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# THE GEOLOGY AND GENESIS OF THE SILURIAN PORTAGE Ni–Cu AND ORDOVICIAN RANGE Cu–Co SHOWINGS, SOUTHWESTERN NEWFOUNDLAND (NTS MAP AREA 12A/05): PRELIMINARY RESULTS

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## ABSTRACT

*The Silurian Portage nickel–copper and Ordovician Range copper–cobalt mineralized occurrences in southwestern Newfoundland (NTS map area 12A/05) were discovered in 2009, and represent new mineralizing styles in this under-explored area of the Province.*

*The* ca. *432 Ma Portage nickel–copper occurrence consists of disseminated to interstitial pyrrhotite–chalcopyrite–pentlandite–pyrite mineralization in rocks ranging from gabbro through to troctolite, which are typically olivine-bearing. Hydrous minerals dominated by biotite or phlogopite are also part of the primary igneous mineral assemblage in most rock types. Sulphide textures suggest an orthomagmatic origin; an interpretation supported by consistent relatively light sulphur ($\delta^{34}S$ approximately 4‰) isotope signatures, suggesting that high-temperature equilibrium was attained in pyrrhotite–pyrite–chalcopyrite assemblages.*

*The Range occurrence is hosted by more than one rock type; the most common being an extremely altered and metamorphosed mafic host rock, with mineralization also hosted by metatonalite, as well as a leucocratic cordierite–quartz-bearing metamorphosed rock type of uncertain parentage. Mineralized rocks are commonly extremely altered to assemblages of chlorite and sericite, and also commonly display overprinting metamorphic assemblages of cordierite and anthophyllite, and a green-blue spinel interpreted as gahnite. Mineralization varies in habit from disseminated sulphide, to vein-like or stringer-like sulphide, and semi-massive to massive mineralization. Sulphides consist of pyrrhotite, pyrite, chalcopyrite, and minor sphalerite. There is an absence of pentlandite or any other nickel-bearing phase. Sulphur isotope signatures are relatively heavy ($\delta^{34}S$ ranging from 7–12 ‰) and differences in $\delta^{34}S$ between sulphide minerals (pyrrhotite, chalcopyrite and pyrite) suggest a lack of high-temperature isotopic equilibrium. The U–Pb zircon geochronological data from a host metatonalite indicate a maximum age of* ca. *463 Ma for mineralization at the Range occurrence. The features of mineralization at the Range occurrence are not consistent with orthomagmatic mineralization. Instead, the Range occurrence is postulated to represent a highly altered and metamorphosed volcanogenic massive sulphide style of mineralization. Further study is required to enhance the interpretation.*

## INTRODUCTION

### PROJECT DESCRIPTION

The Portage nickel–copper (Ni–Cu) and Range copper–cobalt (Cu–Co) mineral occurrences are located in the Notre Dame Subzone of the Dunnage Zone, southwestern Newfoundland, in the Puddle Pond map area (NTS 12A/05; Figure 1). The occurrences are in close spatial proximity (*e.g*., 3–4 km) but are associated with rocks of different ages, and have different styles of mineralization. The Portage occurrence is hosted by mafic intrusive rocks of the *ca*. 432 Ma Puddle Pond complex (van Staal *et al*., 2005; Lissenberg *et al*., 2006) and represents disseminated orthomagmatic sulphide mineralization. The Range Cu–Co occurrence is hosted by older rocks of the *ca*. 463 Ma Southwest Brook complex (*herein*; van Staal *et al*., 2005), dominated by foliated tonalite to granodiorite, and minor metagabbro, metabasalt and mafic enclaves. The mineralization at the Range occurrence is hosted by a variety of rock types and varies in texture from disseminated interstitial sulphide, to 'vein-like' or 'stringer-like' or massive sulphide. The host rocks to the Range occurrence have undergone intense hydrothermal alteration as well as subsequent metamorphism.

