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MAGMATIC SULPHIDE MINERALIZATION AT THE FRASER LAKE PROSPECT (NTS MAP AREA 13L/5), MICHIKAMAU INTRUSION, LABRADOR

B. Dyke[1], A. Kerr[2] and P.J. Sylvester
Department of Earth Sciences, Memorial University of Newfoundland, St. John's, NL, A1B 3X5

ABSTRACT

Nickel–copper sulphide mineralization occurs along the eastern margin of the Mesoproterozoic Michikamau Intrusion, near Fraser Lake, and was explored in the early 1990s. This report summarizes the results of a thesis intended to document both the mineralization and its mafic host rocks.

Four principal rock types were identified in drill core from the Fraser Lake area. These are coarse-grained troctolite, melatroctolite, fine- to medium-grained norite, and foliated norite. The melatroctolite is probably an olivine cumulate developed within the spatially associated troctolite unit, to which it is texturally similar. The troctolite unit contains partially digested gneissic inclusions now composed of plagioclase and green hercynite spinel; these were probably derived from the country rocks of the intrusion. The relationships between the troctolite–melatroctolite unit and the noritic rocks remain uncertain. Geochemical data support a genetic link between troctolite and melatroctolite, and suggest that the foliated norite is an unrelated (older ?) phase of the intrusion. Sulphide mineralization occurs within troctolite, melatroctolite and fine- to medium-grained norite, but not in the foliated norite. The sulphides are dominantly interstitial, and represent syngenetic, orthomagmatic mineralization. Sulphide metal contents are low (generally <1% Ni and Cu), and their Ni/Cu ratio differs according to their host rocks. Olivines in mineralized and unmineralized troctolites are depleted in Ni, relative to the expected trends for sulphide-free systems, indicating that these magmas lost metals to sulphide liquids. The Fraser Lake mineralization is low-grade and subeconomic, but it represents only one small part of a very large intrusive body that remains incompletely explored.

INTRODUCTION

The Michikamau (anorthosite) Intrusion in west-central Labrador and adjacent Québec (Figure 1) was explored for nickel and copper in the early 1990s, prior to the Voisey's Bay discovery. The Fraser Lake prospect, on the east margin of the body, consists of disseminated sulphide mineralization in troctolite and norite at the surface. Diamond drilling intersected similar mineralization in the subsurface, but metal grades were generally low (<1.1 % combined Ni and Cu). A brief summary of the mineralization was given by Kerr (1999a). In 2002, a B.Sc. thesis project by the senior author was initiated to document the mineralization in detail, and to interpret whole-rock and mineral geochemical data. This report presents the main findings of the thesis.

PREVIOUS WORK

The earliest geological work recorded in the region was by A.P. Low, of the Geological Survey of Canada, in the 1890s. The next 65 years saw some prospecting, but there were no published geological studies until Emslie (1970) mapped the area for the Geological Survey of Canada. This work remains the most detailed description of the Michikamau Intrusion. The Labrador portion of the intrusion was also examined by the Newfoundland Department of Mines and Energy (Nunn, 1993). A 1-km^2 gossan zone was discov-

[1] Current address; Cornerstone Capitol Resources, 109 Clyde Avenue, Mount Pearl, NL, Canada, A1N 4R9

[2] Mineral Deposits Section

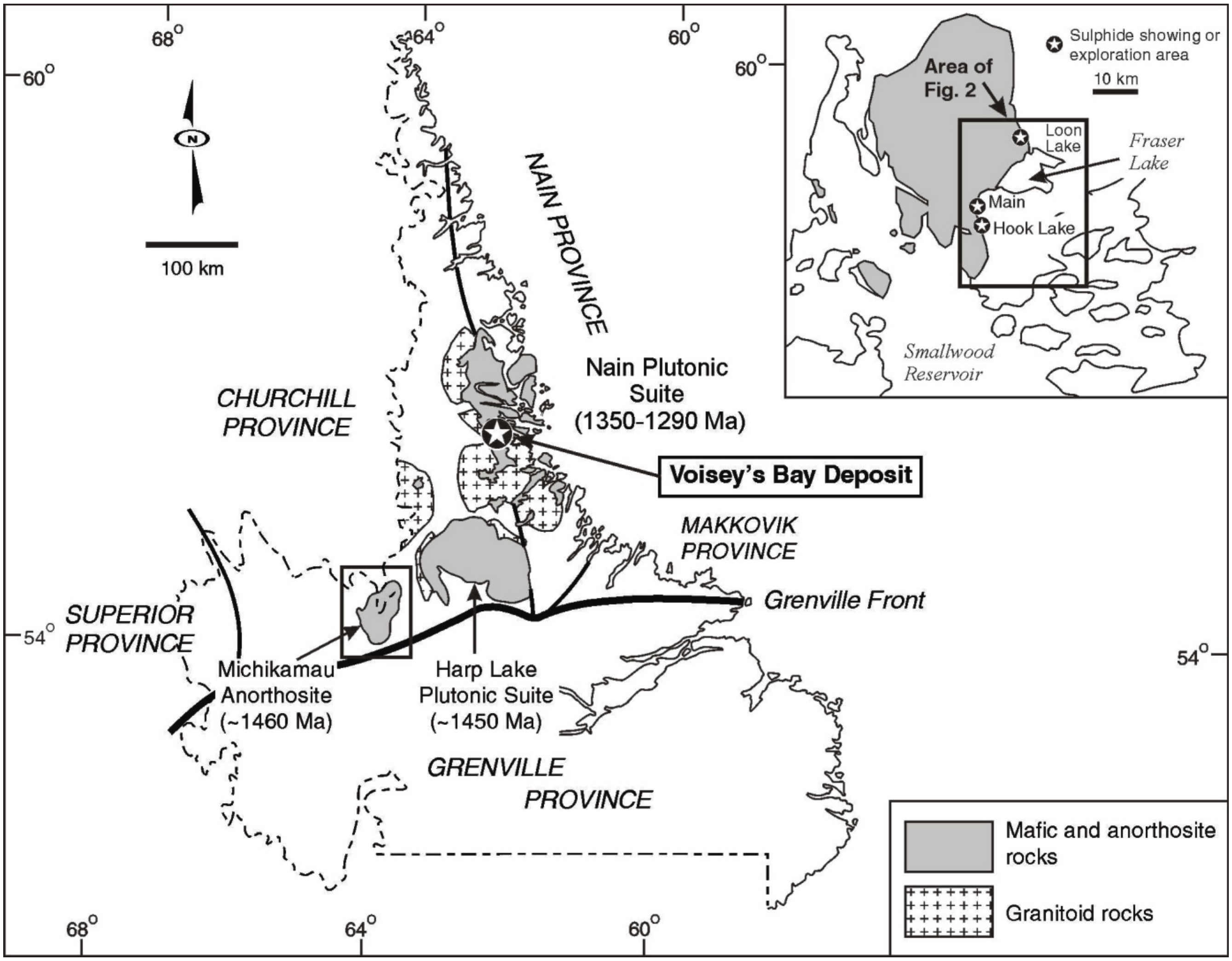

Figure 1. *Locations of major anorogenic anorthosite-dominated plutonic suites and associated granitoid rocks in the Churchill and Nain provinces of Labrador and Québec. Inset map shows the extent of the Michikamau Intrusion, and the location of the areas discussed in this report. Modified after Kerr (1999a).*

ered near Fraser Lake, and shown to be anomalous in Ni and Cu. The Fraser Lake prospect was explored by Kennecott Canada Inc. and Noranda during the early 1990s, and seven drillholes were completed in 1993, most of which intersected subeconomic magmatic sulphide mineralization. No further work was completed, and the property remained dormant during the Voisey's Bay exploration boom, because the land was unavailable for staking. The mineral rights are presently held by Buchans River Ltd.

The Fraser Lake core is stored in the Department of Mines and Energy core library in Goose Bay, and was examined and sampled in 1999 by the second author, who also made brief field visits to Fraser Lake. The drill core was systematically sampled for petrographic and geochemical studies, but only a general description of the mineralization was published at the time (Kerr, 1999a).

