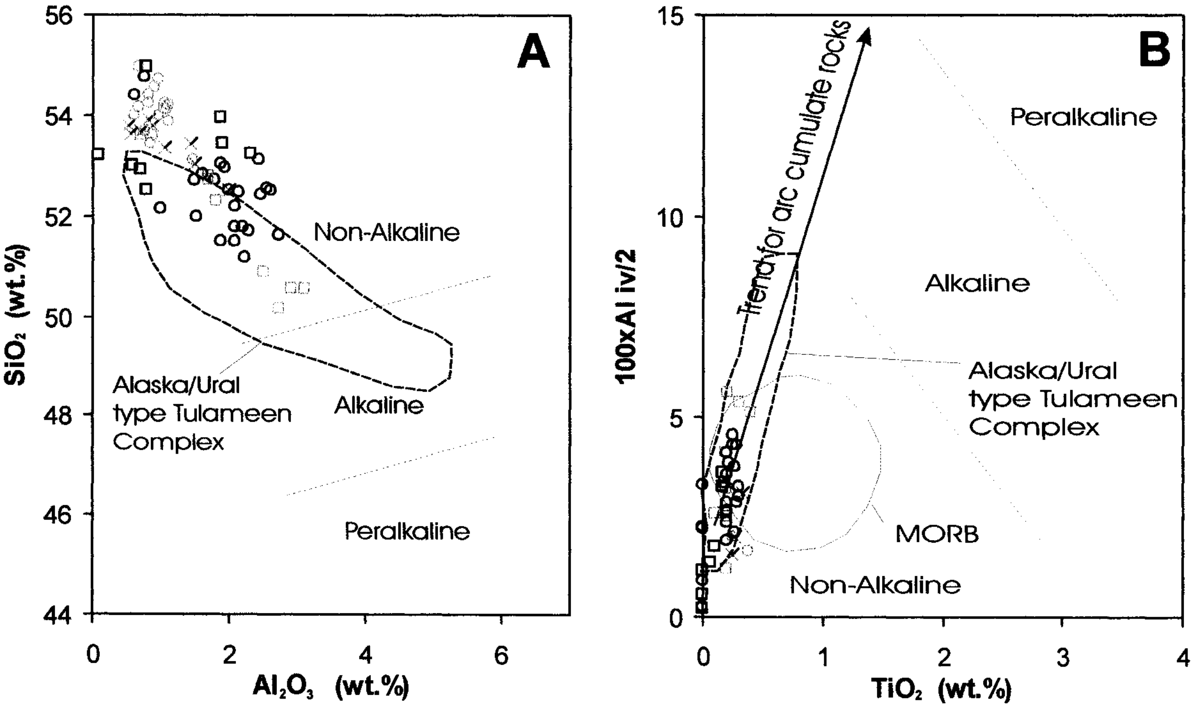
A
56
54
52
50
48
46
44
SiO₂ (wt.%)
0
2
4
6
Al₂O₃ (wt.%)
Non-Alkaline
Alkaline
Peralkaline
Alaska/Ural type Tulameen Complex
B
15
10
5
0
100xAl iv/2
0
1
2
3
4
TiO₂ (wt.%)
Trend for arc cumulate rocks
Peralkaline
Alkaline
Alaska/Ural type Tulameen Complex
MORB
Non-Alkaline

Figure 10.

