Ni-Cu-PGE Deposits in the Pacific Nickel Complex, Southwestern BC; A Profile for Magmatic Ni-Cu-PGE Mineralization in a Transpressional Magmatic Arc

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ABSTRACT

The Giant Mascot mine remains British Columbia's only historic nickel-copper producer, yielding over 26,500 tonnes of Ni, more than 13,000 tonnes of Cu and more than 140 tonnes of Co from 4,319,976 tonnes of ore processed. Significant values of platinum group elements (PGEs) have also been reported. The economic sulphide mineralization is both massive and disseminated. It is hosted by steeply dipping pipes of varying but distinct ultramafic lithology within the Pacific Nickel Complex, proximal to pipe-like apophyses of diorite of the Spuzzum Intrusion. Previous workers noted that the mineralized pipes lie crudely parallel to a regional, northerly-dipping linear fabric.

The Pacific Nickel Complex is an assemblage of undeformed to weakly deformed ultramafic rocks that are spatially associated with gabbronorite and with the Spuzzum Intrusion. Both intrusions cut rocks of the Cascade terrane at the accreted eastern margin of Wrangellia. Pyroxenitic rocks with sulphide mineralization and microscopic and macroscopic textures identical to those at Giant Mascot occur as far north as Fir Creek, 35 km from the mine. These rocks are interpreted as a single petrologic province with a common magmatic heritage.

The pyroxenites are cumulates with a two-stage history of crystallization. In the first stage, spinel, olivine and clinopyroxene crystallized; spinel compositions overlap those of Noril'sk rift-related intrusions which host a world-class Ni-Cu-PGE deposit. The first-stage phenocrysts are overgrown by a thin rim of clear orthopyroxene and enclosed by anhedral oikocrysts of orthopyroxene, intergrown with clinopyroxene and magmatic pyrrhotite, pentlandite and chalcopyrite. The latest phase of magmatic or deuteric activity comprised replacement of orthopyroxene by hornblende.

The Pacific Nickel Complex intrudes banded paragneisses containing kyanite/sillimanite, staurolite and garnet with a metamorphic closure age of 96+6/-3 to 91.5±2 Ma. The Spuzzum suite of intermediate pyroxene and amphibole-phyric intrusive rocks that cut the Pacific Nickel Complex have a closure age between 96 and 93 Ma, indicating that the two intrusions are penecontemporaneous with the Barrovian stage of metamorphism.

Inclusions of paragneiss within Pacific Nickel Complex pyroxenite are partially or completely assimilated, contaminating the pyroxenite with felsic material. Sulphide mineralization increases next to metamorphic xenoliths. A continuous range of textures and modal compositions exists between the Pacific Nickel pyroxenites, "feldspathic pyroxenites" in the Cogburn Creek area and pyroxene or uralitic hornblende-phyric "gabbronorite" and "diorite". Although the chemical compositions of the intrusive rocks in the Pacific Nickel and Spuzzum intrusions overlap and define a general calc-alkaline trend, their incompatible element ratios preclude generation of the more felsic rocks by crystal fractionation of phases observed in the Pacific Nickel cumulates. The near-contemporaneity of the Pacific Nickel and Spuzzum intrusions and the textural evidence of assimilation strongly suggest that the more felsic rocks in either suite were generated by contamination of an ultramafic cumulate mush with material assimilated from the gneissic wallrocks.

We propose a model for this deposit type that is based upon the model for the Aguablanca Ni-Cu-PGE deposit in Spain. According to the model, a primary Pacific Nickel magma was generated in the mantle by decompression melting facilitated by an extensional window created by regional transpressive tectonics. This magma ponded at intermediate levels in the crust and began fractional crystallization of spinel, olivine and clinopyroxene. Both the intercumulate and supernatent fluids gained substantial amounts of sulphur from assimilated pyritic paragneiss and schist, supersaturating the system in sulphur and triggering nucleation of a sulphide liquid; this process was coeval with second-stage crystallization of orthopyroxene oikocrysts. The Spuzzum intrusive suite may represent a felsic component of this hybrid system. The transpressive stress field persisted and permitted injection of both the mineralized pipes and apophyses of felsic magma. This hypothesis allows for exploitation of linear zones of weakness in the transpressive stress field, either by mechanical (sulphide-silicate crystal mush) or high-temperature hydrothermal emplacement of sulphide mineralization.

INTRODUCTION

The Giant Mascot mine remains British Columbia's only historic Ni-Cu producer. Between the years 1958 and 1974, 4,319,976 tonnes of ore were mined. This tonnage

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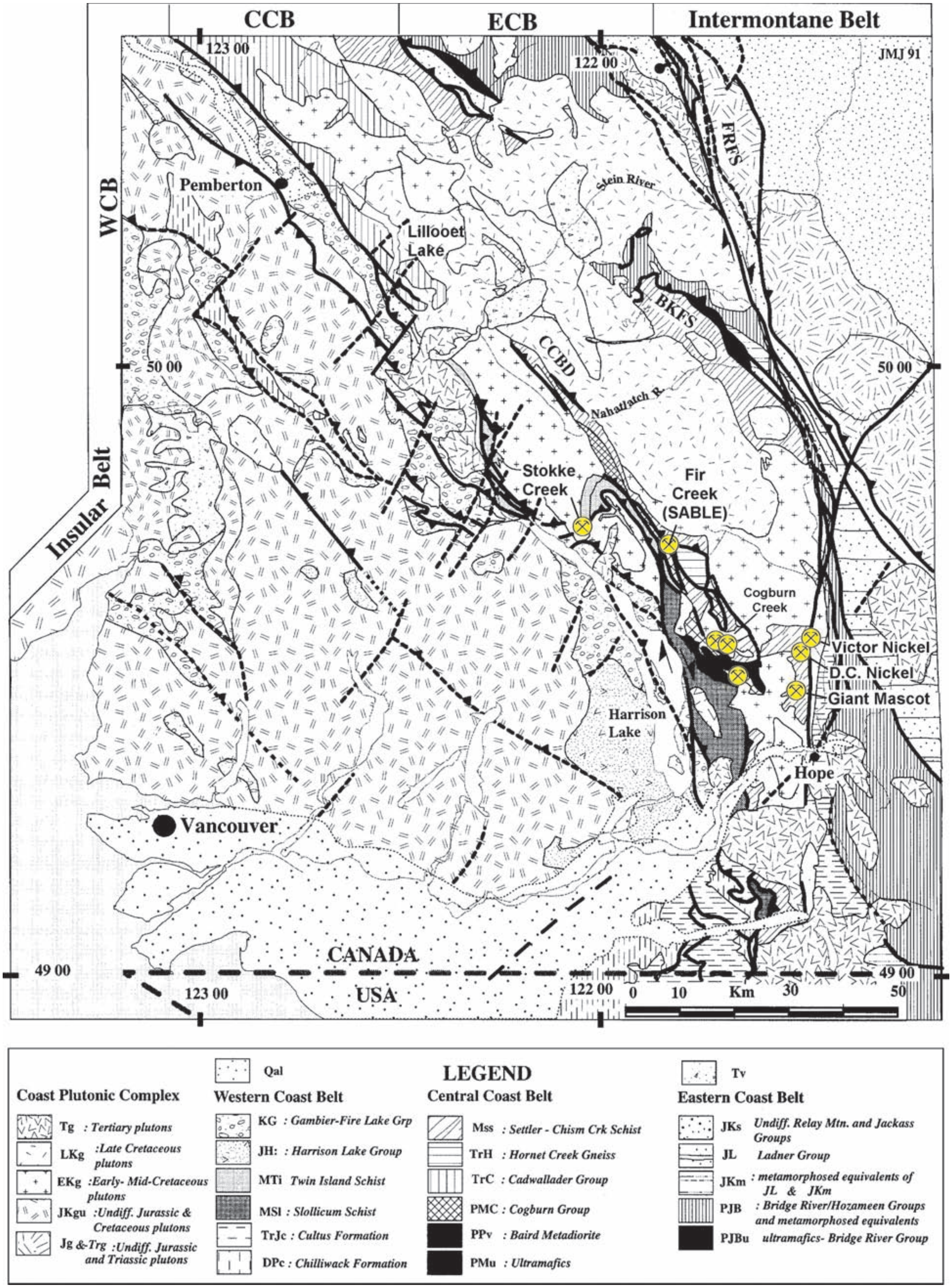

Figure 1. Regional geology of the southern Coast Belt Thrust System adapted from Journeay and Friedman (1993). Abbreviations: Central Coast Belt Detachment (CCBD), Bralorne-Kwoiek Creek Fault System (BKFS), Fraser River Fault System (FRFS). The map shows tectonic belts and the range of occurrences of Ni-Cu occurrences hosted by megacrystic orthopyroxenite (crossed hammers).

yielded: 26,573,090 kg Ni, (reported mean head grade 0.77%), 13,212,770 kg Cu (reported mean head grade 0.34%), 140,700 kg Co, 16,516 gm silver (Ag) and 1,026 gm gold (Au). Platinum values in excess of 1 gram were reported.