REGIONAL GEOLOGY

General Geology

Middle Proterozoic anorogenic plutonic complexes composed mostly of granitoid and anorthosite rocks occur throughout the Churchill and Nain provinces of Labrador (Figure 1). The best-known examples are the Nain Plutonic Suite and the Harp Lake Intrusive Suite (Ryan, 1997). The Michikamau Intrusion of west-central Labrador and adjacent Québec is the third-largest body of its type in the region, and was emplaced at ca. 1460 Ma, based on a U–Pb age from one its youngest phases (Krogh and Davis, 1973). The country rocks of the intrusion include Archean orthogneiss (Sail Lake intrusive suite), Paleoproterozoic supracrustal rocks (Petscapiskau Group) and low-grade Paleoproterozoic volcanic and sedimentary rocks of the

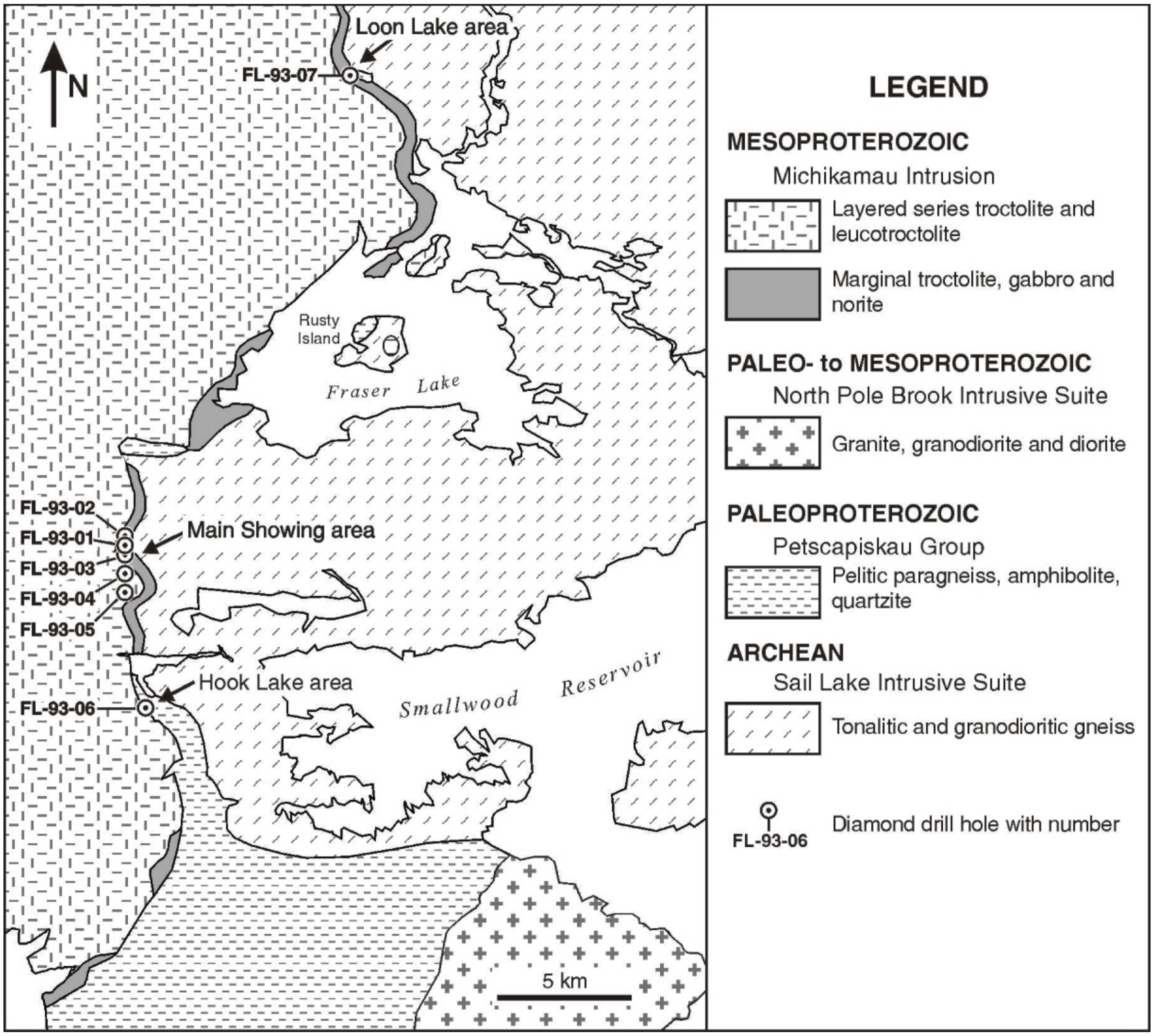

Figure 2. *Simplified geological map of the eastern part of the Michikamau Intrusion in the Fraser Lake area, showing the locations of the drillholes discussed in this report. Geology compiled from Burgess (1993) and Nunn (1993).*

Mackenzie Lake Group (Nunn, 1993). The country rocks are dominated by Archean gneisses, except on the southeastern edge of the intrusion (Emslie, 1970; Nunn, 1993). In the southeast, the dominant country rocks belong to the Petscapiskau Group, consisting of pelitic and psammitic metasedimentary rocks, mafic metavolcanic rocks, quartzite and minor metagabbro (Nunn, 1993). Some sections of the Petscapiskau Group contain disseminated sulphide mineralization, notably on Rusty Island (Figure 2), about 10 km northeast of the Fraser Lake prospect (Figure 2). The Michikamau Intrusion is unconformably overlain by flat-lying red beds of the Seal Lake Group in some localities (Nunn, 1993).

Geology of the Michikamau Intrusion

The Michikamau Intrusion is an unmetamorphosed and undeformed intrusion that originally had a lopolithic shape. It comprises five discrete layered zones, outlined in the following section from bottom to top, inferred to reflect decreasing age. Emslie (1970) provides more detailed descriptions of these subdivisions, and indicates their distribution.

The *marginal zone* occurs on the outer edge of the intrusion, and encloses the intrusion. It includes a contact chill zone that is about 30 cm thick at the immediate boundary with the country rock. Moving inwards, a fine- to medium-grained, thinly banded olivine gabbro is present over a thickness of approximately 250 m, and gives way to medium- to coarse-grained gabbro and troctolite. The marginal zone gabbros grade inward into the rocks of the layered series. The *layered series* is the most voluminous portion of the Michikamau Intrusion; it is dominantly troctolitic, but is divided into four subunits. These consist of troctolite, leucotroctolite, layered gabbro and anorthosite. Evidence of cumulus processes, such as gravity stratification, planar feldspar orientation and rhythmic layering is abundant in the layered series. The *anorthosite zone* overlies the rocks of the layered series with no apparent discrete contact, and is over 3 km thick. It consists of massive, monotonous anorthosites. Emslie (1970) believed that the anorthosite zone formed through the flotation of feldspar from the original basaltic magma, which possibly occurred prior to the development of the underlying layered series. The *upper border zone* comprises leucogabbro and leuconorite, which appear to be gradational with the underlying anorthosite rocks. A thin rind of fine- to medium-grained olivine gabbro locally separates the upper border-zone gabbros from the country rocks. The youngest components are the *transgressive group*, comprising iron-rich ferrosyenite, ferrodiorite and ferromonzonite, which cut the other units, and are dated at ca. 1460 Ma (Krogh and Davis, 1973). Inclusions of wall-rock are rare, and are present mostly in the marginal zone (Emslie, 1970). Lack of inclusions suggests that forceful injection and stoping did not play a major role during emplacement. Late-stage dykes cutting the intrusion range from ferrodiorite to ferromonzonite composition, and resemble the transgressive group (Nunn, 1993).

The Fraser Lake prospect is located on the southeastern margin of the Michikamau Intrusion, north of the Smallwood Reservoir at UTM 445935E 6020075N (± 50 m) (Figure 1). The zone of most interest is termed the "Main Showing", but exploration work was also carried out in Hook Lake and Loon Lake areas, which are also located along the eastern contact of the intrusion (Figures 1 and 2). The geology of the area of the Michikamau Intrusion around Fraser Lake is depicted in Figure 2. The results of the mineral exploration program are discussed in detail by Thein and Rudd (1992) and Burgess (1993).

RESULTS

GEOLOGY AND ROCK TYPES

Overview

This study is based almost entirely on examination of drill core. Seven drillholes were completed in the Fraser Lake area (Figure 2); five drillholes from the Main Showing are the most important in the context of this study, and are discussed in detail in subsequent sections. The holes from the Hook Lake and Loon Lake areas are described briefly. All holes were drilled at an azimuth of 90° (due east) except for FL-93-07, which was drilled at an azimuth of 0° (due north); all holes were inclined –60°. Only one drillhole was completed on each east–west cross-section, and it is therefore difficult to reconstruct the three-dimensional subsurface geology; drillhole parameters are provided in exploration company reports (Burgess, 1993).

Four principal rock types were observed in the drillholes from the Main Showing and the Hook Lake area; these are (1) coarse-grained olivine norite to troctolite, (2) melatroctolite, (3) fine- to medium-grained norite, and (4) banded to foliated norite. For the sake of brevity and clarity, these units are generally referred to below as troctolite, melatroctolite, norite and foliated norite, respectively. Based upon the locations of the drillholes (Figure 2), these four rock types represent the marginal zone and part of the layered sequence. The apparent depth distributions of these four principal units in the five drillholes from the Main Showing area are indicated in Figure 3. Drillholes FL-93-01, 02 and 03 were collared within the marginal zone rocks, whereas FL-93-04 and 05 were collared within the layered series, according to surface mapping (Figure 2). Salient features of individual drillholes are outlined in the next section, and typical examples of various rock types are illustrated in Plate 1.