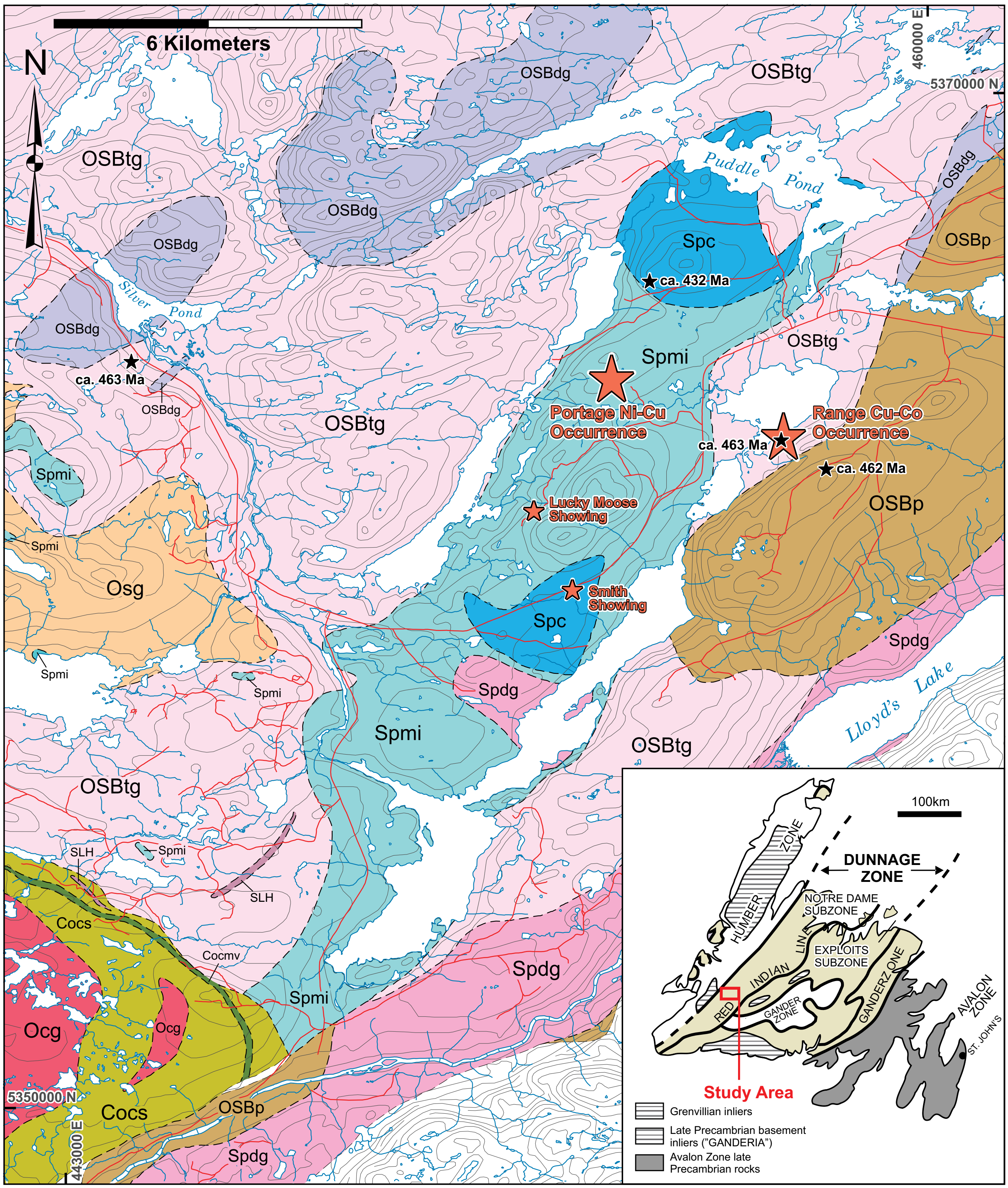



**Figure 1.** *Simplified geological map of the area around the Portage and Range mineral occurrences (modified after van Staal* et al., *2005). For the purposes of this simplified map all contacts are assumed. Only mineral occurrences noted in text are portrayed. Inset regional map of Newfoundland shows the project location. Legend from van Staal* et al. *(2005).*

# LEGEND

## SILURIAN

LAKE OF THE HILLS INTRUSIVE SUITE (*ca.* 430 Ma)

| | |
|---|---|
| SLH | Undivided, pink to white granitic to granodioritic rocks |

PUDDLE POND COMPLEX (*ca.* 431 Ma)

| | |
|---|---|
| Spgd | Unfoliated to foliated, medium- to coarse-grained, orange to white biotite-hornblende tonalite to biotite granite. Biotite is often replaced by chlorite. Contains locally megacrysts of K-feldspar |
| Spmi | Foliated to unfoliated, dark grey to green, mainly medium- to coarse-grained, partly amphibolitized equigranular to plagioclase-phyric hornblende diorite, gabbro, or diabase. Gabbro locally contains layers of pyroxenite and pegmatitic pods. Cut by pink felsic dykes of the Lake of the Hills Intrusive Suite (SLH). Mafic rocks commonly have mixed arc to non-arc like compositions |
| Spc | Foliated to unfoliated, mainly layered cumulate sequence of anorthosite, troctolite, olivine norite, norite, gabbronorite, olivine gabbro, and gabbro, with minor pyroxenite. Minor alteration to epidote, hornblende and/or actinolite and chlorite |