The Pacific Nickel Complex, an assemblage of ultramafic and related rocks exposed within the eastern Coast Belt in southwestern British Columbia, hosts the Giant Mascot Ni-Cu deposits (Figure 1). Three main deposits, Choate, Pride of Emory and Star of Emory, were initially staked in 1923 (Cairnes, 1924). The purpose of this paper is to identify characteristics of the lithologies and mineral deposits associated with the Pacific Nickel Complex, and to describe a mineral deposit profile developed for Giant Mascot and other deposits of this general character.

PREVIOUS WORK

Regional studies of the southern Coast Belt, augmented by thesis studies, have been ongoing since 1912. A detailed review of these regional studies is beyond the scope of this paper, which focuses more on the generation and emplacement of the Pacific Nickel Complex and its associated mineralization. The reader is referred to Ash (2002) and Pinsent (2002) for reviews of studies in this area. We adopt the latest structural synthesis of Monger and Journeay (1994) as a framework within which to discuss the origin and setting of the Pacific Nickel Complex.

The Spuzzum Intrusion (Richards and White, 1970; Richards, 1971; Richards and McTaggart, 1976; Vining, 1977) is of relevance to the present study because of its close spatial and temporal association with the Pacific Nickel Complex. The Spuzzum is described as a polyphase intrusion of intermediate composition, with a dioritic core and a tonalitic margin where it intrudes metamorphic country rocks. Its relationship to the Pacific Nickel Complex and its probable significance to the Ni-Cu-PGE metallogeny has been the subject of recent discussion (Ash, 2002; Pinsent, 2002).

The Giant Mascot mineral deposits and host ultramafic rocks have been studied intermittently since their discovery, beginning with the work of Cairnes (1924), Cockfield and Walker (1933) and Horwood (1936). The comprehensive study made by Aho (1954, 1956) remains the latest detailed mapping of the Giant Mascot Mine area. Thesis studies carried out while the mine was in production include those by Muir (1971), King (1972) and McLeod (1975). Government (and other) studies include those by Clarke (1969), Christopher (1974, 1975) and Christopher and Robinson (1975).

Elevated prices of platinum group elements led to the recent exploration interest in nickel-copper occurrences east of Harrison Lake. Consequent studies by Geological Survey Branch personnel include those by Lett and Jackaman (2002), Ash (2002) Pinsent (2002) and Nixon (2003). Our study of an ultramafic rock assemblage 35 km northwest of the Giant Mascot Mine in 2001 (Metcalfe and McClaren, 2002) and other similar occurrences (Metcalfe and McClaren, unpublished data) prompted this paper. The present work is based on the results of exploration in the area and upon publicly available data on the Giant Mascot deposits.

TECTONIC SETTING

The Pacific Nickel Complex lies within the Cascade terrane, which is located on the eastern flank of Wrangellia (Figure 1). The amalgamation of Wrangellia to North America about 100 million years ago contributed to the complex structural development of this terrane. The tectonic evolution of the region during and after accretion (100-40 Ma) is characterized by a series of structural events that culminated in intense Late Cretaceous to early Tertiary (96-47 Ma) intra-plate contraction and dextral transpression, accompanied by metamorphism and granitic intrusion.

The east Harrison Lake area lies within the imbricate zone of the Coast Belt Thrust System. This region is characterized by low-angle thrust faults that envelop high-grade schists and gneisses of the Breakenridge complex (Monger and Journeay, 1994) and Slollicum Schist (Monger, 1986) and by high angle reverse faults that cut these allochthonous sheets (*e.g.* Big Silver Creek and Breakenridge faults). Relative timing relationships between fold and fault structures found associated with the Coast Belt Thrust System indicate a two-stage history of late Cretaceous shortening:

1. Early stage thin-skinned thrusting above a basal décollement accompanied by Alpine-style folding. The age of this event is bracketed by synorogenic plutonic suites with U/Pb zircon ages of 97±1 Ma and 96 +6/-3 Ma (Monger and Journeay, 1994).
2. High angle reverse faulting and out-of-sequence thick-skinned thrusting that caused southwestward telescoping of the metamorphic hinterland over flanking supracrustal arc sequences of the western Coast Mountains. The age of this event is bracketed by late and post kinematic plutonic suites (with U/Pb zircon ages of 96 +6/-3 Ma and 94 +6/-5 Ma (Monger and Journeay, 1994).

Faults within the Harrison Lake Shear Zone include a network of ductile mylonite zones along the east shore of Harrison Lake. These structures cut thrust-related fabrics in metavolcanic rocks as young as 100 Ma. A dextral strike-slip fault that may be part of the Harrison Lake system is the Big Silver Creek fault. Synkinematic muscovite from the Big Silver Creek fault yielded a Rb-Sr date of 93.5±11.4 Ma (Parrish and Monger, 1992). This implies that strike slip faulting may have been at least partly coeval with thrust imbrication.

METAMORPHISM

Two distinct metamorphic events have been identified in the Cascade terrane. The earliest event is bracketed between 96+6/-3 Ma (Journeay and Friedman, 1993) and 91.5±2 Ma (Friedman *et al*.,1992) by syn- and post-kinematic intrusions.

This early metamorphism is linked directly to the imbrication of thin and thick-skinned thrust nappes. It is characterized by a Barrovian sequence of mineral assemblages that range in grade from lower greenschist facies to middle and upper amphibolite facies. These early metamorphic assemblages are best developed in the imbricate and hinterland zones of the Coast Belt Thrust System, and in isolated pendants of gneissic rock within late and post–kinematic intrusions.

The latest metamorphic event is bracketed by crystallization ages of the Mount Mason and Scuzzy-Mount Rohr plutonic suites, which yielded U-Pb dates of 91.5±2 Ma (Friedman *et al*.,1992) and 86 to 84 Ma, respectively (Friedman and Armstrong, 1990; Parrish and Monger, 1992). This metamorphism is post-kinematic with respect to structures and associated fabrics of the Coast Belt Thrust System, and spatially associated with Late Cretaceous intrusions of the Scuzzy-Mount Rohr intrusive suite. Mineral assemblages that characterize this event include late stage overgrowths and porphyroblastic phases of andalusite, sillimanite, garnet and hornblende.

FIELD RELATIONS AND TIMING OF THE PACIFIC NICKEL COMPLEX AND SPUZZUM INTRUSION

K-AR DATA FROM THE VICINITY OF THE GIANT MASCOT MINE

The relative and absolute ages of rock units proximal to the Giant Mascot mineralization have been in dispute since its discovery. Cairnes (1924) described the immediate area of the showings and inferred that the ultramafic rocks intruded the Spuzzum Diorite. Cockfield and Walker (1933) noted that the converse was more probable. This interpretation was later supported by observations made by Horwood (1936). Later, Aho (1954, 1956), in his comprehensive account of the deposits, again concluded that the ultramafic rocks intrude the Spuzzum Intrusion. McLeod (1975) noted that the problem was unresolved. Most recently, Ash (2002) stated from field observations that the Spuzzum Intrusion cuts the ultramafic rocks and, in places, forms intrusive “pipes” subparallel to the ore-bearing peridotite pipes.

