SULPHIDE PETROLOGY AND MINERALIZATION OF THE OKG Ni–Cu–Co SULPHIDE PROSPECT, UMIAKOVIARUSEK LAKE REGION, LABRADOR

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ABSTRACT

The OKG prospect in the Umiakoviarusek Lake region of Labrador consists of pyroxenite–leucotroctolite-hosted magmatic Ni–Cu–Co sulphide mineralization. Mineralization is exposed in two zones, the Main and North zones. In both zones, podiform massive sulphides are located proximal to both pyroxenitic–leucotroctolitic intrusive rocks and ductile (mylonitic) shear zones. Sulphide mineralization intersected in drill core is associated with pyroxenitic intrusive rocks that have approximately 5 percent sulphide near their tops, and grade downward into semimassive to massive sulphides near their bases.

In both drill core and surface exposures, the pyroxenitic and leucotroctolitic intrusive rocks retain primary igneous textures and mineral assemblages and do not exhibit deformation nor alteration even in proximity to ductile shearing on the surface. In contrast, the anorthositic wall-rocks on the surface locally exhibit ductile shearing, intense recrystallization and secondary replacement of the igneous minerals by greenschist-facies metamorphic assemblages. These ductile shear zones, which are associated with the showings, may have been zones of weakness exploited by the sulphide-bearing pyroxenitic magmas. A Paleoproterozoic age has recently been inferred for the anorthositic host rocks to the pyroxenitic dykes, but the structural and intrusive relationships indicate that the pyroxenite dykes may actually be Mesoproterozoic.

Sulphide mineral assemblages at OKG are dominated by pyrrhotite which hosts, or is in proximity to, all other sulphide–oxide phases. From textural features and comparisons with published phase equilibria data, it is shown that the OKG sulphides are characterized by a high temperature assemblage (pyrrhotite–magnetite) and a lower temperature, subsolidus, exsolution assemblage (pyrite–chalcopyrite–pentlandite). High-temperature phases are marked by the earliest crystallization of magnetite, likely at high oxygen fugacity (ca. 1160° to 1120° to 1055°C), followed by co-crystallizing magnetite and pyrrhotite (ca. 1055 to 1010°C). At subsolidus temperatures (ca. 1010°C and below), the earliest exsolving phase is pyrite (ca. 700°C), followed by chalcopyrite (ca. 450°C), and finally by pentlandite (ca. 250 to 200°C).

INTRODUCTION

The discovery of the Voisey's Bay Ni–Cu–Co sulphide deposit in November 1994 led to an unprecedented staking rush and search for similar styles of mineralization in a region that had been poorly explored. As a result of this exploration, a variety of new occurrences have been discovered that vary both in style and nature (cf., Kerr and Smith, 1997; Kerr, 1998). Although preliminary work has been carried out on both the Voisey's Bay deposit (cf., Ryan *et al.*, 1995; Ryan, 1996; Naldrett *et al.*, 1996; Naldrett, 1997; Lightfoot, 1998; Li and Naldrett, 1998) and other occurrences in Labrador (*see reviews* by Kerr and Smith, 1997, and Kerr 1998), only a cursory understanding of the petrologic and petrographic characteristics of these occurrences exists. One of these occurrences is the OKG prospect in the Umiakoviarusek Lake region (Figures 1 and 2) where disseminated to massive sulphide mineralization is associated

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Figure 1. Precambrian structural provinces of Labrador and related Paleoproterozoic and Mesoproterozoic intrusive rocks, and location of the study area. Modified after James et al. (1996).



LEGEND

QUATERNARY

PALEOPROTEROZOIC

Overburden and glacial drift

Granitoid Plutons

× × ×	Hornblende granite		
+ + +	Quartz monzonite, ovoidal feldspar clinopyroxene quartz monzonite (phase 2 granitoid)		
+ + × + ×	Variably foliated orthopyroxene, fayalite, clinopyroxene, hornblende, biotite-bearing monzonite, syenite (phase 1 granitoid)		
<	Foliated orthopyroxene, fayalite, clinopyroxene, biotite-bearing quartz syenite, monzonite, granite		
Anorthositic Plutons			

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I	

Dark grey and black anorthosite



Buff, olivine-bearing leuconorite



Dark black to light grey anorthosite and leuconorite





Buff-weathering leuconorite and gabbronorite

ARCHEAN





Amphibolite, mafic granulite, metatonalite, quartzofeldspathic gneiss



SYMBOLS

- 780 Foliation or gneissosity, inclined
- Foliation or gneissosity, vertical
- Compressional fault
- -____ Sinistral strike-slip fault
- - Claim boundary