Hole FL-93-01

Drillhole FL-93-01 is dominated by troctolite and melatroctolite; however, norite and foliated norite dominate toward the base (Figure 3). The upper troctolitic rocks have a well-developed igneous lamination, but contain only minor sulphide mineralization. A thin (<4 m) norite interval has an upper contact that is conformable with this magmatic fabric, and is more sulphide-rich (up to 40% locally). A distinctive melatroctolite unit is present within the troctolites. This dark rock type has a banded appearance, caused by serpentine veinlets, having an orientation of 45° to the core axis. The underlying troctolites contain some diffuse gneissic fragments. The lower section of the hole, below 60 m, is dominated by the norite unit, which also contains sulphides and is pyroxene-rich. A thin (<0.3 m) massive pyrrhotite-rich sulphide interval is present at about 75 m (Figure 3), where the noritic rocks pass downward again into troctolites; the underlying troctolites also contain sporadic interstitial sulphides. The lowermost norite unit is unmineralized, and somewhat recrystallized in appearance. It is underlain by foliated norites, which have compositional layering defined by mafic mineral abundance variations. This lower foliated norite unit does not contain significant sulphides.

Hole FL-93-02

Drillhole FL-93-02 resembles FL-93-01 in many aspects (Figure 3). The upper troctolite section contains interstitial oxides and sulphides, and its lower part (below 58 m) contains numerous gneissic inclusions that are fine grained, dark and featureless. Narrow intervals of melatroctolite also occur in this part of the hole. There is a recrystallized interval from 68.5 to 71.3 m, which includes a distinc-

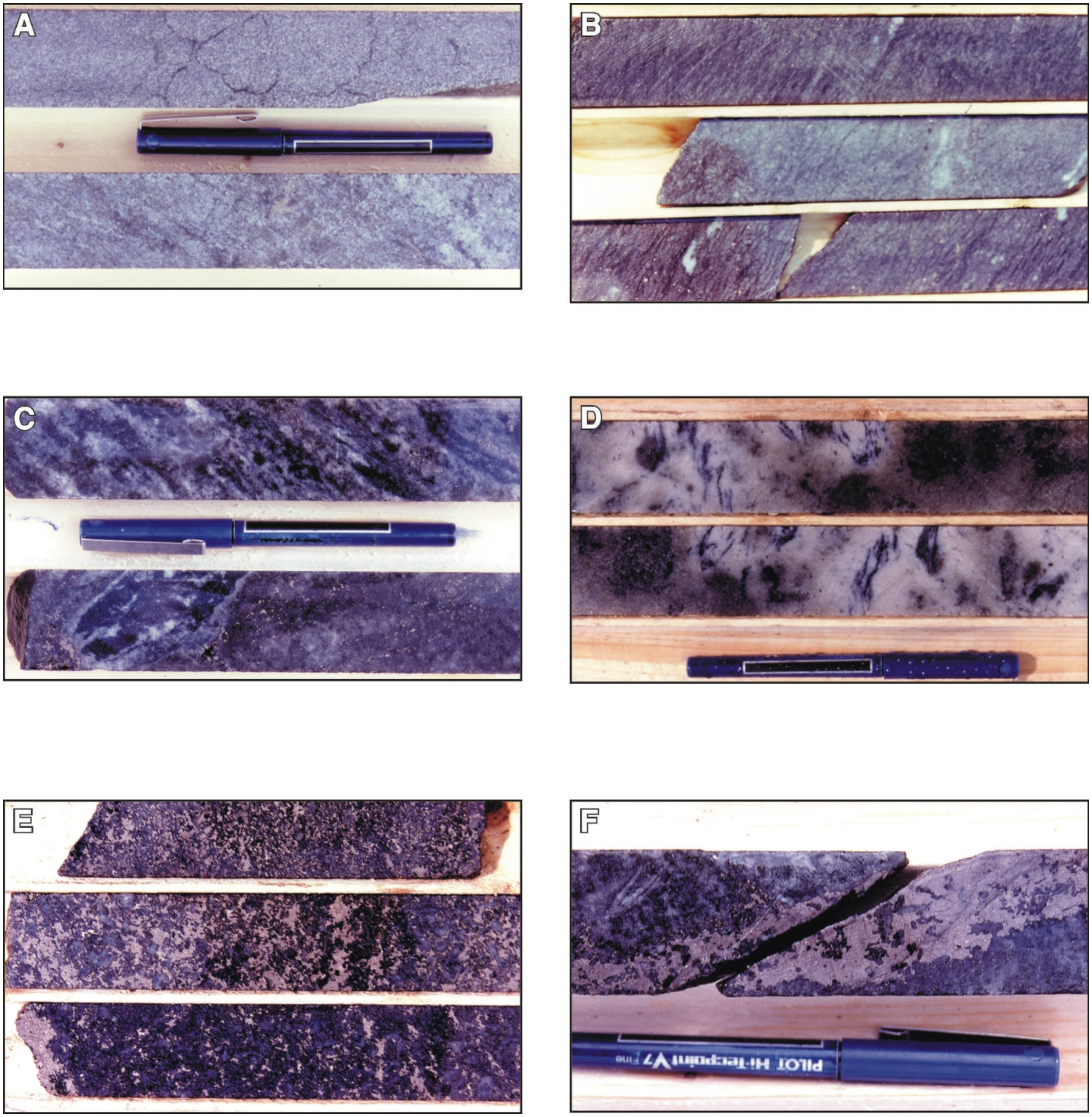

Plate 1. *Examples of rock types from the Fraser Lake area, as seen in drill core. (a) Typical examples of coarse-grained troctolite (bottom) and fine- to medium-grained norite (top); (b) Typical example of olivine-rich melatroctolite, with banding defined by serpentine veinlets; (c) Large gneissic inclusions in troctolite containing disseminated sulphides; (d) Peculiar blue (cordierite-rich ?) inclusions in recrystallized, plagioclase-rich rock; (e) Upper sample is a medium-grained norite containing disseminated sulphides, typical of mineralized zones; lower two samples are mineralized olivine norite to troctolite; (f) Vein-like sulphide zone in coarse-grained troctolite. All drill cores are approximately 3 cm wide.*

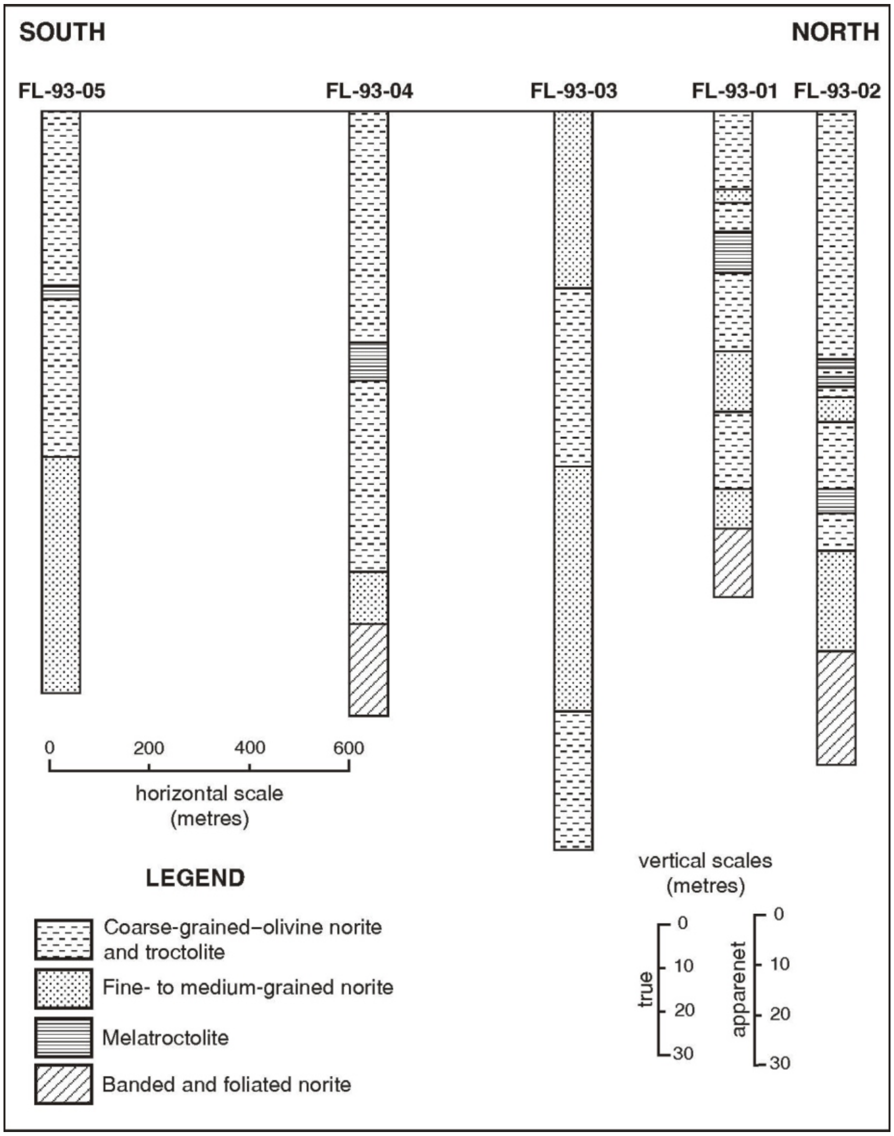

Figure 3. *Schematic illustration of the apparent depth distribution of the four principal rock types identified in drill core from the Main Showing area, and the locations of the main zones of sulphide mineralization. As all drillholes have the same inclination (60°, toward the reader), these are also true depth projections if the appropriate depth scale is used.*