McLeod (1975) and McLeod *et al.* (1976) measured the age of the Pacific Nickel Complex using the K-Ar method on hornblende and biotite from eleven samples. McLeod’s data are given in Table 1, with the ages recalculated using the modified decay constant of Steiger and Jäger (1977). A range of ages from 122 Ma to 96.4 Ma was ob-

TABLE 1
K-AR DATA FOR THE PACIFIC NICKEL COMPLEX AND SPUZZUM INTRUSION NEAR THE GIANT MASCOT DEPOSITS (FROM MCLEOD, 1975 AND MCLEOD *ET AL*., 1976)

Sample	Location	Longitude	Lithology	Mineral	K wt %	Radiogenic Argon 40Ar* nl/g	%	Age (Ma) (Harakal)	Error (Ma)
Spuzzum	#1, 8 k m W of Hope	121 31 48	Hypersthene hornblende biotite diorite	hornblende	0.654	2.477	86.5	94.9	7
Spuzzum	#1, 8 k m W of Hope	121 31 48	Hypersthene hornblende biotite diorite	biotite	3.70	14.876	83.9	101.0	3
OO4	6.5 mi WSW of Hope	121 34 48	Foliated quartz diorite	biotite	5.73	24.040	82.0	105.0	3
141A	3050 X/C	121 31 20	Feldspathic hornblendite	hornblende	0.258	1.093	64.0	106.0	4
157A-1	3050 X/C	121 31 20	Mineralized hornblendite	hornblende	0.261	1.154	61.4	112.0	4
120A	3050 X/C	121 31 20	Hornblende pyroxenite	hornblende - pyroxene	0.130	0.6357	43.3	121.6	4
#7	Road to Giant Mascot	121 29 35	Tonalite	biotite	5.86	18.808	83.6	80.7	2.5
#7	Road to Giant Mascot	121 29 35	Tonalite	hornblende	0.464	1.600	58.4	86.6	2.8
#8	Several miles S of Giant Mascot 1.8 miles W of Haig, N side of Fraser R.	121 29 30	Hornblende diorite	hornblende	0.536	1.945	58.4	91.0	2.8
#4	Intersection of Lower Haulage and Texas Creek	121 30 05	Hornblende pyroxene diorite (Spuzzum)	hornblende	0.334	1.214	42.7	91.2	3
79A-2	3050 X/C	121 31 20	Hornblendite?	hornblende	0.183	0.7043	63.8	96.4	4

tained from hornblende and biotite from hornblendites and hornblende pyroxenites of the Pacific Nickel Complex collected at the Giant Mascot Mine. A similar range (105 Ma to 80.7 Ma) was obtained for Spuzzum pyroxene diorites adjacent to the pyroxenites.

All analyses were carried out at the University of British Columbia. The ages have been recalculated using the modified decay constants of Steiger and Jäger (1977) and an isotopic abundance (^{40}K/K) of 0.01167 (atomic %). Errors are two standard deviations.

Two factors complicate the interpretation of these K-Ar dates. The first is that argon only starts to accumulate in minerals as the rock cools down below a closure temperature after an intrusive or metamorphic event. The closure temperatures vary for different minerals; for hornblende it is 450-550^{o}C (Harrison, 1981). In a slow-cooling intrusion or deep-seated metamorphic event, the K-Ar dates may be younger than the time of the event.

The second factor is that hornblende is susceptible to retention of excess radiogenic argon (radiogenic ^{40}Ar that is incorporated into the mineral from some source other than the *in situ* decay of ^{40}K) which has the effect of producing conventional dates that are older than the age of the rock. The lower the potassium content, the more pronounced the effect. In a geochemically coherent suite, this problem can be addressed by construction of an isochron diagram of ^{40}K/^{36}Ar *versus* ^{40}Ar/^{36}Ar (Faure, 1977); the technique is used primarily in Rb-Sr, Re-Os, Lu-Hf and Sm-Nd geochronology and in Pearce element ratio analysis.

In the case of McLeod's data, the isotopic ratios were not recorded, but a similar diagram can be constructed by plotting ^{40}Ar *versus* ^{40}K, using data from Table 1. The results are shown on Figure 2. On this diagram, the conventional K-Ar age can be calculated from the slope of the line joining any point to the origin. The presence of excess argon is indicated by non-zero intercepts on the y axis.

Two analyses, a hornblende-biotite pair from tonalite lie on an isochron, a line which passes through the origin and within error of each sample. The line corresponds to an age of 80 Ma, clearly younger than the other samples. These analyses are discarded for present purposes.

The analytical data for biotite and hornblende in all McLeod's diorites lie on a crude line from the origin (Figure 2). This line does not pass through all the error envelopes and is therefore merely a pseudoisochron. Analyses from a coexisting hornblende and biotite pair for a Spuzzum diorite sample taken near Hope (Table 1, Figure 2) permit an isochron to be constructed. The range of possible lines (isochrons) connecting these points to the origin have slopes corresponding to ages between 99 and 96 Ma.

The three hornblende analyses from the diorites (Figure 3) lie on a regression line corresponding to an age of 97 Ma but which intercepts the y axis at a negative value for ^{40}Ar. Possible lines through the origin and the error envelopes (Figure 3) correspond to ages between 95 Ma and 91 Ma; a best-fit line has a slope corresponding to 93 Ma. An age approximating to this last value and to the minimum possible age from the hornblende-biotite pair (96-93 Ma) is our best estimate of the K-Ar closure age of the Spuzzum Intrusion.

Hornblende data from the Pacific Nickel hornblendites are more scattered; one of the samples (79A-2) clearly lies beyond any possible Pacific Nickel isochron (but lies within error of the diorite isochrons). It is impossible to construct an isochron which passes through the origin and within the error envelopes of the three remaining Pacific Nickel samples. A best-fit line, indicating some retention of Ar, gives an estimated K-Ar closure age of between 96 and 95 Ma for the Pacific Nickel Complex.

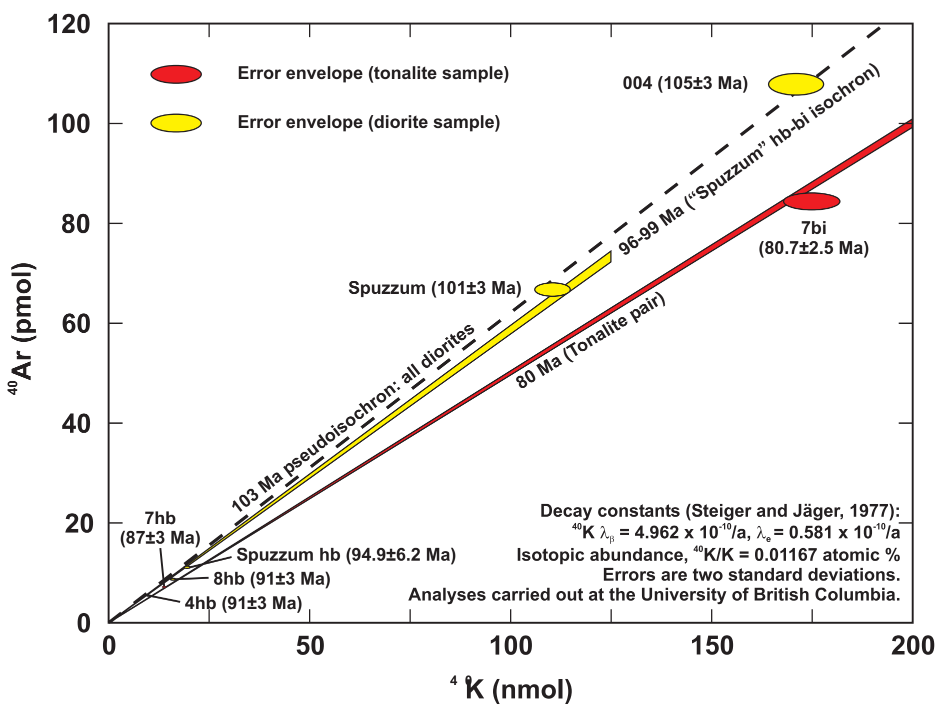

Figure 2. Graph of ^{40}K *versus* ^{40}Ar using data from McLeod (1975) and McLeod *et al*. (1976) for samples taken at or near the Giant Mascot mine. In the absence of recorded errors, the axes of error ellipses are derived using errors of 4% and 2% (2 standard deviations) for ^{40}K and ^{40}Ar, respectively. A hornblende-biotite pair from tonalite define an age of 80 Ma, clearly younger than the other samples. A second hornblende-biotite pair (from diorite) gives a range of possible isochrons corresponding to ages between 96 and 99 Ma (*cf*. Figure 3).