Figure 2. Geological setting of the OKG prospect. Geology inside property boundaries from Piercey (1998), outside of property boundaries from Ryan et al. (1997, 1998) and Emslie et al. (1997).

with pyroxenitic intrusions (*ensu lato*) (cf., Wilton and Baker, 1996; Kerr and Smith, 1997; Piercey, 1997, 1998; Piercey and Wilton, 1998; Kerr, 1998). This paper provides 1) a descriptive overview of the nature and style of mineralization at the OKG prospect, 2) a documentation and overview of the petrographic features of the sulphide mineralization at the OKG prospect, and 3) preliminary interpretations on the nature of emplacement and the sulphide petrographic relationships of magmatic Ni–Cu–Co mineralization at the OKG prospect.

(Bertrand *et al.*, 1993; Van Kranendonk and Wardle, 1994, 1997; Van Kranendonk, 1996; Ryan *et al.*, 1997, 1998; Hamilton, 1997; Hamilton *et al.*, 1998). The anorthositic and granitoid rocks at the OKG prospect have features consistent with pre-Torngat Orogen emplacement, and later influence of the Torngat Orogen, including (*after* Ryan *et al.*, 1998; and Piercey, 1998) 1) widespread, yet inhomogeneous, greenschist-facies, metamorphic mineral assemblages; 2) well-developed recrystallization of primary igneous mineralogy; 3) intrusion of metabasic dykes that contain greenschist-facies mineral assemblages, and are locally deformed; and 4) localized mylonitic deformation and sinistral strike-slip faulting (Figures 2 and 3).

REGIONAL SETTING

The geology of Labrador is characterized by five Precambrian structural provinces of the Canadian Shield (cf., Taylor, 1971) and anorogenic igneous intrusive suites (Figure 1). These are 1) the Archean Nain and Superior provinces in northeastern and western Labrador, respectively; 2) the Churchill Province in north-central to central Labrador, sandwiched between the Nain and Superior provinces, itself having an Archean core; 3) the Paleoproterozoic Makkovik Province along the southern margin of the Nain Province; 5) the Grenville Province along the southern edge of Labrador; and 6) a series of anorogenic anorthosite-mangerite-charnockitegranite (AMCG) suites that include the Mesoproterozoic Nain Plutonic Suite (NPS) (Figure 1). The NPS comprises a significant proportion of north-central Labrador, encompassing nearly 18 000 km², and the constituent magmas were emplaced between ca. 1350 to 1290 Ma (Emslie, 1978, 1985; Ryan and Emslie, 1994; Emslie et al., 1994; Ryan et al., 1995; Hamilton, 1997). Recently, Paleoproterozoic (2135 to 2045 Ma) AMCG-suite magmatism has been documented in the region from Webb's Bay to Okak Bay (Ryan et al., 1997, 1998; Emslie et al., 1997; Hamilton, 1997; Hamilton et al., 1998; Ryan and Hamilton, 1998). These Paleoproterozoic anorthositic and granitoid bodies differ from the NPS in exhibiting a variable metamorphic and deformation influence from the Paleoproterozoic, ca. 1.87 to 1.74 Ga Torngat Orogen



Figure 3. Geological map and nature of surface mineralization of the Main zone and North zone of mineralization. Modified after T.P. Ryan (1996a) and Piercey (1998).



Plate 1. Typical mineralized orthopyroxenitic dyke from the OKG prospect. Note the intercumulus, black sulphide mineralization (plane-polarized light, magnification = 2.5x) and the fairly fresh orthopyroxenes (light coloured), even though this sample is from near a fault.

In contrast to the anorthositic and granitoid rocks, the mineralized pyroxenites of the OKG prospect do not exhibit evidence of influence by the Torngat Orogen, and are likely of Mesoproterozoic age (cf., Piercey, 1998). The mineralized pyroxenitic dykes are fresh, retaining primary igneous mineralogy and textures, even in proximity to ductile faulting (Figure 3; Plates 1 and 2). The surrounding anorthositic rocks, on the other hand, exhibit either partial or complete replacement of the mafic minerals by chlorite-actinolite assemblages, even plagioclase is replaced by sericite-epidote assemblages and some anorthositic rocks are cut by small veinlets of chlorite, quartz, carbonate (calcite and dolomite), and sericite. Furthermore, the pyroxenitic dykes do not exhibit deformation along their margins, features common to both mafic and felsic dykes of Paleoproterozoic age (cf., Ryan et al., 1997, 1998; Figure 4). The likely Mesoproterozoic age for the pyroxenitic-leucotroctolitic intrusive rocks provides, at least, a cursory link to the Mesoproterozoic NPS magmatic event (cf., Ryan and Emslie, 1994; Emslie et al., 1994). It is possible that basaltic underplating associated with the NPS may have been responsible for mantle-melting and genesis of the observed pyroxenitic-leucotroctolitic intrusive rocks (Piercey, 1998); however, this is beyond the scope of the objectives of this paper and will not be discussed further.