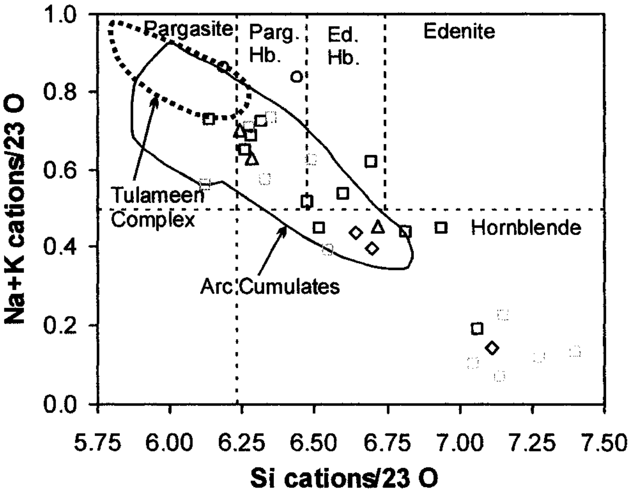
Pargasite
Parg. Hb.
Ed. Hb.
Edenite
Hornblende
Tulameen Complex
Arc Cumulates
Na+K cations/23 O
Si cations/23 O
1.0
0.8
0.6
0.4
0.2
0.0
5.75
6.00
6.25
6.50
6.75
7.00
7.25
7.50

Figure 11.

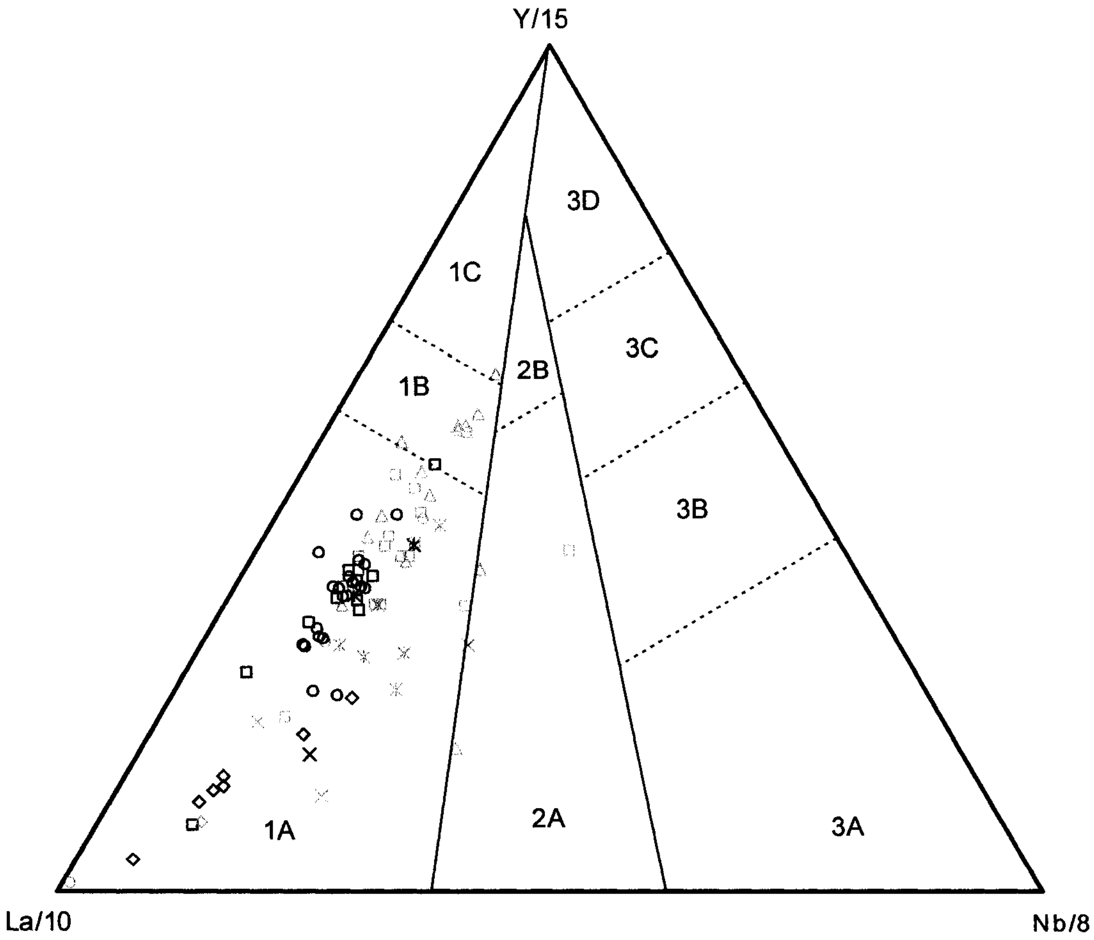

Figure 12.