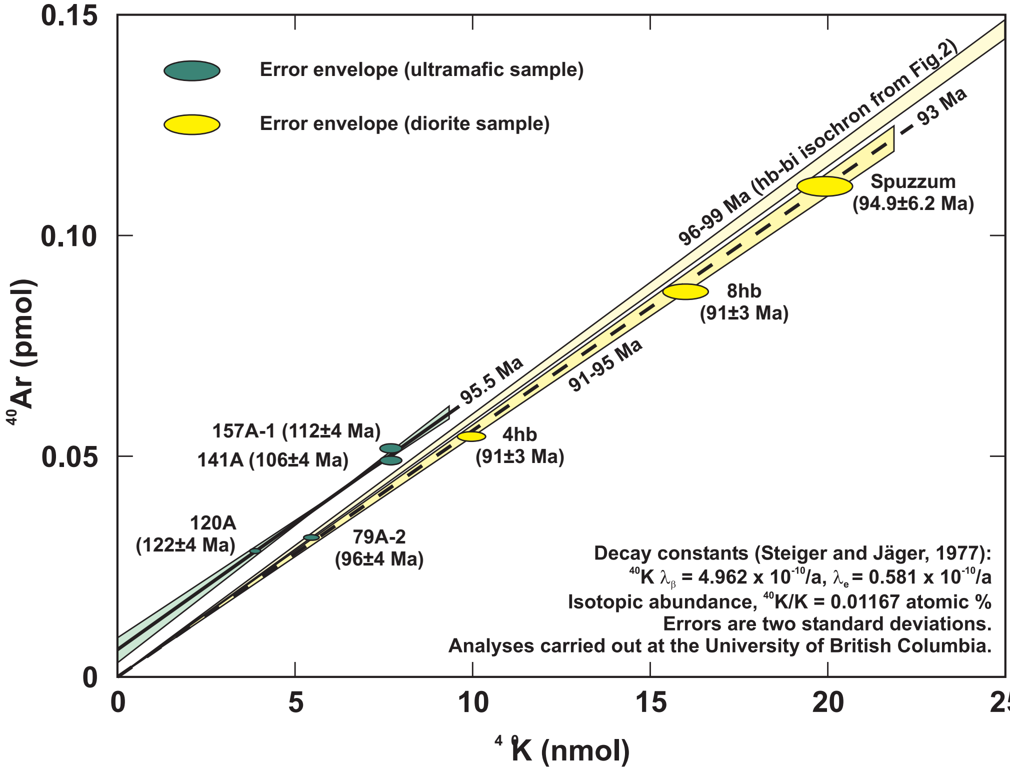

Figure 3. Graph of ^{40}K *versus* ^{40}Ar for hornblende; data and constants as for Figure 2. Hornblende data for the three diorites permit isochrons corresponding to ages between 95 and 91 Ma; the best estimate from these data is 93 Ma (cf. Figure 2). Hornblende data for the ultramafic rocks do not permit construction of an isochron, although one hornblendite sample lies within error of the isochron for the Spuzzum diorites. The remaining samples define a line indicative of argon retention. The best estimate of the age of the ultramafic rocks is 95-96 Ma. These ages are in reasonably good agreement with more recent work using U-Pb and Ar-Ar isotopic methods (Ash, Pinsent, unpubl. data, 2003).

Figures 2 and 3 permit the following comments. Although the relative ages of the two assemblages cannot be resolved within error, it is certain that the same thermal event affected the K-Ar data from not only the three ultramafic samples but also the five Spuzzum hornblende samples and that the thermal event probably took place between 96 and 95 Ma. This range corresponds to the closure date of the U-Pb system given by zircon analyses from the Spuzzum and related intrusions (Journeay and Friedman, 1993). The K-Ar data from the ultramafic rocks indicate a similar age for the Pacific Nickel Complex.

FIELD RELATIONS AT SABLE

Field data collected at Fir Creek, 35 km northwest of the Giant Mascot deposits (Metcalfe and McClaren, 2002) define the relationship between an ultramafic body and enclosing high-grade metamorphic rocks. The metamorphic rocks were assigned to the Settler Schist by Monger (1986, 1989, 1991). In the Fir Creek area (Journeay and Csontos, 1989) and in the Cogburn Creek area to the south (Gabites, 1985; Monger *et al.,* 1990; Journeay and Friedman, 1993), the contact of the Settler Schist with the structurally underlying Cogburn Group is a sharply defined sheared thrust.

On the SABLE mineral claim, near the confluence of Fir Creek with Big Silver Creek, a dyke-like body of pyroxenite and feldspathic pyroxenite intrudes Settler Schist country rock (Metcalfe and McClaren, 2002). The margin of the ultramafic body consists of black hornblendite with a weak to moderate foliation that is oriented parallel to that in the gneiss. The pyroxenite is coarse-grained, unfoliated and oikocrystic. The lack of a penetrative fabric and metamorphic mineral assemblage consistent with that in the wallrock clearly indicates that the mafic intrusion postdates the early Barrovian style metamorphic event. Away from the contact the pyroxenite contains abundant subangular inclusions of a hornblendite that have a planar fabric (Figure 4). The inclusions show rounding and/or plastic deformation, but only minimal resorption. Around the inclusions, the grain size of the enclosing pyroxenites decreases. They are interpreted as fragments of the first-cooled border phase of the mafic intrusion, which were stoped into the magma or crystal mush.

Field observations also permit speculation on the relationship of the pyroxenite to the intermediate intrusive rocks. Angular to subrounded xenoliths of foliated and

Figure 4. Hornblendite xenolith enclosed in coarse-grained oikocrystic pyroxenite. The xenolith is identical in texture to the fine-grained hornblendic margin of the intrusion, moderately foliated and interpreted as a stoped fragment of the intrusive margin.

Figure 5. Angular to subrounded xenolith of Settler Schist included in the pyroxenite. The grain size of the pyroxenite is shown by a reflective cleavage surface in an orthopyroxene oikocryst, upper left. The xenolith is broken and an apopysis of the pyroxenite separates the fragments. Peripheral to the xenolith are areas of very coarse-grained, feldspar-rich intrusive rock with coarse phenocrysts of pyroxene or, more probably, uralitic hornblende of a grain size nearly identical to that of the host pyroxenite.

banded Settler Schist also occur in the pyroxenite (Figure 5). These xenoliths exhibit a complete range in texture from those with clearly defined metamorphic fabrics to those preserved only as areas of felsic melt which have included pyroxene megacrysts from the enclosing pyroxenite. Such areas are pyroxene- or uralitic amphibole-megacrystic gabbronorite (Figure 6), with coarse intersertal plagioclase and sparse anhedral quartz. Locally, the equant, subhedral mafic phenocrysts transect the boundary between the gabbronorite areas and the enclosing pyroxenite. Similar areas of gabbronorite occur as reaction rims at the contacts of unmelted gneissic xenoliths (Figure 5). The textural evidence indicates that contamination of the pyroxenite cumulate mush by anatexis and assimilation of the gneiss produced these feldspar-rich areas. Textures observed in these areas strongly resemble those in phases of the Spuzzum Intrusion.