NATURE AND STYLE OF SULPHIDE MINERALIZATION

Sulphide mineralization at the OKG prospect is variable, ranging from disseminated to massive, and is spatially and genetically associated with pyroxenitic (*sensu lato*), and in one case leucotroctolitic, intrusive rocks (Figures 3 and 4). Exposed mineralization is restricted to a region approximately 450 m long by 40 m wide, associated with two



Plate 2. Typical leucotroctolite to olivine gabbro from the OKG prospect with cracked, high relief olivine crystals, white cumulus plagioclase, and intercumulus clinopyroxene (pink), and sulphide (black; plane-polarized light, magnification = 2.5x).

zones: 1) the Main zone (MZ), and 2) the North zone (NZ; Figure 3). A gossan developed on the Main zone was discovered by Castle Rock Exploration Limited (now Castle Metals Limited) geologists in September, 1995. In both zones, pyroxenite related mineralization is spatially associated with north-northwest- to south-southeast-trending ductile shear zones; however, even in proximity to these shear zones the pyroxenitic rocks retain primary igneous textures and mineral types (Plates 1 and 2). Massive sulphide samples collected from the surface showings have assayed up to 1.78 % Ni, 1.41 % Cu, and 0.21 % Co (cf., Wilton and Baker, 1996; Kerr and Smith, 1997; Piercey, 1997, 1998; Piercey and Wilton, 1998; Kerr, 1998). Diamond drilling has intersected similar disseminated to massive sulphides associated predominantly with pyroxenitic intrusive rocks (cf., Wilton and Baker, 1996; Kerr and Smith, 1997; Kerr, 1998; Piercey, 1998); a summary of representative grades and intersections in drill core from the OKG is presented in Table 1. The remainder of this section outlines the nature of mineralization in the surface zones and drill core.

MAIN ZONE MINERALIZATION

The Main zone (MZ) of mineralization is characterized by significant sulphide burn and sulphide mineralization associated with irregularly shaped zones (0.5 to 1 m by 2 to 3 m) that are in proximity (within 2 to 3 m) to pyroxenitic intrusive rocks (Figure 3). Sulphide minerals are dominated by pyrrhotite and chalcopyrite, with pyrrhotite being the predominant sulphide mineral. The pyrrhotite occurs as large, euhedral grains approximately 0.5 to 5 cm in size. Chalcopyrite rarely exceeds 10 percent of the sulphide mineralogy, occurring as 1 to 3 mm by 2 cm stringers along pyrrhotite grain boundaries or as individual rounded grains 3 to 7 mm in diameter.



Figure 4. Schematic diagram illustrating the drill-core relationship of pyroxenitic dykes, sulphide mineralization and surrounding wall-rock for subsurface mineralization at the OKG prospect (cf., Wilton and Baker, 1996; Kerr, 1998; Piercey, 1998). Vertical and horizontal scales not inferred.

Chalcopyrite typically occurs in association with included fragments of anorthositic wall-rock in massive sulphides; it is located along both the grain edges of the anorthosite xenoliths and the internal crystallographic axes or fractures in the anorthositic fragments. These 0.5 to 5 cm anorthosite fragments are the most abundant inclusion type in the sulphides and most contain relict subhedral edges that are locally rounded from reaction with the sulphide liquid.

Main zone disseminated sulphide mineralization occurs in both anorthositic and, more commonly, pyroxenitic–leucotroctolitic host rocks (Plates 1 and 2). Disseminated anorthosite-hosted sulphides consist predominantly of finegrained, anhedral (1 to 3 mm) pyrrhotite, and lesser flecks of anhedral chalcopyrite (ca. 1 mm). Semimassive anorthosite-hosted sulphides contain coarser pyrrhotite, between 1.5 to 2 cm, that is interstitial to plagioclase having similar stringer- and fleck-like chalcopyrite.