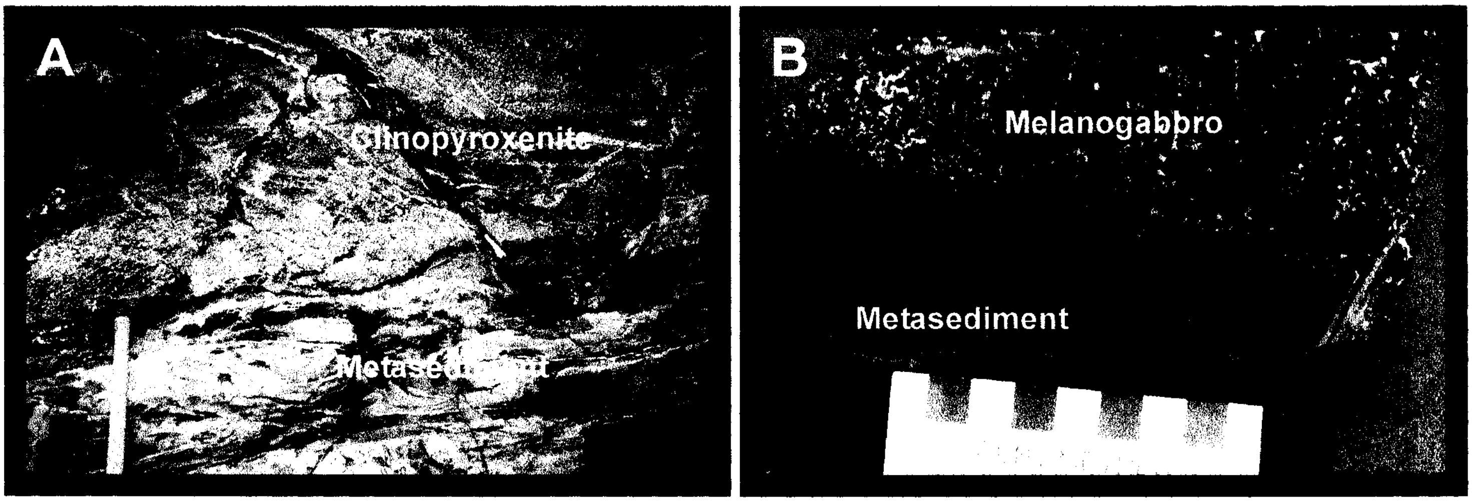
A
Clinopyroxenite
Metasediment
B
Melanogabbro
Metasediment

Figure 13.