Both the pyroxenite and the areas of feldspathic pyroxenite are crosscut by thin dykes or sills of pyroxene- or hornblende-bearing, medium grained granodiorite. These in turn are cut by dykes and sills of progressively finer-grained and more leucocratic granodiorite or granophyre (Figure 7). These more leucocratic intrusions are non-porphyritic, allotriomorphic, and contain 10-15% anhedral quartz, and 85-90% anhedral untwinned feldspar. Mafic minerals are scarce to absent. The leucocratic intrusions generally have sharp contacts with the pyroxenite. In places, the volume of granophyre injected was sufficient to brecciate the enclosing pyroxenite and to heal the resultant subangular breccia with a network of anastomosing granophyric "veins" (Figure 8). The intrusive sequence ex-

Figure 6. Feldspathic pyroxenite or gabbronorite in contact with pyroxenite, surrounding and "soaking" subrounded fragments of the pyroxenite.

Figure 7. Fine-grained leucocratic dyke, containing virtually no mafic minerals, cuts both the pyroxenite and a banded hornblendite inclusion shown in Figure 4. These are the latest-formed dykes in the area and form the network or matrix of breccias with subrounded pyroxenite fragments.

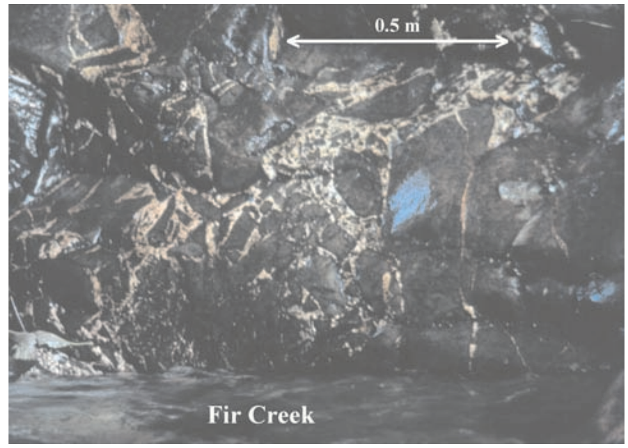

Figure 8. Pyroxenite, brecciated and veined by leucocratic intermediate magma, possibly derived from melting of feldspathic wallrock. Similar textures exist in the mafic ring complex of Ardnamurchan, northwest Scotland (Richey and Thomas, 1930).

posed on the SABLE claim is interpreted to represent partial or complete melting of the metamorphic wallrock.

Barrovian metamorphism waned and Ar retention temperature was reached between 96 +6/-3 and 91.5±2 Ma. As described above, the SABLE ultramafic body clearly post-dates the Barrovian metamorphism. The hornblende data suggest that the ages of the mafic and felsic intrusions are much closer than indicated by the individual measurements. Furthermore, field relationships described above suggest that the more felsic intrusions are either hybridized zones in the mafic intrusions, or melts derived from the gneissic country rocks. Further work is required to confirm this relationship.

PETROGRAPHY

The description of the rock units in the Pacific Nickel Complex relies heavily on previous work (Aho, 1954, 1956; McLeod, 1975; Pinsent, 2002). Additional petrographic work has been carried out by Greig (2002) and by Metcalfe and McClaren (2002) in areas to the east of Harrison Lake.

Rocks included in the Pacific Nickel Complex contain both orthopyroxene and clinopyroxene but lack titaniferous augite. The complex is therefore subalkaline. The general lack of deformation and alteration permit identification of magmatic textures. Layering is generally absent within the presently-defined boundaries of the Pacific Nickel Complex.

The Pacific Nickel Complex comprises three main lithologies: peridotites, pyroxenites and feldspathic pyroxenites. This assemblage is characterized by large oikocrysts of pyroxene or uralitic hornblende. Rocks identified with the assemblage are exposed at various locations between Giant Mascot Mine and the eastern shore of Lillooet Lake (Figure 1). Sulphide mineralization is sporadically associated with these lithologies along the entire length of the "belt".

Rocks most commonly observed in the Pacific Nickel Complex are coarse-grained pyroxenites that are black to dark green on fresh surfaces and weather to dark green or rusty brown. The pyroxenites comprise 15-30% euhedral to anhedral primary phenocrysts of olivine and pyroxene, 1-2 mm in size. These phenocrysts are enclosed by 55-70% subhedral to anhedral oikocrysts of bronze-black pyroxene and 15% subhedral to anhedral crystals of jet-black pyroxene. The later-formed pyroxenes are 7-10 mm in size (although they may be as large as 20 mm) and exhibit a mu-

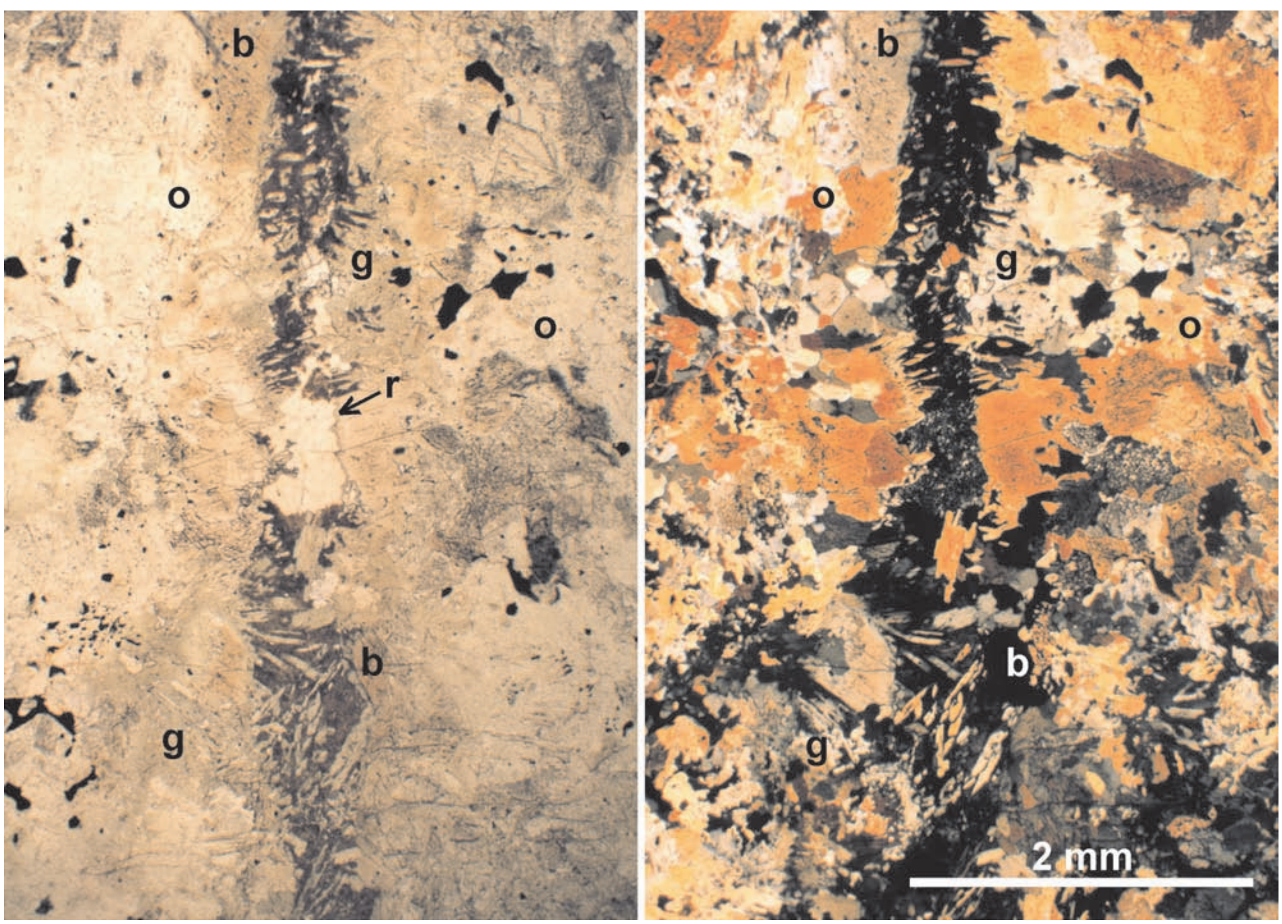

Figure 10. Orthopyroxene oikocrysts (o) altering to brown (b) and green (g) hornblende adjacent to a felsic microveinlet (f) in the pyroxenite sample shown in Figure 9. The hornblende itself shows a reaction rim (r) against the felsic material. Opaque grains are intersertal sulphide minerals, dominantly pyrrhotite. Plane polarized view on right, crossed polars on left.

tually interpenetrant and interlocking texture with 5-15% pyrrhotite, which often contains minor exsolved chalcopyrite.