Disseminated pyroxenite-hosted sulphide is the most common type of disseminated mineralization associated with the MZ and is associated with discontinuous and irregularly shaped pyroxenitic dykes (and plugs) with variable widths, strike lengths and shape. Some outcrops of the pyroxenitic rocks are almost plug like (ca. 1 to 2 m in size), but most are in the form of dykes 10 cm to 1 m wide having strike lengths ranging from 1.5 to 5 m. Dyke margins are not easily discernable, but appear to be irregular and bulbous. None of the exposed dykes contain fragments of wall-rock anorthositic material. Sulphide mineralization occurs in the form of disseminated, 0.5 to 4 mm anhedral pyrrhotite with chalcopyrite along pyrrhotite grain edges (with minor magnetite) and together they comprise ca. 5 to 25 modal percent. In contrast to the disseminated anorthosite-hosted sulphides, the pyroxenite-hosted sulphides appear to be intercumulus, syngenetic sulphides, which are genetically related to the dykes (cf., Wilton and Baker, 1996; Kerr, 1998; Piercey and Wilton, 1998; Piercey, 1997, 1998).

NORTH ZONE MINERALIZATION

The North zone (NZ) mineralization is spatially associated with a ductile shear zone and mylonitic rocks located approximately 350 m northwest of the Main zone of mineralization (Figure 3). Similar to the MZ, the pyroxenitic intrusives are unaffected by the

shearing and retain pristine igneous textures and primary igneous mineralogy. Mineralization in the NZ consists predominantly of disseminated sulphide with lesser massive sulphide, and similar to the MZ mineralization, occurs in both anorthositic and pyroxenitic rocks. Sulphide minerals intrude moderately silicified anorthositic material that has been recrystallized by faulting. The sulphides constitute <5 percent of the anorthositic rocks and occur as 1 to 2 mm to 1 cm disseminations of fleck-like and blebby, anhedral pyrrhotite; lesser chalcopyrite occurs as isolated blebs and flecks on the edges of pyrrhotite grains. Pyroxenite-hosted disseminated sulphides are similar to those of the MZ containing anhedral pyrrhotite blebs having chalcopyrite edges and stringers.

Drillhole	Intersection	Grade	Notes	
Surface showings	Grab samples	Best assay: up to 1.78% Ni, up to 1.44% Cu, up to 0.21% Co	Massive sulphide pods in anorthosite, associated with pyroxenites	
OKG-1, 2	Four intersections over 5 m	Not quoted	Associated with pyroxenites	
OKG-3	3.2-m-wide intersection	up to 1.10% Ni, up to 0.93% Cu, up to 0.104% Co	Associated with pyroxenites	
OKG-4	3-m-wide 30-50% po+cp in pyroxenites	1.10% Ni, up to 0.37% Cu, up to 0.06% Co	Associated with pyroxenites	
OKG-5	Four intersections, 1.1-7.5 m	0.86-1.07% Ni, 0.45-0.72% Cu, 0.04-0.09% Co	Pyroxenite layers, basal massive sulphide grading upward into semimassive and disseminated (CTP-PR Dec. 18, 1995).	
OKG-96-09	Four 1 m intersections over 14 m interval	0.26-0.87% Ni, 0.09-0.43% Cu, 0.04-0.11% Co	Associated with pyroxenitic "layers' and had four intervals over apparent 14 m	
OKG-96-10	2 intersections 0.5-1.0 m	0.34-0.67% Ni, 0.26-0.71% Cu, 0.04-0.08% Co	Associated with pyroxenites	
OKG-96-13	2 intersections 1.0-1.11 m wide	0.25-0.44% Ni, 0.16-0.34% Cu, 0.04-0.07% Co	Associated with pyroxenites	
OKG-96-16	6.10 m intersection	up to 0.6% Ni, up to 0.32% Cu, up to 0.10% Co	Ten pyroxenite lenses over interval	
OKG-97-20	NA1	subeconomic grades	Pyroxenite hosted, magnetite rich with disseminated sulphide	
OKG-97-21	NA1	subeconomic grades	Intrusive "gabbroic" textured ultramafic; 20% magnetite and disseminated sulphide	
¹ NA = not applicable				

Table 1. Summary of representative intersections and grades from the OKG prospect. Data compiled from Castle Rock

 Exploration press releases and Kerr and Smith (1997)

Massive sulphide mineralization associated with the NZ is much less abundant than that of the MZ, occurring as irregularly shaped pockets 30 to 45 cm in size. Sulphides are predominantly coarse-grained pyrrhotite having very little

chalcopyrite; the latter only comprising 1 to 2 percent of the total sulphides. Pyrrhotite occurs as 0.5 to 1 cm euhedral grains that have a pinkish hue, unlike the pyrrhotite of the MZ.