tive plagioclase-rich rock containing prominent blue cordierite. The origin of this rock type is unclear, but the cordierite-rich patches could represent relict gneissic inclusions in an altered mafic rock. Alternatively, the rock could represent a larger inclusion of the country rocks (D. James, personal communication, 2003). The recrystallized interval grades into an underlying norite interval, which also contains patchy disseminated sulphides. An underlying interval of troctolite also appears to be gradational with the norite, and there is no clear boundary between the two. The lower section of troctolite includes a sulphide-rich interval (77.5 to 84 m), underlain by a fractured zone possibly representing a fault. The sulphides have a primary, interstitial, habit and are dominated by pyrrhotite, accompanied by minor chalcopyrite. Melatroctolites also occur in the lower part of this section, and resemble those in FL-93-01. Below 110 m, troctolite passes gradationally into norite, which passes abruptly into banded and foliated norite. As in FL-93-01, the lowermost section of the hole contains very little sulphide mineralization.

Hole FL-93-03

Drillhole FL-93-03 does not contain significant mineralization and is only briefly described. It contains two thick intervals of norite, and two thick intervals of troctolite, and unlike Fl-93-01 and 02, the troctolites do not contain melatroctolite intervals (Figure 3). The foliated norite unit in holes FL-93-01 and FL-93-02 is absent. Minor amounts of sulphide occur locally in the fine- to medium-grained norite, generally associated with pyroxene-rich material.

Hole FL-93-04

Drillhole FL-93-04 is dominated by troctolite (Figure 3). The upper section (0 to 58 m) shows magmatic layering and plagioclase lamination at about 50° to the core axis. It contains disseminated sulphides, which range up to 25 percent by volume toward the top of the hole. The troctolites have more varied grain size than their equivalents in the holes previously described, but are otherwise identical. A melatroctolite interval about 10 m thick occurs in the middle of the hole, and has a banded, serpentinized appearance; it also contains minor interstitial sulphide mineralization. A second interval of troctolite occurs beneath the melatroctolite unit, and this contains sulphide-rich sections from 67.4 to 95.4 m and from 107 to 115 m. The sulphides are dominantly interstitial, but there are some local vein-like sulphide zones. Fine- to coarse-grained gneissic fragments are also present in the upper mineralized interval. The troctolites grade into norite, which contains sporadic sulphide concentrations. The contact between the troctolites and the underlying foliated norites is obscured by a thin altered and bleached zone. The lowermost interval also includes a banded, pinkish, recrystallized anorthosite.

Hole FL-93-05

Drillhole Fl-93-05 comprises an upper section of troctolite, and a lower section of norite (Figure 3); the former also includes a thin (1.6 m) interval of serpentinized melatroctolite. The troctolites contain variable amounts of interstitial sulphides, as seen in other holes, and also contain small digested gneissic fragments. The norite also contains substantial sulphide mineralization, notably from 86 to 99 m. These sulphides are generally interstitial, but are locally semi-massive. Below about 100 m, the norite is sulphide-poor. Foliated norites are absent from the lower part of the hole.

Hole FL-93-06

Drillhole FL-93-06 is located in the Hook Lake area, about 4 km south of the Main Showing (Figure 2), and contains rock types that are similar to those described above from the Main Showing. The upper section (to 70 m) is dominated by coarse-grained troctolite followed by a thick interval of norite from 70 to 93.7 m. About 4 m of serpentinized melatroctolites occur beneath the norite interval, and are underlain by banded and foliated norites extending to the end of the hole. Interstitial sulphide mineralization is locally present in all units except the foliated norite.

Hole FL-93-07

Drillhole FL-93-07 is located in the Loon Lake area, about 15 km northeast of the Main Showing (Figure 2). It does not clearly resemble any of the holes described above, although it does contain similar melatroctolites. The upper section (to 78 m) consists of a coarse-grained, heterogeneous norite that resembles the coarse-grained olivine norite seen in the other holes. It exhibits increased deformation with depth, and becomes banded. It also contains numerous gneissic fragments, and minor interstitial sulphide mineralization. It is underlain by a dark, massive, serpentinized rock type that is similar to the melatroctolite seen in other holes. The lower part of the hole consists of a mixture of coarse-grained norite, olivine–norite and pyroxenite. Some of the pyroxenites contain interstitial to semimassive sulphide mineralization.

PETROLOGY

Coarse-Grained Olivine Norite and Troctolite

This unit, although referred to generally as “troctolite”, includes both olivine–norite and troctolite. Typical examples are massive, light to dark-grey rocks in which greenish olivine is prominent. The silicate fraction of the olivine–norite typically consists of plagioclase (~ 55%), orthopyroxene (~ 20%), olivine (~ 20%) and clinopyroxene (~ 5%). The accessory minerals include sulphides, oxides, biotite and green hercynitic spinel. Mineralized samples may contain up to 40 percent sulphides. Plagioclase, olivine and orthopyroxene crystallized early, but their exact order of crystallization varies. Clinopyroxene crystallized late, along with interstitial oxides and sulphides. Clinopyroxene exsolution lamellae occur in orthopyroxene and rutile inclusions are found in orthopyroxene. In sulphide-rich samples from drillhole FL-93-02, plagioclase grain boundaries are thermally eroded by sulphides, indicating late crystallization of sulphides. Some olivine–norite samples lack significant amouts of fresh olivine but do contain abundant serpentine. These are texturally similar to the fresher olivine–norites, but are generally more altered. The average plagioclase composition, determined optically, is about An_{46}.

The silicate fraction of troctolitic variants typically consists of plagioclase (~ 70%), olivine (~ 25%), and minor amounts (~ 5%) of orthopyroxene and clinopyroxene. The accessory minerals present are sulphides and oxides. Textures indicate either simultaneous crystallization of olivine and plagioclase, or crystallization of olivine before plagioclase. Orthopyroxene, clinopyroxene, sulphides and oxides all have interstitial habits, and crystallized late in the sequence. Locally, troctolites display a poikilitic texture, in which olivine grains are enclosed by plagioclase. Serpentine alteration, mainly after olivine, is present in many thin sections. The average plagioclase anorthite content, determined optically, is about An_{44}.

Other samples assigned to this unit have mineral proportions that are intermediate between those typical of olivine–norite and troctolite, and are more difficult to classify. In these coarse-grained rocks, estimates of mineral proportions based on observations in thin sections are very approximate. Thus, the distinction between “olivine–norite” and “troctolite” may be in part artificial, and these rocks probably have a continuum of compositions. The textures suggest that they are plagioclase–olivine cumulates.

Melatroctolite

The melatroctolites are dark greenish-grey to black rocks that typically have a “banded” appearance, caused by numerous serpentine veinlets. They appear superficially fine grained, but this is deceptive, as individual grains range up to 3 mm in thin section. However, they are generally finer grained than the olivine–norites and troctolites. They typically consist of variably serpentinized olivine (~ 70%), plagioclase (~ 25%) and orthopyroxene (~ 5%). The accessory minerals observed are sulphides, oxides and biotite, but sulphides are less abundant than in other units. The melatroctolite displays an orthocumulate texture, in which plagioclase and orthopyroxene are intercumulus and late, with respect to granular cumulus olivine. The crystallization sequence is olivine, followed by orthopyroxene, then plagioclase. Serpentine veinlets are ubiquitous, and some samples are strongly altered, containing only relict olivine. The average plagioclase anorthite content, determined optically, is about An_{48}.

Fine- to Medium-Grained Norite

Fine- to medium-grained norite is typically a dark-grey, homogeneous rock type. The silicate fraction typically consists of plagioclase (~ 60%), orthopyroxene (~ 30%) and clinopyroxene (~ 10%). However, the proportions of plagioclase and orthopyroxene vary significantly within some thin sections. Accessory minerals present are oxides (locally abundant), sulphides, green hercynitic spinel, and biotite. Mineralized samples may contain up to 40 percent sulphides. The typical crystallization sequence is orthopyroxene, followed by plagioclase, and then by clinopyroxene. A granoblastic texture is observed in many examples, but there is no pervasive recrystallization. Poikilitic textures are present, in which orthopyroxene grains are enclosed by plagioclase. The average plagioclase anorthite content, determined optically, is about about An_{46}.