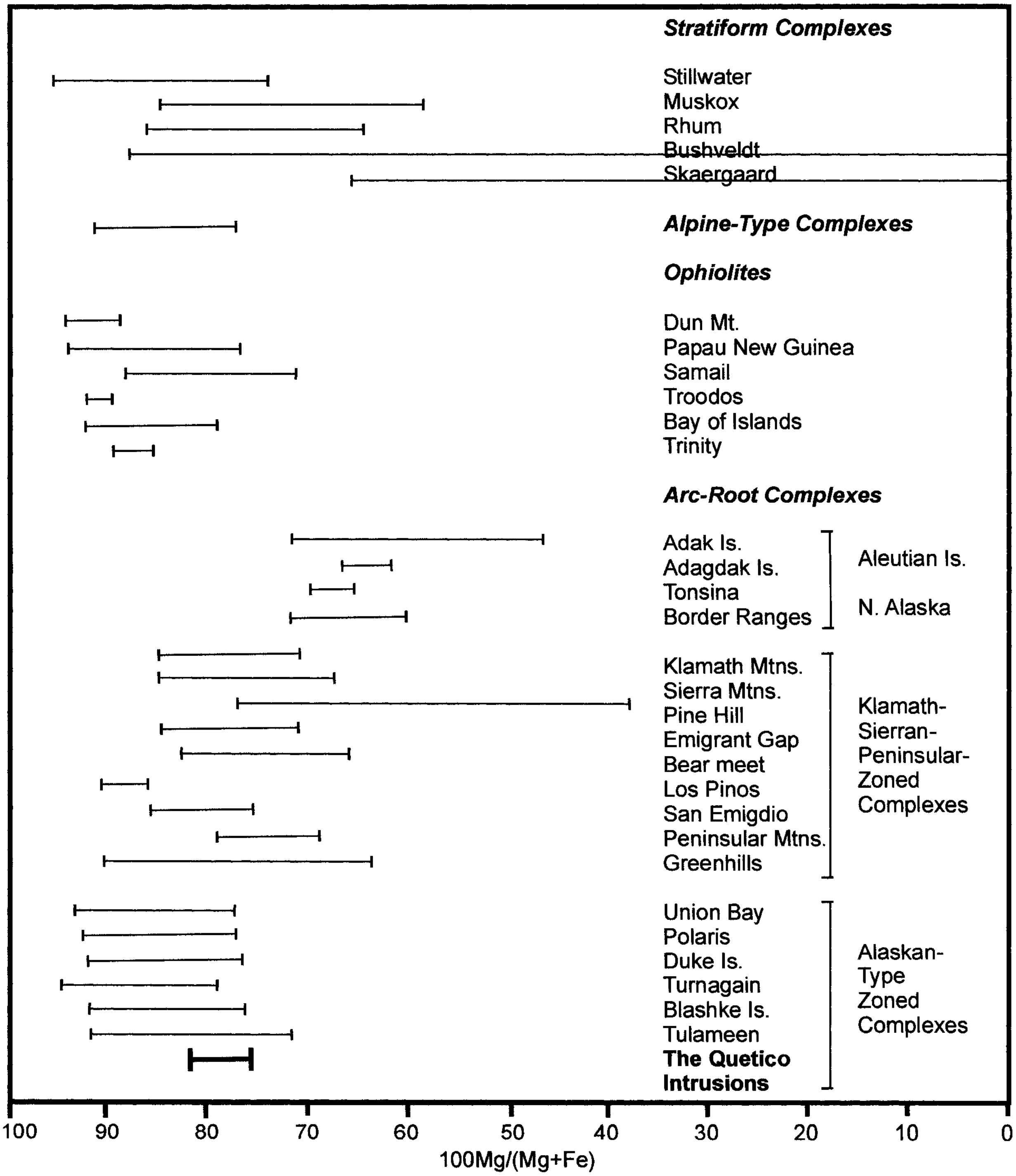
Stratiform Complexes
Stillwater
Muskox
Rhum
Bushveldt
Skaergaard
Alpine-Type Complexes
Ophiolites
Dun Mt.
Papau New Guinea
Samail
Troodos
Bay of Islands
Trinity
Arc-Root Complexes
Adak Is.
Adagdak Is.
Tonsina
Border Ranges
Aleutian Is.
N. Alaska
Klamath Mtns.
Sierra Mtns.
Pine Hill
Emigrant Gap
Bear meet
Los Pinos
San Emigdio
Peninsular Mtns.
Greenhills
Klamath-Sierran-Peninsular-Zoned Complexes
Union Bay
Polaris
Duke Is.
Turnagain
Blashke Is.
Tulameen
The Quetico Intrusions
Alaskan-Type Zoned Complexes
100
90
80
70
60
50
40
30
20
10
0
100Mg/(Mg+Fe)

Figure 14.