DRILL-CORE MINERALIZATION

To date, 21 diamond-drill holes have been drilled on the OKG prospect, but thus far no economic ore body has been delineated. The diamond-drill core, however, exposes variable and interesting intersections of pyroxenite-hosted Ni–Cu–Co sulphide mineralization (Table 1). Detailed drill-core logging was not undertaken as part of this project; however, observations on the generalities of the style and nature of mineralization were made for this study (Figure 4). Further details on the nature of core mineralization can be obtained from T. Ryan (1996a,b), Wilton and Baker (1996), and Kerr (1998).

Sulphide mineralization intersected in drill core provides unequivocal evidence of the genetic relationship between the pyroxenitic dykes and Ni-Cu-Co sulphide mineralization. The pyroxenitic intrusive rocks show very sharp contacts with the surrounding anorthositic wall-rock material and in all cases contain disseminated sulphide mineralization. The pyroxenite-sulphide relationship is typically a gradational one, grading from disseminated (ca. 5 percent) sulphide near the tops of the dykes with increasing concentration from semimassive through massive sulphide near their bases (Figure 4; cf., Wilton and Baker, 1996; Kerr, 1998; Piercey, 1998). Within the basal massive sulphides minor centimetre-sized inclusions of anorthositic host-rock material are present (Figure 4), that likely represent entrainment upon emplacement of the pyroxenitic dykes and associated sulphide. Sulphide stringers are also common in anorthositic rocks within a few centimetres of the basal contacts with the pyroxenites (Figure 4; cf., Kerr, 1998).

SULPHIDE PETROLOGY

The OKG sulphides are dominated by a pyrrhotitechalcopyrite-pentlandite-pyrite-magnetite assemblage in the disseminated to massive sulphides, regardless of the host rock. The massive sulphides provide the best indicators of the interrelationships between sulphide minerals, whereas the pyroxenitic sulphides illustrate the best relationships between silicates and sulphides. Massive and semimassive sulphides from both surface and drill core contain predominantly pyrrhotite that is host or in proximity to all other sulphide-oxide phases (e.g., Plates 3 to 9). Pyrrhotite occurs as euhedral, and lesser subhedral grains that comprise 75 to 85 percent of the sulphide minerals. In outcrop samples, the pyrrhotite is altered because abundant hematite is developed along the basal partings and fractures of the grains. In drill core, on the other hand, pyrrhotite is fresh and lacks hematite, from which it can be inferred that the outcrop samples underwent surface weathering (cf., Craig, 1990).

In the massive sulphides, chalcopyrite and pentlandite comprise 5 to 10 percent of the sulphide minerals and are in

roughly subequal proportions. Chalcopyrite is present in a variety of forms, occurring along pyrrhotite grain boundaries or as grains radiating inward from the pyrrhotite grainboundaries. Edge-type chalcopyrite occurs as very anhedral stringers ca. 0.1 to 1 mm wide by 0.5 to 7 mm long; some of these stringers occur along the fractures intergrown with hematite. Inwardly extending chalcopyrite has a variety of shapes including: 0.25- to 0.5-mm-wide flame-like grains, similar-sized rounded and blebby grains (Plates 3 and 4), and 0.1- to 0.5-mm-elongate worm-like grains (Plate 3). In addition to the pyrrhotite associated chalcopyrite, chalcopyrite forms 0.5 to 2 mm anhedral coronas that partially or fully enclose the silicate mineral grains (plagioclase and orthopyroxene), and pyrite (Plate 5).



Plate 3. Pyrrhotite grains (dark beige) containing an intergrowth of magnetite (dark grey) and exsolved chalcopyrite (yellow) blebs and flame to blebby pentlandite (light beige) exsolution. Features of particular note include the subophitic intergrowth of magnetite and pyrrhotite, and the partial rim of blebby pentlandite on the chalcopyrite (transmitted light, magnification = 10x).



Plate 4. Blebby exsolution of chalcopyrite (yellow) radiating inward from pyrrhotite (beige) grain boundaries. The lower left-hand bleb of chalcopyrite (yellow) also has pentlandite (light beige) along the bleb edge (transmitted light, magnification = 10x).