Banded and Foliated Norite

The banded and foliated norites are mineralogically similar to fine- to medium-grained norite, but differ in texture. They consist of plagioclase (~ 65%), orthopyroxene (~ 25%), and clinopyroxene (~ 10%). Accessory minerals include oxides, biotite and hercynite. The rocks are generally strongly recrystallized, with a granoblastic texture, and plagioclase forms a mosaic of small polygonal grains. The mafic minerals occur together in linear aggregates, which define the compositional banding visible in core samples. However, the banding defined by these mafic mineral aggregates is not accompanied by a strong shape fabric or preferred orientation of individual crystals. The average plagioclase anorthite content, determined optically, is about An_{52}.

Gneissic Inclusions

All of the gneissic inclusions observed in the Main Showing area occur within the coarse-grained olivine–norite and troctolite unit. The inclusions are light to dark grey, homogenous and generally fine grained. They are composed dominantly of intergrown plagioclase and hercynite. The plagioclase is anhedral to subhedral and individual grains are typically <0.4 mm in diameter; hercynite grains have a similar size range. Plagioclase compositions could not be estimated, due to the small size of the grains. Twinning patterns, alteration and the colour of some gneissic inclusions suggest that they may also contain cordierite.

"Spinel Gabbro"

Hole FL-93-07 was not examined in detail, but its rocks have some unusual features. Its mafic rocks are rich in gneissic inclusions, which consist mostly of green spinel and fine-grained plagioclase; some also contain corundum. A mafic rock near the top of the hole consists almost entirely of plagioclase and spinel, but displays a beautiful igneous texture in which green spinel is interstitial to cumulus plagioclase. The spinel in this sample appears to have crystallized directly from the magma, rather than representing restitic material from digested inclusions. The origin of this unusual rock is uncertain, but it might have crystallized from a strongly contaminated magma, in which a high alumina content promoted formation of spinel rather than common mafic silicates.

Sulphide Mineral Assemblages

Reflected light microscopy was completed on three polished sections from drillhole FL-93-02. These include two melatroctolites, and a coarse-grained olivine–norite. Sulphides in the melatroctolites consist dominantly of pyrrhotite, with only a few percent chalcopyrite and pentlandite. The pyrrhotite and chalcopyrite are closely associated, and are disseminated throughout the rock. Network-textured sulphides in olivine–norite are similarly pyrrhotite-rich, but contain up to 5% pentlandite. Chalcopyrite is visible to the naked eye, although pentlandite grains are very small. The textures are typical of magmatic sulphides, in which both chalcopyrite and pentlandite exsolve from an original high-temperature phase termed monosulphide solid solution (MSS).

WHOLE-ROCK GEOCHEMISTRY

Overview

Samples were analyzed for major and trace elements at the Newfoundland Department of Mines and Energy (NDME) laboratory, using inductively-coupled plasma emission-spectroscopy (ICP-ES) methods. A subset of samples was analyzed for rare-earth-elements (REE) and additional trace elements by inductively-coupled plasma mass spectrometry (ICP-MS) at Memorial University (MUN). A selection of mineralized samples were analyzed for sulphur at a commercial laboratory, using the Leco furnace method. Accuracy and precision information for major and trace elements are summarized by Finch (1998) and Jenner *et al.* (1990) for the NDME and MUN laboratories, respectively. The precision of sulphur analysis is discussed by Kerr (2001). No analytical data are tabulated in this report, but complete data for all samples, including REE analyses, are presented in Dyke (2003).

The presence of sulphides distorts the geochemistry to some extent, and such effects are illustrated by using the Mg Number, i.e., molecular [MgO/(MgO + FeO)] as a variation index in scatter diagrams (Figures 4 and 5). The high FeO contents of mineralized samples result in anomalously low Mg Numbers (<0.3), and these samples are denoted by solid symbols. Other samples that have Mg Numbers below 0.5 contain minor sulphides, but the sulphides have less impact upon the geochemistry. The following discussion of variation diagrams is based mostly on "unmineralized" samples with Mg Numbers >0.4. The extended trace-element plots (Figure 6) are not influenced by the sulphide contents of samples.

Coarse-Grained Olivine Norite and Troctolite

Mg Number values for this unit range from 0.33 to 0.66, excluding sulphide-rich samples. The major elements (Na_2O + K_2O) and Al_2O_3 are negatively correlated with Mg Number, but there is little systematic variation in CaO, SiO_2 and TiO_2 (Figure 4). There is significant scatter in the data, best illustrated by CaO, for which variation mostly reflects plagioclase abundance. Patterns of this type are typical of cumulate rocks. The trends for Co, Cu and Ni are obviously controlled by sulphides at low Mg Numbers (Figure 5), but there appears to be a negative correlation between Ni, Co and Mg Number in unmineralized rocks, perhaps indicating control by olivine. Copper is generally scattered at higher Mg Numbers. The pattern for Sr resembles that seen for CaO, suggesting it is influenced mostly by plagioclase. Extended trace-element plots, normalized to primitive mantle, show variable patterns. Two samples have essentially flat patterns except for Th depletion (Figure 6). The third sample is strongly depleted in rare-earth-elements, and has positive Zr, Hf and Eu anomalies. The positive Eu anomaly indicates that the sample is rich in cumulus plagioclase. The low REE values probably in part reflect dilution by plagioclase, which excludes all REE except Eu. Patterns of this type are typical of plagioclase cumulates, including many anorthosites.

Melatroctolite

The Mg Numbers for the melatroctolites range from 0.56 to 0.73, and these samples do not contain large amounts of sulphide. These rocks have significantly higher Mg Numbers than the olivine–norite and troctolite unit, and correspondingly lower (Na_2O + K_2O), CaO, TiO_2, Al_2O_3 and SiO_2 (Figure 4). These rocks have similar Ni, Cu and Co contents to unmineralized troctolites, but lower Sr and Sc contents (Figure 5). Melatroctolites generally lie at the high-Mg end of the diffuse trends defined by the olivine–norite to troctolite unit (*see above*; Figures 4 and 5). Extended trace-element plots for the melatroctolite are very flat, and resemble those from the troctolite unit, but have smaller or nonexistent Eu anomalies (Figure 6). This indicates a relative lack of cumulus plagioclase.

Fine- to Medium-Grained Norite

Mg Numbers for the fine- to medium-grained norite range from 0.36 to 0.60, excluding two sulphide-rich samples. With the exception of TiO_2, major-element trends do not differ significantly from those defined by troctolites and melatroctolites (Figure 4). There are two subgroups defined by the TiO_2 plot, one of which corresonds with the troctolites and melatroctolites. The other has much higher TiO_2 contents (>3%). These subgroups are not readily visible in the distribution of other trace elements (Figure 5). The high-Ti samples do not show any systematic spatial grouping with respect to drillholes or depth within drillholes, and it seems likely that they record local enrichment in Fe–Ti oxides. Extended trace-element plots demonstrate that the norites are distinct from the troctolites and melatroctolites. Samples show prominent Th depletion and variable Nb, Ta, Zr, Hf and Eu enrichment. The REE patterns are slightly concave in shape and show enrichment in the heavy rare-earth-elements (HREE; i.e., Tb to Lu), which contrasts with the generally flat to negatively sloping HREE patterns shown by the troctolite and melatroctolite (Figure 6).

Banded and Foliated Norite

Mg Numbers for the banded and foliated norite range from 0.49 to 0.56, and they do not contain sulphides. Only 5 samples were analyzed, so these compositions may not be fully representative of this varied unit. The major elements (Na_2O + K_2O), CaO, TiO_2, Al_2O_3 and SiO_2 are poorly correlated with Mg Numbers (Figure 4). Elevated (Na_2O + K_2O), CaO and Al_2O_3 values suggest a higher plagioclase content compared to the other norites. A high Sr content compared to other units probably also indicates increased plagioclase contents (Figure 5). The foliated norite unit also has a lower Ni content than all other units (Figure 5). The extended trace-element pattern for the one foliated norite sample that was analyzed is distinctly different from all the other units, in that it has elevated REE contents, and depletion in Hf, Zr and Ta (Figure 6).