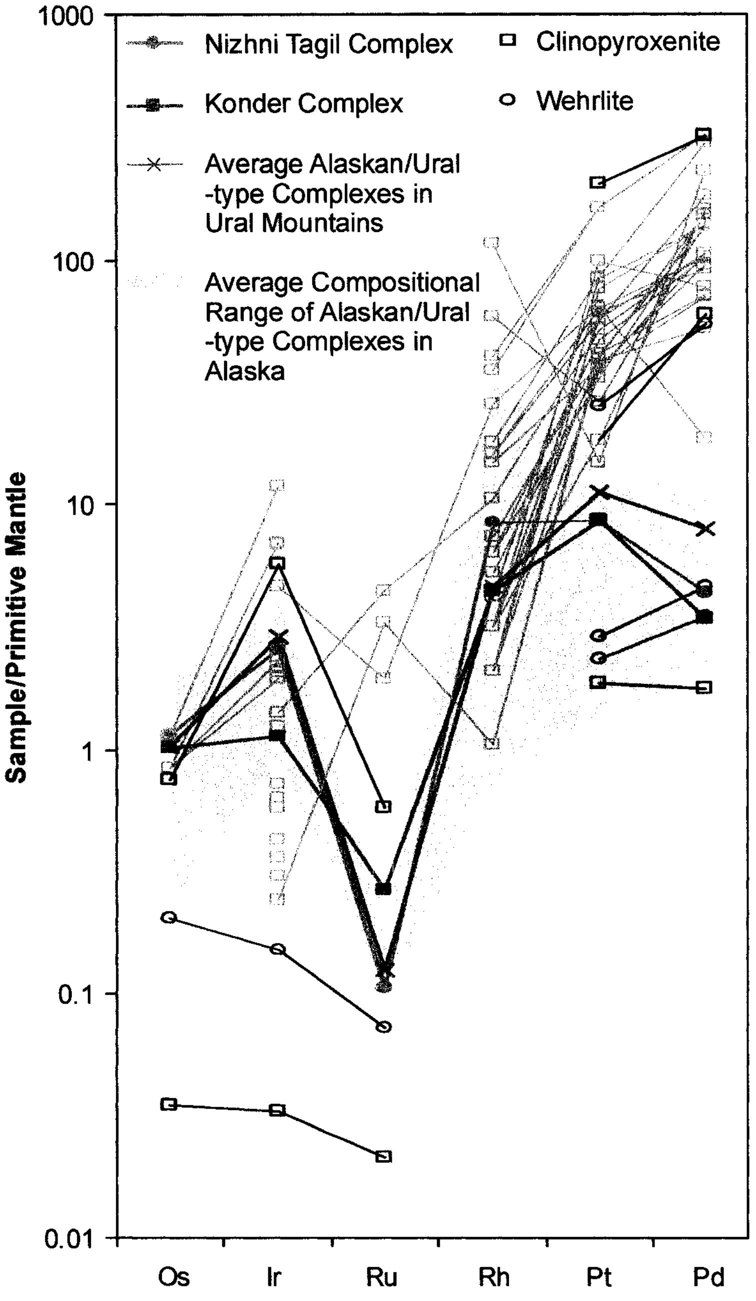
Nizhni Tagil Complex
Konder Complex
Average Alaskan/Ural -type Complexes in Ural Mountains
Average Compositional Range of Alaskan/Ural -type Complexes in Alaska
Clinopyroxenite
Wehrlite
Sample/Primitive Mantle
1000
100
10
1
0.1
0.01
Os
Ir
Ru
Rh
Pt
Pd

Figure 15.

Summary and Conclusions

A series of late Archean mafic-ultramafic intrusions have been recognized in the southern Wabigoon and northern Quetico subprovinces of the western Superior Province. They are commonly accompanied by PGE mineralization, and one of which located at Lac des Iles, in the southern Wabigoon Subprovince hosts Canada's only Pd mine. The distribution of these mafic intrusions appear to show a broad array across the subprovince boundary, however a detailed examination indicates that the mafic-ultramafic intrusions in the southern Wabigoon Subprovince are distinctly different from those in the Quetico Subprovince. The Legris Lake Complex of the Wabigoon Subprovince and the Samuels Lake Intrusion in the centre of the Quetico Subprovince were selected for detailed study.