A photomicrograph of pyroxenite from the SABLE mineral claim, 35 km northwest of the Giant Mascot Mine, is shown in Figure 9. In thin section, the first-formed phenocryst phases are 10-20% euhedral to subhedral clinopyroxene and 5-10% anhedral olivine, 0.5-2 mm in size. Each early phenocryst has a clear, zoned rim of orthopyroxene, 0.01-0.03 mm wide. These composite phenocrysts are enclosed as discrete euhedral to anhedral inclusions in large anhedral pyroxene oikocrysts, which are dominantly orthopyroxene. The orthopyroxene contains numerous opaque microinclusions.

The orthopyroxene oikocrysts in the sample shown in Figure 9 are adjacent to an equant oikocryst of amphibole with a texture identical to that of the orthopyroxene. In addition, felsic material intruded along fine fractures in the pyroxenite is bordered by reaction rims of amphibole which have optical orientations nearly identical to those of the orthopyroxene cores (Figure 10). This replacement is either very late magmatic or very high-temperature hydrothermal. Biotite alteration after amphibole also occurs at the Giant Mascot Mine (Aho, 1956) and in pyroxenites from east of Harrison Lake (Greig, 2002).

Feldspathic pyroxenite has been observed throughout the belt (Pinsent, 2002; Metcalfe and McClaren, 2002). In this petrologic variant (Figure 6), plagioclase is intersertal between mafic phases such as pyroxene and uralitic amphibole, in amounts that vary from traces to as much as 55% of the whole rock. These rocks are sulphide poor and commonly contain accessory quartz. Plagioclase exhibits predominately normal zoning irrespective of core composition (McLeod, 1975).

McLeod (1975) interpreted the pyroxenites at Giant Mascot as sulphide-bearing cumulates based on a mean pyroxene equilibration temperature of 990±50°C. The mineral textures of the pyroxenites record an initial history of normal olivine and clinopyroxene crystallization from a subalkaline melt. The rounded edges of the olivine grains mark a peritectic reaction between magnesian olivine and a silica-saturated liquid (Bowen, 1928). Sodic feldspar and quartz found in some olivine-bearing pyroxenites constitute a metastable assemblage. Pyroxenites with mineral textures like those seen at the Giant Mascot Mine occur on the SABLE mineral claim and at Stokke Creek near the northeast end of Harrison Lake (Figure 1). We conclude that these mafic rocks form part of a single petrologic province, with a similar magmatic heritage, that extends for at least 35 km.

The volume of peridotites in the Pacific Nickel Complex is small and they are generally constrained in pipe-like bodies such as those at the Giant Mascot Mine. They are typically medium to fine-grained, dense, dark greenish grey, lack layering and contain abundant talc, antigorite and subordinate amounts of magnetite. They weather medium grey. At Giant Mascot, olivine in the peridotites is euhedral to subhedral, as coarse as 4 mm and may be supported by nickeliferous pyrrhotite and chalcopyrite in a classic net texture (Aho, 1954, 1956; McLeod, 1975; Pinsent, 2002).

A peridotite sample taken from the SABLE mineral claim, shown in Figure 11, is an altered dunite with relic, fractured olivine surrounded by haloes of alteration products, including antigorite, talc and magnetite. The absence of a pronounced deformational fabric in the alteration products indicates that this alteration took place after regional deformation and metamorphism.

WHOLE ROCK CHEMICAL COMPOSITION AND PETROGENETIC CONSTRAINTS

Chemical analyses that exist in the public domain for rocks of the Pacific Nickel Complex are the whole rock data of Pinsent (2002), and the comprehensive studies of Muir (1971) and McLeod (1975). Richards (1971), McLeod (1975), McLeod *et al*. (1976) and Vining (1977) carried out work on the whole rock composition and age of the Spuzzum Intrusion. Recent work by Pinsent (2002) allows for geochemical classification and limited petrogenetic testing of a diverse suite of rocks within the Cogburn Creek and Giant Mascot mine areas.

The abundance of orthopyroxene indicates that the rocks are subalkaline. Silica concentrations in rocks of the Pacific Nickel Complex have similar ranges to those from Aguablanca, Spain and Las Aguilas, Argentina (Figure 12). In addition, there is an overlap in silica values between rocks identified as diorites (SiO_2 contents range from 45 to 60 wt. %) and those identified as pyroxenites (45 to 53 wt. %). Therefore it is probable that some silica has been introduced by wallrock contamination. Ultramafic rocks of the Pacific Nickel Complex lie along the F-M join on an AFM diagram (Figure 13). The feldspathic pyroxenites of Cogburn Creek and non-ultramafic rocks from both of Pinsent's field areas straddle the boundary between tholeiitic and calc-alkaline fields.

The hornblendites collected by Pinsent have whole rock chemical compositions which lie in the basaltic field of Figure 12. Those collected from Cogburn Creek are somewhat richer in silica than those from the Giant Mascot mine. Anhydrous norms vary from those containing minor amounts of nepheline to those with moderate amounts of hypersthene. Ash (2002) interprets the hornblendites at the contact between Spuzzum Intrusion and Pacific Nickel Complex as products of metasomatism. If instead these compositions are representative of the original composition of a contact phase, then the Pacific Nickel magma was a transitional basalt.

Samples from any comagmatic suite of rocks must have constant ratios of incompatible elements (*i.e.* those excluded from phenocryst phases). Some geochemically similar incompatible elements (*e.g.* K and Rb) in both pyroxenites and feldspathic pyroxenites have generally consistent ratios, but the range of Zr/Ti ratios (Figure 14) indicates that the more felsic rocks of the Pacific Nickel Complex did not evolve solely by a process of fractional crystallization.