Plate 5. Exsolved pyrite (bright beige, high relief) and chalcopyrite (yellow) exsolution within a pyrrhotite (dark beige); pentlandite is intergrown with chalcopyrite and as flames in pyrrhotite. Note the close association of the pyrite with the pyrrhotite grain edges as well as the distinctive mantling of the pyrite by chalcopyrite (transmitted light, magnification = 50x).

Pentlandite occurs in a wide variety of forms including, flame-like exsolution lamellae (<0.1 mm; Plates 6 to 8), and as 0.25- to 1-mm-rounded blebs, worm-like, and irregularly shaped granular exsolved grains (Plate 6). The flame and bleb types are associated with the interiors of the pyrrhotite grains. Along grain boundaries, partings, and fractures in the pyrrhotite crystals, flame-like pentlandite lamellae are pseudo-orthogonal to the fracture boundaries (Plates 6 and 7), whereas anhedral, 0.5 to 1 mm rims of pentlandite partially, and locally fully, enclose the pyrrhotite crystals (e.g., loop textures; Plate 8). Pentlandite is also intergrown with chalcopyrite, forming partial coronas to the chalcopyrite (Plate 3).



Plate 6. Euhedral magnetite octahedra (dark grey) included within a pyrrhotite crystal (dark beige), along with flame-like exsolution lamellae of pentlandite (light beige). Some of the pentlandite lamellae also have pseudo-orthogonal behaviour with respect to fractures in the pyrrhotite crystals (transmitted light, magnification = 10x).



Plate 7. *Flame-like and blebby, worm-like exsolution lamellae of pentlandite (light beige) within pyrrhotite (dark beige) grains (transmitted light, magnification = 10x).*



Plate 8. Pyrrhotite (dark beige) with both high- and lowtemperature pentlandite exsolution (light beige). The higher temperature pentlandite exsolution forms a partial enclosure of the pyrrhotite grain along the boundary of the pyrrhotite grain. Lower temperature pentlandite exsolution occur as small flames within the pyrrhotite grain (transmitted light, magnification = 10x).

Pyrite grains, in lesser abundance relative to pyrrhotite, pentlandite and chalcopyrite, are present in most massive sulphide samples. In all cases, the pyrite occurs as anhedral, resorbed grains included within the pyrrhotite, but generally on the pyrrhotite grain boundaries (Plate 5). Furthermore, the pyrite has a full or partial rim of irregularly shaped chalcopyrite (Plate 5).

Unlike the sulphides, magnetite is not a ubiquitous mineral and ranges between 0 to 5 percent modally. It occurs as 0.5 to 7 mm euhedral to subhedral octahedra that are fully and partially enclosed by pyrrhotite (Plates 6 and 9). Less commonly, magnetite occurs as 0.5- to 3-mm-rounded to irregular-shaped grains on the edges of the pyrrhotite grains in pseudo-subophitic textures, or as 0.5 to 1 mm isolated grains between crystals associated with hematite (Plate 9).



Plate 9. Intergrowths of euhedral to subhedral magnetite (dark grey) and pyrrhotite (dark beige), also present are small blebs of exsolved pentlandite (light beige; transmitted light, magnification = 10x).

The sulphides disseminated within the pyroxenitic and leucotroctolitic intrusive rocks are also dominated by pyrrhotite, with lesser chalcopyrite, pentlandite, and magnetite. Pyrrhotite occurs predominantly as 0.25 to 4 mm intercumulus material that contains pyrite, chalcopyrite and pentlandite in similar forms to those in the massive sulphides. However, pentlandite appears to be dominated by flame and blebby exsolution within and along the pyrrhotite grain edges (radiating inward), and minor exsolved flames and blebs occur as irregular pseudo-rims on chalcopyrite grain edges; chalcopyrite also occurs alone as small intercumulus disseminations. Magnetite is typically present as intercumulus material having a habit similar to pyrrhotite, or is intergrown with pyrrhotite, in particular near pyrrhotite grain boundaries.

Leucotroctolite-hosted sulphides are also disseminated and show similar sulphide assemblages; however, in a few cases ca. 0.5 to 0.75 cm accumulations of intercumulus sulphide have been observed. Anorthosite-hosted sulphides are predominantly disseminated pyrrhotite containing exsolved flames/blebs of pyrite, chalcopyrite and pentlandite, and have similar sulphide textures as the massive sulphides and pyroxenite-hosted sulphides. However, field relationships suggest that the sulphide liquid was epigenetically emplaced into the anorthositic rocks and cooled upon emplacement accounting for the observed sulphide minerals and textures.