The Legris Lake Complex

The Legris Lake Complex is a northeast trending 7.3 by 3.5 kilometre mafic-ultramafic intrusive complex located in the southern Wabigoon Subprovince. It is part of a circular series of mafic-ultramafic complexes, the most notable of which is the Lac des Iles Complex, which is host to Canada's only Pd mine. The surficial 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 be a cap rock overlying the less evolved rocks of the Complex. The Northwestern Border area, which is host to the bulk of the Cu-Ni-PGE mineralization, possesses very different textures and lithologies. The area underwent multiple injections of primitive magmas into clastic metasedimentary rock 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. These magmas were enriched in volatiles during crystallization through assimilation and dehydration of sedimentary xenoliths and volume reduction of the magma. The discharge of such fluids from the magmas contributed to the extensive brecciation and resulted in deuteric alteration of the already solidified rocks.

The most abundant style of PGE mineralization is associated with disseminated magmatic sulphides (generally less than 5 vol.%) and occurs in leucogabbro overlying basal ultramafic and mafic units within sill-shaped intrusive bodies. The mineralization is Cu- and Pd-rich with Pt/Pd ratio of ~0.2 and Cu/Ni ratio of ~3, and bulk rock samples show a positive correlation between PGEs and base metals. The mineralization is interpreted to be the result of sulphur saturation in the parental magmas due to volume reduction of 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 likely of hydrothermal origin.

The geology of the Legris Lake Complex displays many similarities to the Lac des Iles and the River Valley mafic-ultramafic complexes. However, the occurrence of mineralization in leucogabbro near the contact with underlying ultramafic rocks is similar to that of large layered mafic-ultramafic stratiform deposits such as the Stillwater and Munni Munni complexes of Montana USA and Australia respectively.

The Samuels Lake Intrusion

The Samuels Lake intrusion belongs to a 45 km linear array of mafic-ultramafic intrusion located near the northern margin of the Quetico belt and parallel to the Quetico-Wabigoon subprovince boundary, which are referred to as the Quetico Intrusions. The identification of the Stawson Lake, Samuels Lake and Red Horse Lake intrusion in the centre and southwestern part of the Quetico Subprovince by the authors as Quetico Intrusion has extended this array to 125 km.

The Samuels Lake intrusion located in the centre of the Quetico Subprovince is a roughly concentrically zoned, northeast-southwest trending, elliptical (500 m by 250 m) body with a wehrlite core surrounded by clinopyroxenite, which has been intruded by hornblendite and minor late diorite dykes and plugs. The intrusion also hosts two style of Cu-Ni-PGE mineralization. It intruded ca. 2688+6/-5 Ma, most likely during the early stages of D2 or late stages of D1 and before or during the early stages of M2 as indicated by metamorphic age of ca. 2668+/- 6 in metamorphic titanite. The Samuels Lake Intrusion formed by the fractionation of a single sub-alkaline magma with strong arc-like signatures.

The Quetico Intrusions show many similarities with the Phanerozoic Alaskan/Ural-type complexes. These include, relatively small size of the intrusions, linear distribution of the intrusions near major regional structures, concentric zonation of lithologies with olivine-rich cores and more gabbroic rims, arc-like geochemical signatures, sub alkaline affinities, mineralogy, notably the lack of orthopyroxene, poikilitic textures, and PGE mineralization. Although Alaskan/Ural-type Intrusions are typically associated with chromite-bearing PGE mineralization, sulphide-rich Cu-Ni-PGE mineralized examples do occur such as the Duke Island Complex and Salt Chuck Intrusion. Therefore, the Quetico Intrusions most likely represent sulphide-bearing neo-Archean examples of Phanerozoic, Alaskan/Ural-type mafic-ultramafic Intrusions.