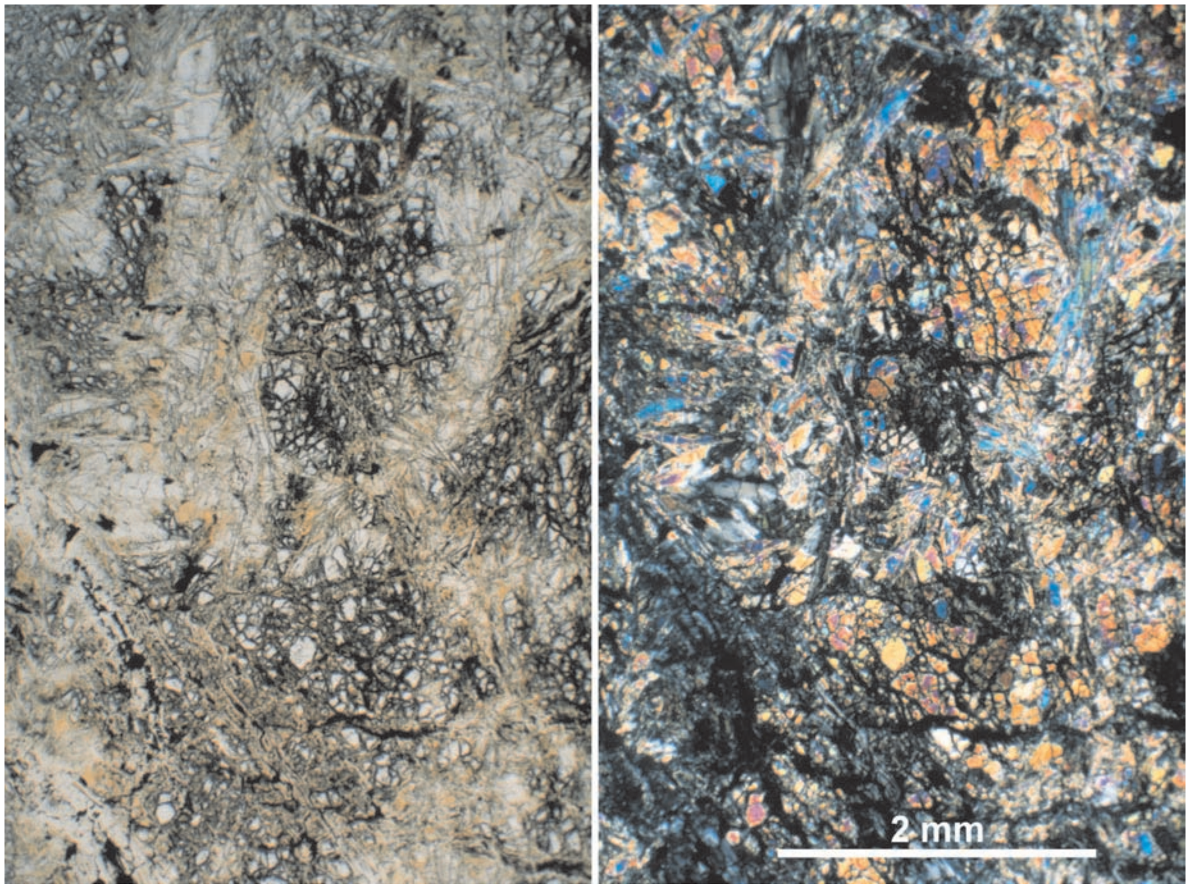

Figure 11. Photomicrograph of an altered peridotite taken from the SABLE mineral claim, 35 km northwest of Giant Mascot. Plane polarized view on right, crossed polars on left. The sample is an altered dunite with relic, fractured olivine surrounded by alteration products, antigorite, talc and magnetite. The absence of a pronounced deformational fabric in alteration products indicates that the alteration was not affected by regional deformation and metamorphism.

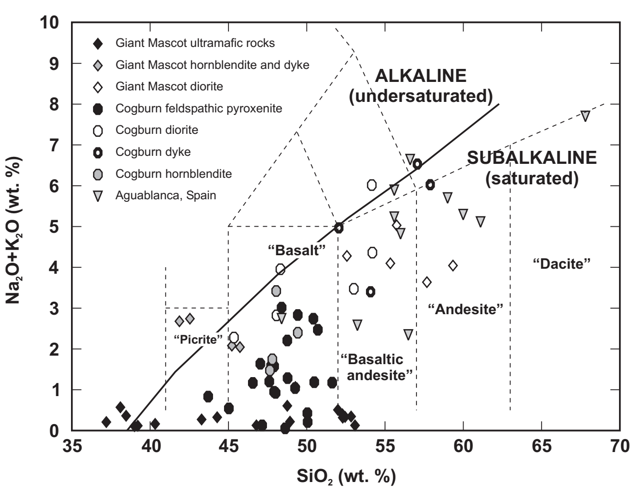

Figure 12. Silica *versus* total alkalies for rocks associated with the Pacific Nickel Complex, including rocks of the Spuzzum Intrusion. Data are from Pinsent (2002). Mafic samples are black, intermediate samples grey, and felsic samples white. Comparative data are from Aguablanca, Spain (Casquet *et al*., 2001).

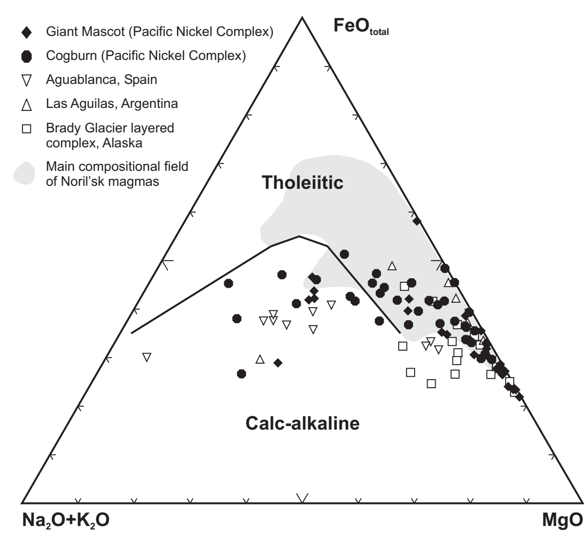

Figure 13. AFM plot (Irvine and Baragar, 1971) for rocks associated with the Pacific Nickel Complex at Giant Mascot and at Cogburn Creek, some 20 km northwest of the mine. Data sources as for Figure 12; additional data are from Las Aguilas, Argentina (Skirrow and Sims, 1999) and from the Brady Glacier layered ultramafic complex (Himmelberg and Loney, 1981). The compositional field of Noril'sk (Lightfoot *et al*., 1993; Hawkesworth *et al*., 1995) is shown in grey.

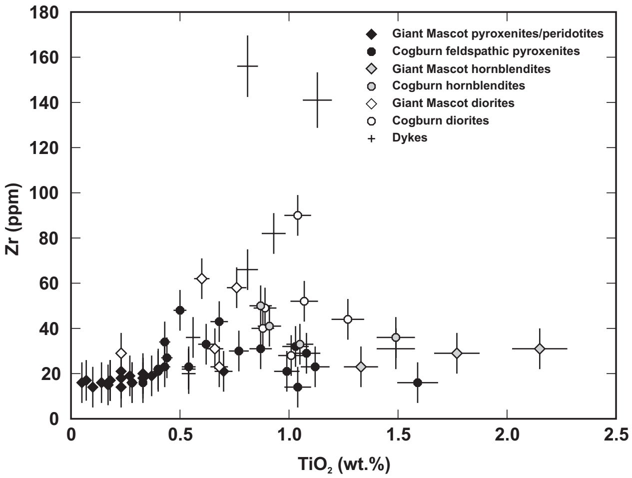

Figure 14. TiO_2 *versus* Zr for rocks associated with the Pacific Nickel Complex. The absence of comprehensive trace element data precludes rigorous testing for an element which is conserved within the suite of rocks. However, the range of incompatible element ratios shown here indicates that the compositional range in rocks of the Pacific Nickel Complex cannot have occurred through simple fractionation of the phenocryst phases observed in the cumulates.

Conserved element ratios in diorites and feldspathic pyroxenites from Pinsent's field areas are variable. However, the range of conserved element ratios measured in diorites is nearly identical to that measured in feldspathic pyroxenites. In addition, each sample of diorite collected proximal to a feldspathic pyroxenite sample in the Cogburn Creek area has an incompatible element ratio similar to that in the feldspathic pyroxenite collected at the same location. These two suites probably reflect variable amounts of contamination of pyroxenitic crystal mush and intercumulus liquid by metamorphic wallrock assimilation. This hypothesis requires further testing by isotopic and trace element methods.