DISCUSSION

The geology and nature of mineralization at the OKG prospect suggest that these sulphides represent true magmatic Ni–Cu–Co sulphide mineralization in the strictest sense and are genetically related to the pyroxenitic and leucotroctolitic intrusive rocks (cf., Wilton and Baker, 1996; Kerr and Smith, 1997; Piercey, 1997, 1998; Kerr, 1998; Piercey and Wilton, 1998). The nature, style, and petrographic features of the mineralization give clues as to the emplacement characteristics, possible age, and the evolutionary sequence of sulphide–oxide minerals within the OKG Ni–Cu sulphide mineralization.

The age of the mineralization at the OKG prospect remains problematic; however, a Mesoproterozoic age is inferred based on a number of criteria. First, within both the Main and North zones of mineralization, ductile, mylonitic shearing, faulting and folding are abundant, and in response to this faulting there is nearly a complete replacement of primary igneous minerals with secondary, greenschist-facies metamorphic assemblages in wall-rock anorthositic material (cf., Piercey, 1998). In contrast, the mineralized pyroxenites in these regions do not exhibit evidence of their deformation, retain pristine igneous textures, and do not exhibit secondary metamorphic mineral assemblages (e.g., Plates 1 and 2). Furthermore, in drill core there is no evidence of deformation along pyroxenite dyke margins, a feature that is common to Paleoproterozoic mafic and felsic dykes (Figure 4; cf., Kerr, 1998; Piercey, 1998). Although this does not prove a Mesoproterozoic age, it provides strong arguments against a Paleoproterozoic age and the influence of the Torngat Orogen.

The spatial relationship of the pyroxenite dykes, proximal to ductile fault zones, also suggests that the dykes may have exploited these pre-existing zones of weakness during emplacement. The mineralization exposed in outcrop represents intrusive leaks related to the subsurface pyroxenitic mineralization. The presence of centimetre-scale rounded inclusions of anorthositic material in the massive sulphides also suggests that some degree of turbulence accompanied the emplacement of the pyroxenitic intrusive rocks and their related sulphides.

The petrographic characteristics of the sulphides from both the dykes and massive sulphides are similar, and are dominated by pyrrhotite that hosts, or is in proximity to, all other oxide and sulphide phases (Plates 3 to 9). Both the pyroxenite-hosted disseminated sulphide and massive sulphide mineralization have pyrrhotite as the dominant sulphide phase, either containing euhedral inclusions of magnetite (Plate 6), or pseudo-subophitic intergrowths of pyrrhotite and magnetite (Plate 9). Phase relationships in the Fe-S-O system (Naldrett, 1969, 1989) suggest that at temperatures above the solidus for sulphide melts (ca. 1010 to 1050 °C) and below the liquidus (ca. 1160 to 1120°C), at high oxygen fugacities (/O2), magnetite should crystallize before pyrrhotite; however, this is not the case in most natural ores (Naldrett, 1989). In contrast, the pseudo-subophitic nature of magnetite and pyrrhotite suggest co-crystallization. Naldrett (1969) has shown that at temperatures below the liquidus in the Fe-S-O system, early crystallization of



Figure 5. Sketch of interpreted crystallization and exsolution sequence of the OKG sulphide**n**oxide assemblages. Sources of estimated temperatures are cited in the text.

pyrrhotite can increase /O2 in the residual liquid causing magnetite formation and co-crystallization of magnetite and pyrrhotite on a cotectic. Coats and Snajdr (1984), citing the work of Craig and Kellerud (1969), Kellerud *et al.* (1969) and Naldrett and Kellerud (1967), have stated that for ores from the North Range (Onaping–Levack area) at Sudbury this co-crystallization would begin at ca. 1055 °C. Naldrett (1969) suggests that this co-crystallization would continue until the Fe–S–O solidus was reached (1050 to 1010°C). The inclusion of euhedral magnetite within the pyrrhotite suggests that this was an early crystallizing phase within the sulphide–oxide assemblage at the OKG Prospect.