MINERAL GEOCHEMISTRY

Ni, Cu and Co Contents of Magmatic Sulphides

The Ni, Cu and Co data from whole-rock analyses were recalculated to estimate the metal contents of the total sulphides. This method assumes that essentially all of the sul-

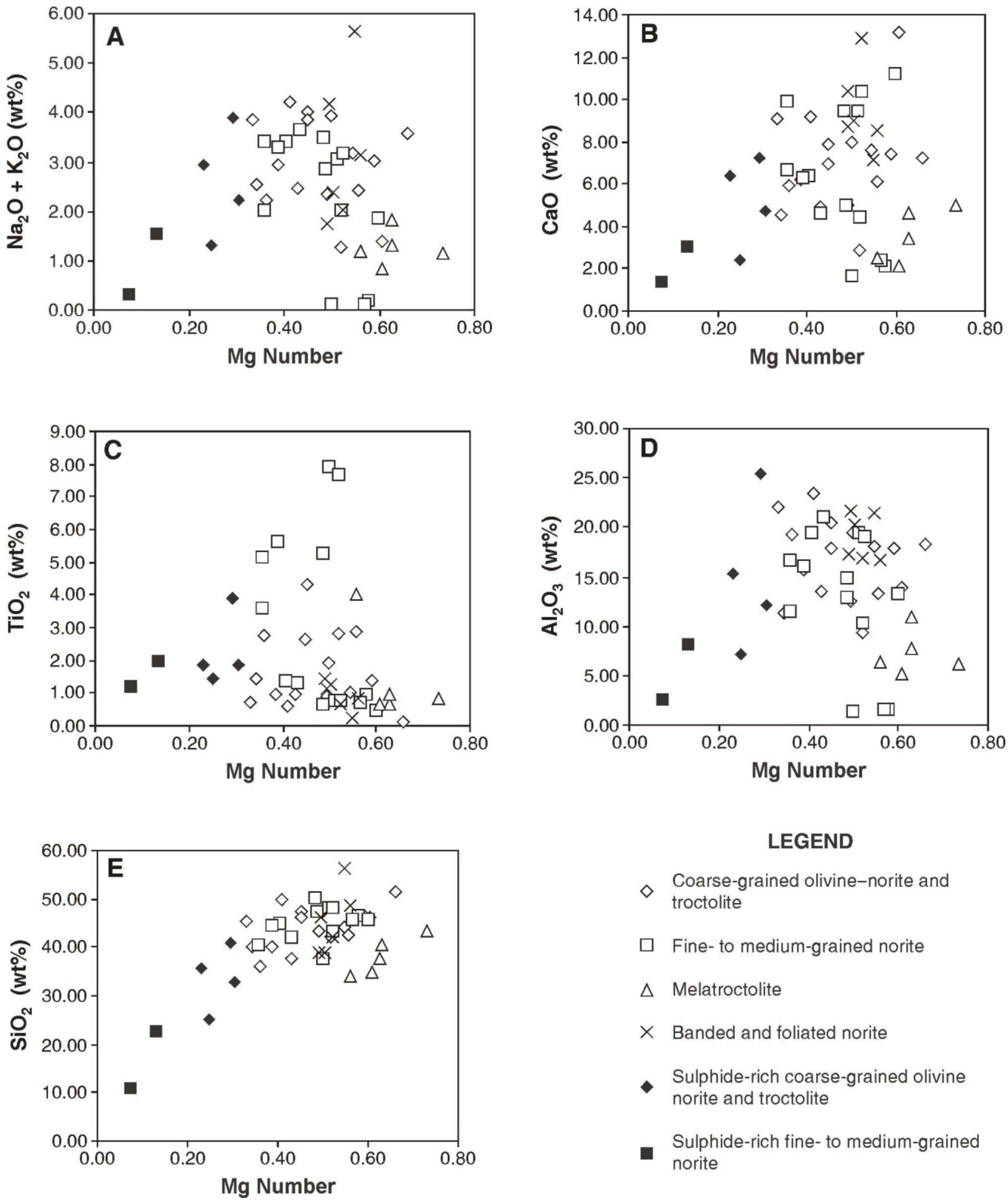

Figure 4. *Variation diagrams for selected major elements plotted against Mg Number (molecular [MgO/MgO+FeO]) for the Fraser Lake samples. (a) (Na_2O+K_2O) variation. (b) CaO variation. (c) TiO_2 variation. (d) Al_2O_3 variation. (e) SiO_2 variation.*

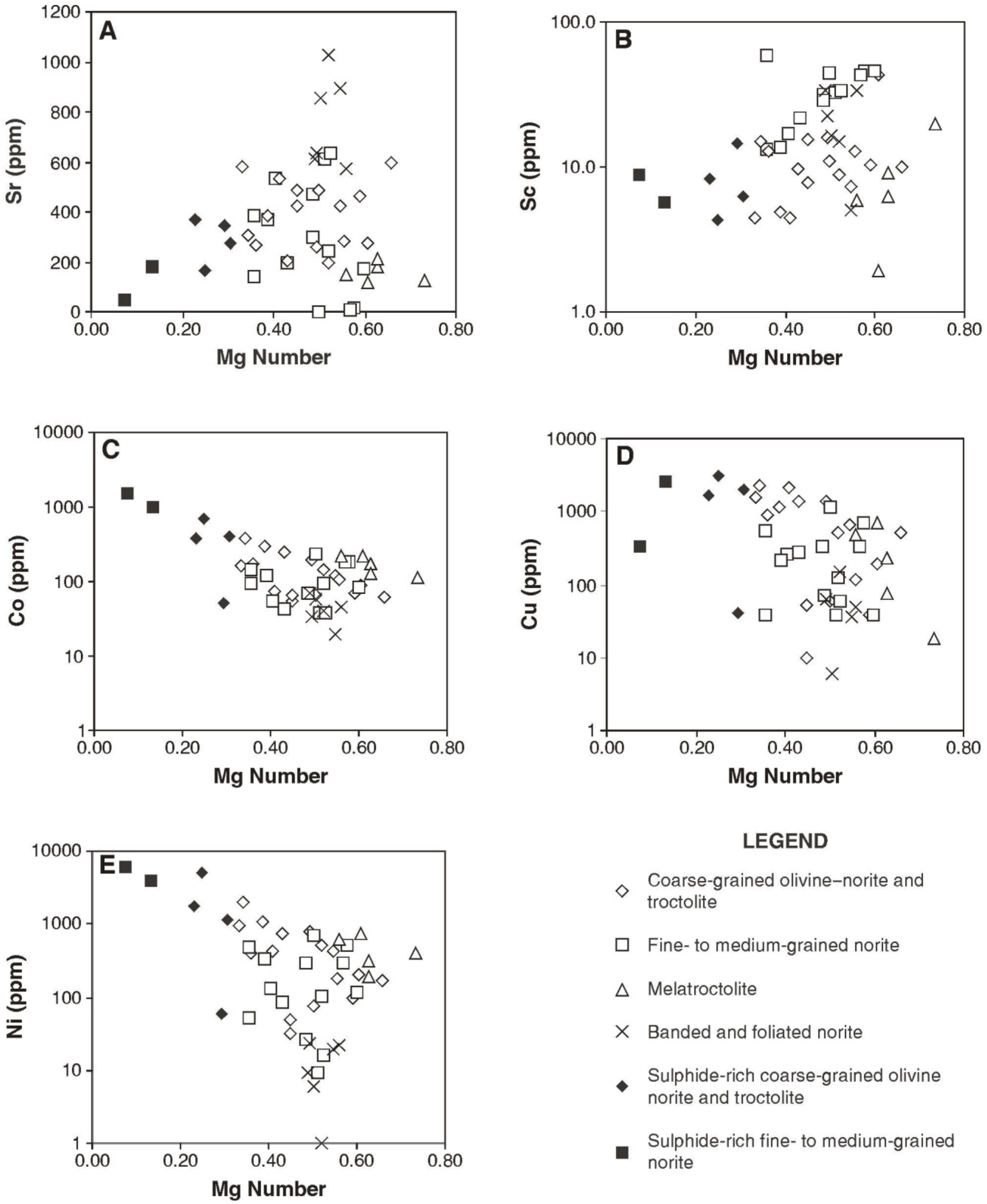

Figure 5. *Variation diagrams for trace elements plotted against Mg Number (molecular [MgO/MgO+FeO]) for the Fraser Lake samples. (a) Sr variation. (b) Sc variation. (c) Co variation. (d) Cu variation. (e) Ni variation. Y axis scales are logarithmic for all elements but Sr.*