DISCUSSION

The following observations were made during the present study and in previous studies:

1. At the Giant Mascot mine, ultramafic rocks of the Pacific Nickel Complex are undeformed to weakly deformed and contain xenoliths of "crystalline schist" of the Jura-Cretaceous Settler Schist. Some of these inclusions attain the size of screens or pendants (Cockfield and Walker, 1933).
2. Identical contact relationships were observed during the present study on the SABLE claim, 35 km north of the Giant Mascot Mine (Metcalfe and McClaren, 2002). Undeformed pyroxenite cuts intensely deformed and metamorphosed quartzofeldspathic schists and gneisses of the Settler Schist. Xenoliths and screens of Settler Schist are included in the pyroxenite.
3. Barrovian metamorphism in the Harrison Lake area is bracketed by the dates of 96.0+6/-3 to 91.5±2 Ma (102 to 89.5 Ma). Error limits and the K-Ar data of McLeod (1975) and McLeod *et al*. (1976) indicate that the Pacific Nickel Complex can be no younger than 95 Ma. The time of emplacement of the Pacific Nickel Complex is therefore between 102 and 95 Ma, a period of intraplate contraction and dextral transpression.
4. Pinsent (2002) confirmed cumulus textures reported by Cairnes (1924) in rocks of the Pacific Nickel Complex at the Giant Mascot Mine.
5. Pyroxenites 35 km north of Giant Mascot demonstrate a clear progression from initial formation of spinel, olivine and clinopyroxene microphenocrysts to rapid two-pyroxene oikocryst formation dominated by orthopyroxene with coincident precipitation of magmatic sulphide. Adjacent to felsic veinlets, alteration of orthopyroxene to amphibole occurred after crystallization of the pyroxenite and without disturbing its poikilitic texture. The two stages of crystallization evident in the ultramafic rocks suggest a profound change in either the physical or compositional state of the magma. This change is associated with segregation of magmatic sulphide from the silicate magma.
6. Spinel group minerals were the first to crystallize from the primary magma and their compositions are not correlated with those of the sulphides (Horwood, 1936). Nixon (2003) noted that the spinel compositions approximate those of spinels in the tholeiitic rift-related magmas of Noril'sk.
7. Textures in xenoliths of the gneissic wallrock included in the ultramafic rocks demonstrate varying degrees of anatexis, indicating that considerable assimilation of metamorphic wallrock has occurred in the Pacific Nickel Complex. The resultant feldspathic hybrid resembles phases of the Spuzzum Intrusion in mineralogy and texture.
8. The Pacific Nickel Complex is subalkaline with a compositional variation on an AFM diagram towards the calc-alkaline field occupied by rocks of the Spuzzum Intrusion (Pinsent, 2002). There is an overlap in the ranges of major element concentrations in diorites of the Spuzzum Intrusion and those in pyroxenites with intersertal feldspar (feldspathic pyroxenites of Pinsent (2002), assigned to the Pacific Nickel Complex. This compositional continuum ranges from gabbronorite to diorite.
9. Cockfield and Walker (1933) note that: "the diorites to the south (of the Giant Mascot Mine) show a striking relationship to the hornblendites (ultramafic rocks) since both groups carry the same minerals although in different proportions".
10. Ranges of incompatible element ratios in both the Spuzzum diorites and Pacific Nickel feldspathic pyroxenites are inconsistent with igneous systems evolving exclusively by fractional crystallization of the observed phenocryst phases. Chemical variation in the ultramafic cumulate rocks is consistent with the crystallization of olivine, orthopyroxene and clinopyroxene.
11. The hornblendites have the composition of transitional gabbro to subalkaline gabbronorite with norms varying from those containing minor nepheline to those with sig-

nificant orthopyroxene. Their observed chemical variation is minor and is unlikely to have occurred through fractionation of any of the phases observed in cumulates of the Pacific Nickel Complex. Minor variations in Al could be caused by spinel crystallization or by assimilation of aluminous wallrock.

The lack of coherence in ratios of the incompatible elements and the variation in major elements in rocks associated with the Pacific Nickel Complex suggests modification of the original subalkaline mafic magma by a contaminant. The most likely candidates are the surrounding Settler schists and gneisses. Contamination of an ultramafic crystal mush with wallrock rich in intermediate plagioclase feldspar would result in formation of the feldspathic pyroxenites. Progressive anatexis and further contamination with this felsic material would produce progressively more felsic hybrids and may, ultimately, have produced parts of the Spuzzum Intrusion. Detailed trace element, sulphur isotope and radiogenic isotope studies (*cf*. Casquet *et al.*, 2001) are required to test this hypothesis.

Casquet *et al.* (2001) and Tornos *et al.* (2001) recognized a similar geological and tectonic setting for the Aguablanca Ni-Cu-PGE deposit in Spain. Consequently, a mineral deposit profile similar to that developed for the Aguablanca deposit can be applied to the Giant Mascot Ni-Cu-PGE deposit. The Aguablanca deposit is a gabbroic pipe that was emplaced along with its calc-alkaline host, the Santa Ollala plutonic complex, during a period of transpressive tectonics. Petrological work on the Aguablanca stock and associated mineralization (Casquet *et al*., 2001; Tornos *et al*., 2001) clearly indicates that contamination of the magma by sulphide-bearing crustal material was crucial to generation of the deposit.

CONCLUSION

The age, spinel composition, and tectonic setting of the Pacific Nickel Complex indicate that its parent was a primary, mantle-derived tholeiitic magma with characteristics of a continental rift setting but which was generated and emplaced in a convergent continental margin environment. Late Cretaceous to early Tertiary deformation and metamorphism resulted from accretion of Wrangellia to the continental margin of North America (Monger and Journeay, 1994; Monger *et al.*, 1990). This period of accretion was characterized by intraplate contraction and dextral transpression. The Aguablanca deposit in Spain is also a synorogenic, orthomagmatic Ni-Cu-PGE deposit that was emplaced in a transpressional magmatic arc (Casquet *et al.*, 2001; Tornos *et al.*, 2001). A proposed profile for the generation and emplacement of the Pacific Nickel Complex and its mineralization has been adapted from the Aguablanca model.

Our interpretation is that the primary, tholeiitic Pacific Nickel magma was emplaced within the continental crust during the Late Cretaceous. The magma ponded at a depth of approximately 12 km and began crystallization of olivine and clinopyroxene, progressing in composition towards the olivine-liquid-orthopyroxene peritectic (Bowen, 1928). Known mafic-ultramafic exposures with nearly identical petrologic characteristics distributed along a 35-kilometre belt suggest the presence of a large intrusive body.

The metamorphic host rocks of the Pacific Nickel Complex contain mineral assemblages characteristic of intermediate crustal depths. Metamorphosed pyritic host rocks were within 100°C of their wet solidi at the time of intrusion. Assimilation of these aluminous rocks substantially enriched the tholeiitic magma in felsic components and silica, driving the magma composition into the calc-alkaline field and past the peritectic point in the olivine-orthopyroxene-silica system. The enrichment in H_2O derived from breakdown of hydrous metamorphic minerals promoted crystal formation, and the smelted sulphide minerals from the gneisses triggered supersaturation of sulphur in the magma and nucleation of a magmatic sulphide liquid. Segregation of this sulphide liquid resulted in concentration of nickel, copper and platinum group metals.

At Aguablanca orthopyroxene is less abundant in the mafic rocks and the wallrocks are of lower metamorphic grade and different composition (Casquet *et al*., 2001; Tornos *et al*., 2001; Pevida, pers. comm., 2003) from those of the Giant Mascot deposit. The abundance of orthopyroxene at Giant Mascot may be due to the susceptibility of host rock silicate minerals to dissolution that was dependant on host rock composition and temperature at the time of intrusion of the tholeiitic magma.

The Aguablanca deposit model invokes two stages of magma ponding, one at mid-crustal and the other at shallow crustal levels. In our view, a general profile for these magmatic deposits does not require emplacement at shallow crustal levels. Sulphur supersaturation by crustal contamination is considered to be the critical factor in the formation of an immiscible sulphide phase and consequent concentration of the nickel, copper and platinum group metals.

Mobilization of the Ni-Cu sulphide mineralization into pipe-like bodies at Giant Mascot has been ascribed to both mechanical and hydrothermal processes (Aho,1956). At Aguablanca, Tornos *et al*. (2001) stress a dominantly mechanical process of emplacement.

Features that constitute a favourable environment for this particular style of magmatic sulphide deposit include the following:

1. Location on a collisional continental or insular margin;
2. Evidence of a transpressive structural environment during generation and emplacement of the metallogenic melt;
3. An abundant external (wallrock) source of sulphur;
4. Evidence of sulphide smelting in low metamorphic grade wallrock, or wholesale assimilation in a high-grade metamorphic setting.

The ultramafic Pacific Nickel Complex and its related deposits have hitherto been regarded as being of restricted extent. Field observations indicate that this is not the case and that the Giant Mascot deposit is part of a far more extensive metallogenic event affecting eastern Wrangellia.

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