In contrast to magnetite and pyrrhotite, the sulphide petrographic features of pyrite, chalcopyrite and pentlandite are solely subsolidus phenomena. Work on the Cu–Fe–Ni–S system has shown that at temperatures just below the solidus, pyrrhotite–pentlandite–chalcopyrite–magnetite ores would consist of two phases: 1) a nickeliferous cupriferous pyrrhotite solid solution (monosulphide solid solution, MSS); and 2) magnetite (Naldrett, 1969, 1989). With decreases in temperature, the MSS would have an effective decrease in the metal:sulphur ratio and exsolution of pyrite will occur (Naldrett, 1984), typically in the vicinity of 700°C and below (Kullerud *et al.*, 1969; Coats and Snajdr, 1984), which is consistent with observed pyrite–pyrrhotite textural relationships (Plate 5).

The mantling of pyrite by chalcopyrite infers that chalcopyrite exsolution postdated pyrite and at lower temperatures, likely at <450 °C (Kellerud *et al.*, 1969: Coats and Snajdr, 1984; Plate 5, Figure 5). The presence of pentlandite, which is locally intergrown with and partially mantles chalcopyrite, suggests that the Nibearing sulphide was the lowest temperature phase to exsolve (Plate 3). Naldrett (1984) has stated that pentlandite in the Sudbury ores likely resulted from the breakdown of the MSS into Nipoor and Ni-rich variants resulting in the exsolution of pentlandite in pyrrhotite. Furthermore, Naldrett (op. cit.) suggested that this occurs at between about 200 and 250°C.

Further qualitative textural subtypes of pentlandite exsolution can also be suggested based on the

work of Craig (1990), who determined that early, higher temperature, pentlandite exsolution will occur as blebs on the edges of the MSS (pyrrhotite) grains which, with continued exsolution and temperature decrease, will result in the coalescence of blebs and the formation of the partial to full enclosures of pentlandite (e.g., loop textures), as observed on many of the pyrrhotite grains (Plate 8). In contrast, the lower temperature pentlandite exsolution occurs mainly as flames and blebby exsolution within the pyrrhotite grains (*op. cit.*; Plates 5 to 7).

CONCLUSIONS

Mineralization at the OKG prospect is truly syngenetic in that it is ubiquitously spatially, and likely genetically, related to pyroxenitic intrusive rocks, although in one case, leucotroctolitic intrusive rocks host disseminated mineralization. Surface mineralization is associated with two zones, the Main zone and North zone. In both zones, the pyroxenitic intrusive rocks and related sulphides are proximal to ductile shear zones; however, in contrast to the anorthositic rocks in proximity to these faults, the pyroxenitic intrusive rocks retain primary igneous mineralogy and do not exhibit secondary metamorphic, greenschist-facies, mineral assemblages typical of the anorthositic rocks in the region. The anorthosite-hosted sulphides appear to have been epigenetically emplaced into the anorthositic material as a sulphide liquid, and were likely derived from the proximal pyroxenite-hosted mineralization.

The spatial association of the intrusive rocks with zones of ductile faulting suggests that they postdate this deformation in the prospect, and along with the absence of secondary metamorphic mineral assemblages, suggests that the dykes may be of Mesoproterozoic age. Geochronological data are required to prove or disprove this interpretation.

Their spatial association with mylonitic faulting further suggests that the pyroxenite rocks exploited the pre-existing faults and zones of weakness as a means of reaching the surface. The presence of centimetre-scale anorthositic fragments associated with massive sulphides from the dykes suggests that the emplacement of the dykes and related sulphide mineralization may have had some degree of turbulence.

Sulphide petrographic features of pyroxenitic- and anorthositic-hosted, and massive sulphide mineralization, have similar sulphide-oxide assemblages and relationships. Pyrrhotite is the dominant sulphide that either hosts, or is in proximity to, all other sulphide-oxide phases; these latter being magnetite, pyrite, chalcopyrite and pentlandite. From textural features, it is interpreted that magnetite initially crystallized before any sulphide due to elevated oxygen fugacities, which was followed by co-crystallization of magnetite and pyrrhotite until the MSS solidus was reached (ca. 1010 to 1050°C, Figure 5). All other sulphide minerals are a result of subsolidus reactions. In particular, pyrite exsolved from the MSS at ca. 700°C or below, followed by textural coronas of exsolved chalcopyrite at ca. 450°C and below, followed by lower temperature pentlandite at ca. 200 to 250°C. It is clear from the textural relationships that the sulphide-oxide textural relationships are in accordance with literature-phase relationships and natural sulphide-oxide occurrences (e.g., Sudbury ores).

The nature of sulphide mineralization associated with the dykes suggests sulphur saturation prior to emplacement into the anorthositic rocks, and therefore the S phase was not locally controlled by anorthositic material.

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308

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