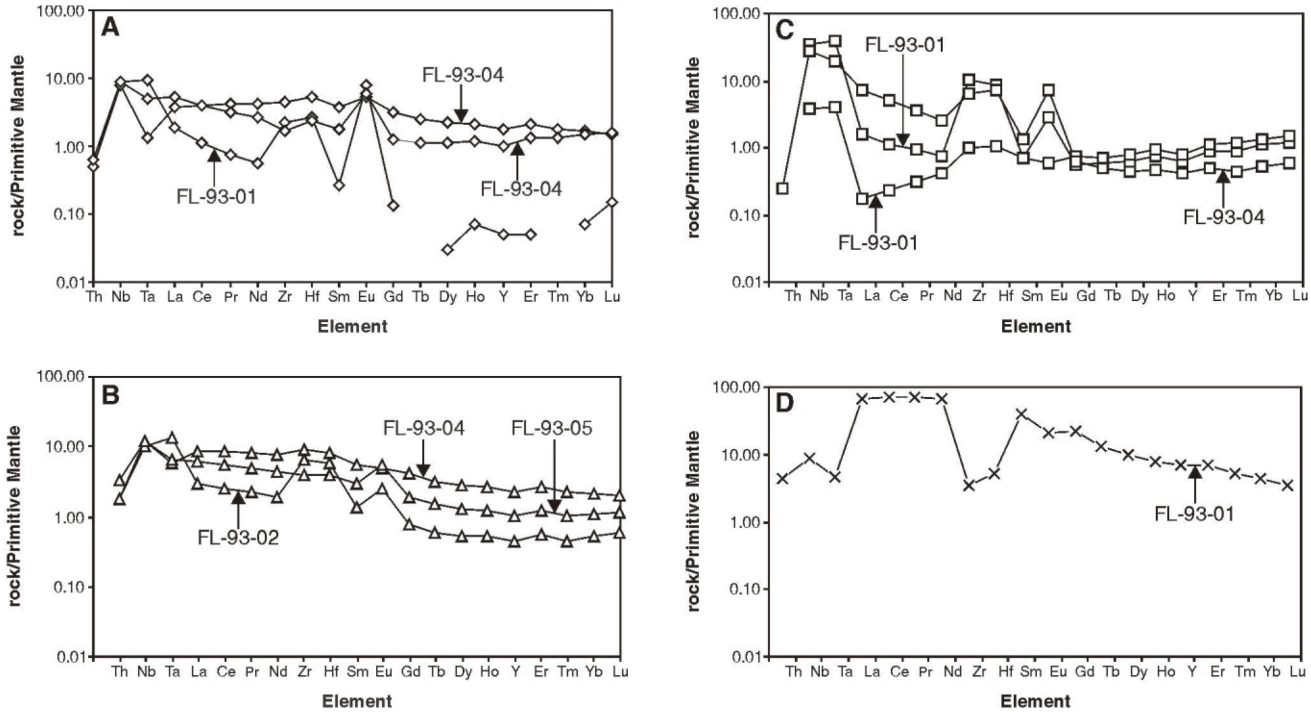

Figure 6. *Extended trace-element variation diagrams for the four principal units at Fraser Lake, normalized to primitive mantle values. (a) Coarse-grained olivine–norite and troctolite unit; (b) Melatroctolite unit; (c) Fine- to medium-grained norite unit; (d) Banded and foliated norite unit; Normalization values are listed by Dyke (2003).*

phur, Ni, Cu and Co are contained within the sulphide minerals. If the amount of sulphur is known, the percentage of sulphide can be calculated, and thus the metal contents of the original sulphide liquid. The method is widely used in the study of magmatic sulphide deposits, although methods of calculation vary slightly; the method used here is that suggested by Kerr (2001). In order to account for metals that may be present in non-sulphide minerals, a small correction was applied, assuming that sulphide-free samples contain 100 ppm each of Co, Ni and Cu, as implied by Figure 5. Results are tabulated by Dyke (2003), and illustrated in Figure 7. Sulphide Ni contents have an overall mean and standard deviation of 0.70% ± 0.24%. Values are slightly higher for the troctolite unit (0.70% Ni) than for the norite unit (0.61% Ni). Sulphides in a nearly massive sulphide sample contain 1.08% Ni. Sulphide Cu contents are more variable, with an overall mean and standard deviation of 0.98% ± 1.17%. Values are significantly higher in the troctolite unit (1.29% Cu) than in the norite unit (0.43% Cu), but this difference is partly due to a single Cu-rich sample amongst the mineralized troctolites. The massive sulphide sample has a low Cu content of 0.05%. Mean sulphide Co contents are low, at 0.16% ± 0.04, for all rock types. Ni/Co ratios (Figure 7a) vary only slightly compared to Ni/Cu, which ranges from <1 to >10 (Figure 7b). The contrasts in sulphide Ni and Cu contents between the troctolite and norite units suggest that the sulphide mineralization in each has slightly different origins, despite a general similarity in texture and mineralogy. The massive sulphide sample, which is associated with a fine- to medium-grained norite, shows high Ni/Cu consistent with other samples from this unit.

Dyke (2003) also conducted electron microprobe analyses of sulphide minerals. The compositions of pyrrhotite, chalcopyrite and pentlandite in three samples from hole FL-93-02 are closely similar, and no zoning was detected in individual grains. The Ni contents of pyrrhotite are variable, ranging from negligable to around 0.5% Ni; however, some of this variation could reflect submicroscopic pentlandite inclusions. Pentlandite grains contain 4% to 6% Co, but the Co contents of pyrrhotite and chalcopyrite are negligable.

Olivine Compositions

Electron microprobe analyses of olivines from four samples in hole FL-93-02 were completed at Memorial University of Newfoundland using a CAMECA SX-50 instrument. The methods used in data acquisition and treatment are described by Dyke (2003). Olivines were analyzed for SiO_2, FeO(t), MnO, MgO and NiO. The detection limits for major oxides are estimated at 300 ppm (0.03%), and the detection limit for NiO is estimated at 130 ppm (0.013%), or

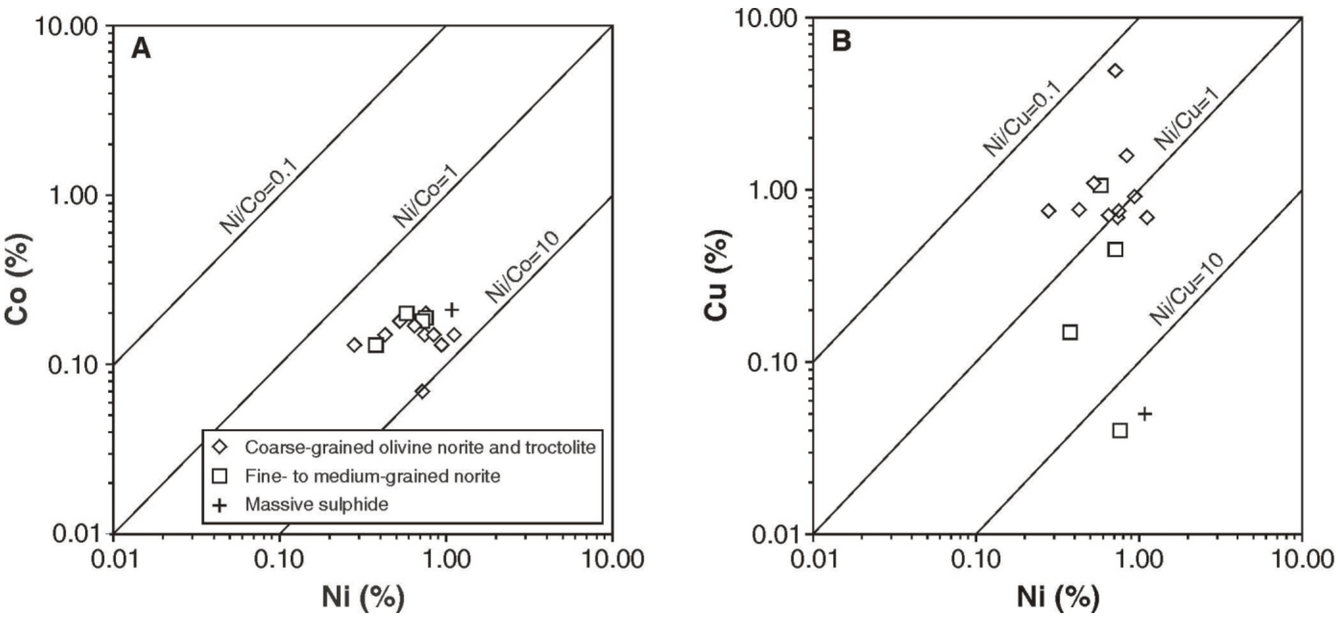

Figure 7. *Calculated sulphide metal contents for mineralized samples from the Fraser Lake prospect. (a) Co vs Ni, in sulphide; (b) Cu vs Ni, in sulphide;* See *text for calculation methods.*

roughly 100 ppm Ni. Precision for Ni-in-olivine measurements is estimated at approximately 26% at 200 ppm and approximately 11% at 500 ppm, i.e. about ± 50 ppm in the concentration range of interest. The analytical data are presented in full by Dyke (2003).

The olivine grains analysed generally do not exhibit significant variations in composition from core to rim. The unmineralized troctolite contains a more Fe-rich olivine, (58.8 to 60.9 mole percent forsterite) than its mineralized equivalent, or the mineralized melatroctolite (63.2 to 65.5 mole percent forsterite). The relationship between mole percent forsterite and Ni in olivines is illustrated in Figure 8, which is adapted from the study by Li and Naldrett (1999) on the Voisey's Bay deposit. Here, the sulphide-absent fractionation trend represents a magma that initially crystallized olivine with 3150 ppm Ni and 81 mole percent forsterite, and precipitated olivine and plagioclase in equal proportions. The sulphide-present fractionation trend represents an identical magma that exsolved sulphide liquid after about 20 percent crystallization, and then separated olivine, plagioclase and sulphide liquid at a ratio of (olivine + plagioclase)/sulphide = 50:1.

All of the Fraser Lake olivines lie below the sulphide-absent fractionation trend and in close proximity to the sulphide-present fractionation trend. This suggests that the olivines crystallized from a magma that was depleted in Ni due to its removal by sulphide liquids. The unmineralized troctolite unit has measurably higher Ni contents then its mineralized equivalent, but still lies well below the sulphide-absent fractionation trend (Figure 8). Thus, all of the troctolitic rocks examined at Fraser Lake experienced nickel depletion. Figure 8 also implies that olivines from the mineralized melatroctolite have slighly higher Ni contents than those from mineralized troctolite, but the actual difference between them is similar to the estimated uncertainty in analysis (*see above*).

The Ni contents of the olivines are surprisingly high in comparison to the low Ni contents (<1%) calculated above for the sulphide liquids. Assuming that the partition coefficient for Ni between olivine and silicate magma remains constant at about 10, this implies a partition coefficient for Ni of about 200 between sulphide liquid and silicate magma, rather than the value of 500 or more calculated for other nickeliferous intrusions in Labrador. For example, in the Pants Lake Intrusion, sulphide liquids contained up to 2% Ni, but the olivines in associated rocks have lower Ni contents than those at Fraser Lake (Kerr *et al*., 2001; Kerr, 2003). This observation is important for any future prediction of sulphide metal contents from the Ni contents of olivines or unmineralized rocks in the Michikamau Intrusion.

SUMMARY AND DISCUSSION

This study provides the first petrological and geochemical data on the Fraser Lake mineralization and its host rocks. Although, many questions remain unanswered, several key points emerge from the geological, petrological and geochemical data presented above.

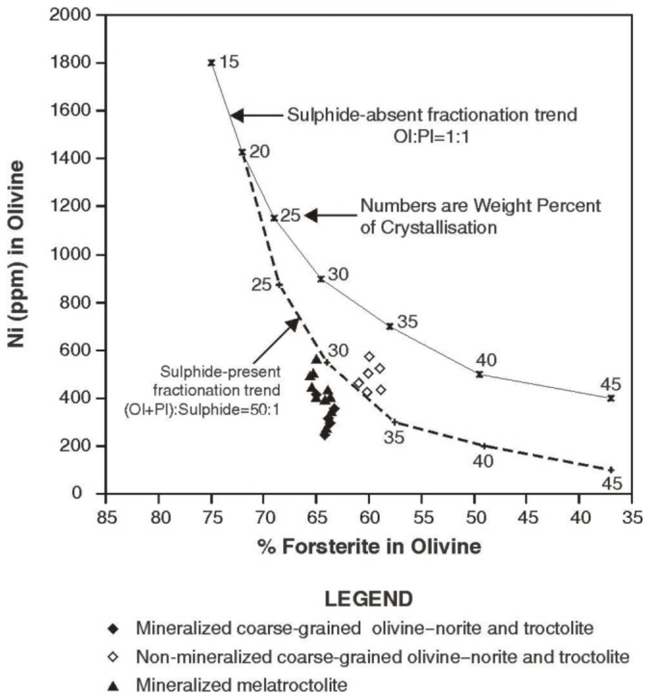

Figure 8. *Plot of Ni in olivine versus mole percent forsterite ($MgSiO_4$) in olivine for troctolite and melatroctolite at Fraser Lake. The fractionation trends in the diagram illustrate the contrasting behaviour of sulphide-free and sulphide-bearing mafic magmas, after the suggestions of Li and Naldrett (1999).* See *text for discussion.*

It is clear that none of the holes at Fraser Lake intersected the quartzofeldspathic gneisses or paragneisses that form country rocks to this part of the Michikamau Intrusion, i.e., the Sail Lake intrusive suite or the Petscapiskau Group. The lowermost unit in three of the Main Showing drillholes, and at Hook Lake, instead comprises a banded to foliated rock of broadly noritic composition, presumably part of the marginal zone of Emslie (1970). It does not appear that the outer (basal) contact of the intrusion was penetrated during drilling, and the four principal rock types identified in the drill core likely form part of the Michikamau Intrusion.

However, the relationships between these four rock types are more difficult to establish. The upper sections of holes FL-93-01 to FL-93-06 all reveal alternating units of troctolite, serpentinized melatroctolite, and norite, so three of these four rock types have a close spatial association. The melatroctolites invariably form intervals within coarse-grained troctolites, but are not observed within the fine- to medium-grained norite unit. Similarly, gneissic inclusions are fairly common in troctolites, but are absent from the norite unit. Textural similarites suggest that the melatroctolites represent olivine-rich cumulates developed within the plagioclase ± olivine cumulates that dominate the troctolite unit. Such a link is also supported by geochemical data, which show that the troctolites and melatroctolites define a common trend, and have closely similar trace-element patterns, aside from the magnitude of Eu anomalies. The relationship between these olivine-bearing units and the fine- to medium-grained norites is less clear, because the latter exhibit a rather different trace-element pattern. However, it is tentatively suggested that the norites are broadly synchronous with the troctolite–melatroctolite association, such that the two units may have coexisted in an unconsolidated state. In such a model, the norites could either represent a partially solidified earlier magma that was then disrupted by the parental magma of the troctolites and melatroctolites, or they could represent irregular later dykes and veins that disrupted partly solidified troctolitic cumulates.

Sulphide mineralization occurs in troctolites, melatroctolites, and norites, but is absent from the banded and foliated norites. This observation implies that the latter are different in origin and (or) age. The deformation and recrystallization in these rocks suggests that the foliated norite unit is older than the other units. It also has an evolved trace-element pattern that is completely different from the other units, which argues against a direct genetic relationship with them. It could perhaps represent the earliest phase of the Michikamau Intrusion, which underwent metamorphism during emplacement of the main mass of the intrusion. Foliated margins of this type have been reported around other anorthositic plutons in Labrador (Ryan, 1997).

The gneissic inclusions in the troctolite unit are mineralogically similar to gneissic inclusions observed in the Voisey's Bay Intrusion (Li and Naldrett, 1999) and the Pants Lake Intrusion (Kerr, 1999b, 2003), and were probably derived from the country rocks, as suggested by these workers. Assimilation processes are potential triggers for sulphide liquid exsolution if sufficient quantities of sulphide and/or silica are added to a crystallizing magma. There are sulphides present in the Petscapiskau Group paragneiss along the east side of the Michikamau Intrusion (Figure 2) and these may have contributed to the development of sulphide liquids in the mafic magmas.

The sulphide mineralization observed in the Fraser Lake drillholes appears to be of primary magmatic origin. The sulphide patches commonly have an interstitial habit, and are intergrown with the silicate minerals in the host rocks, most notably with late-crystallizing pyroxene and plagioclase. However, there are a few examples of vein-like sulphide zones that appear to have at least locally "intruded" or "percolated" into the surrounding rock. Interestingly, sulphides in the norite unit have higher Ni/Cu than those in the troctolite and melatroctolite, supporting the idea that these rocks have slightly different origins. The one massive sulphide interval is spatially associated with norites, and has similarly high Ni/Cu.

Microprobe analyses of olivines from the troctolitic rocks show that they are depleted in Ni relative to expected compositions for sulphide-free systems, suggesting that Ni was stripped from the parent magmas by sulphide liquids. However, the Ni contents of olivines are high compared to the low calculated Ni content of the sulphide liquids, suggesting that the partition coefficient for Ni between sulphide liquid and silicate magma was relatively low during sulphide liquid formation. The low sulphide Ni contents may in part reflect this influence. However, several other factors can influence sulphide metal contents, most notably the mass ratio of silicate to sulphide liquids, termed the R-factor by Campbell and Naldrett (1979). Low R factors also typically result in metal-poor sulphide liquids.

From an economic perspective, calculated sulphide metal contents, which rarely exceed 1% Ni, and 1% Cu, are discouraging. Such results imply that massive sulphide deposits, should they eventually be found at the Fraser Lake prospect, would likely be subeconomic. However, Fraser Lake is only one small part of a large area in which troctolitic rocks are abundant, and this study has identified potentially important regional processes such as assimilation of sulphide-bearing country rocks. Thus, the low-grade disseminated mineralization at Fraser Lake may not represent all potential environments within the Michikamau Intrusion, which is large and incompletely explored.

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