## ORDOVICIAN - SILURIAN

| | |
|---|---|
| OSg | Foliated to unfoliated biotite granodiorite and/or granite, locally with K-feldspar megacrysts. May in part be equivalent to Spgd. Some granites contain muscovite. Also includes biotite-muscovite granite, which may in part be equivalent to the Lake of the Hills Intrusive Complex |

## ORDOVICIAN

SOUTHWEST BROOK COMPLEX (*ca.* 461 Ma)

| | |
|---|---|
| OSBp | PORTAGE LAKE GABBRO. Foliated to unfoliated, medium- to coarse-grained, two feldspar porphyritic hornblende monzogabbro to monzonite. Characteristically contains abundant lath-shaped, feldspar phenocrysts with variable degrees of hematization and epidote alteration |
| OSBtg | Generally well-foliated, white, medium- to coarse-grained, mainly biotite – and/or hornblende-bearing, tonalite and/or granodiorite. Includes minor quartz-diorite. Commonly contains abundant mafic enclaves or schollen of diorite, amphibolite, and hornblendite. Mafic enclaves or schollen are locally so abundant that the rock appears agmatitic. The mafic enclaves/schollen in part probably represent relict co-mingling structures largely destroyed by continuous veining by tonalite. Commonly displays epidote alteration. Locally include crosscutting pink muscovite-bearing aplite granite and pegmatite dykes of the Lake of the Hills suite (SLH) and gabbro or diorite of the Puddle Pond Complex (SPMI) |
| OSBdg | Generally well-foliated, grey, fine- to medium-grained, biotite bearing, hornblende diorite, hornblende gabbro, amphibolite, and rare hornblendite. Locally contains abundant tonalite dykes and veins (OSBtg) |

## NEOPROTEROZOIC TO MIDDLE ORDOVICIAN

CORMACKS LAKE COMPLEX (> 455 Ma)

| | |
|---|---|
| OCg | Mainly well-banded granodiorite to tonalite orthogneiss (*ca.* 483 Ma) |
| COcmv | Strongly foliated; locally pillowed or layered mafic volcanic rock. Probably also includes minor diabase and gabbro. Generally intensely metamorphosed into garnet and/or clinopyroxene-bearing amphibolite. Some mafic rocks contain layers rich in gedrite, which suggests that some volcanic rocks experienced pre-metamorphic hydrothermal alteration |
| COcs | Strongly foliated, generally strongly migmatitic sillimanite-garnet schist commonly interlayered with abundant gedrite +/- cordierite rock, minor metapsammite, and rare calcsilicate. Sequence in part has a felsic volcanic protolith dated at circa 489 Ma. Locally interlayered with COcmv |

This preliminary account presents field and petrographic observations, sulphur isotope analyses and a U–Pb zircon date. The objective is to describe the mineralizing styles associated with these two newly discovered mineral occurrences.

**PREVIOUS WORK AND EXPLORATION HISTORY**

The earliest regional mapping in the area was conducted by Riley (1957), who mapped the west side of the Red Indian Lake map sheet at a scale of 1 inch to 4 miles and identified gabbro and diabase in the vicinity of the Portage occurrence, and granite, quartz–feldspar porphyry and granodiorite in the vicinity of the Range occurrence. This was followed by regional mapping programs by Dunning and Herd (1979), and 1:50 000 mapping by van Berkel and Currie (1988) and van Staal *et al*. (2005). A regional lake-sediment geochemistry survey by the Provincial Geological Survey in the 1980s (Davenport *et al*., 1990), indicated anomalous nickel in lake sediments in the vicinity of the Silurian gabbroic rocks that host the Portage occurrence. Whalen *et al*. (2006) and Lissenberg *et al.* (2006) investigated the tectonomagmatic processes and petrogenesis of the Silurian igneous rocks in this part of the Notre Dame Subzone. The Portage and Range occurrences were the focus of a B.Sc. (Hons) thesis by Bath (2010) who completed petrographic and lithogeochemical studies on a small sample suite collected from mineralized drillcore.

The study area saw only limited systematic exploration prior to 2008. Prospecting by Smith (2001) in the Silurian Puddle Pond (gabbroic) complex located nickel–copper mineralization, where grab samples from the Smith showing (Figure 1) returned up to 1% Cu and 0.3% Ni. Subsequent prospecting (Quinlan, 2006) discovered the Lucky Moose showing (Figure 1) in the same host rocks, with grab samples returning up to 0.28% Ni and 0.36% Cu.

Follow-up exploration of several regional airborne-electromagnetic anomalies by Buchans Minerals Corporation (formerly Royal Roads Corporation) in 2009, led to the discovery of the Portage occurrence in the Silurian Puddle Pond complex, and the Range occurrence in the 463 Ma Southwest Brook complex (Figure 1). Grab samples of mineralized gabbroic rocks at the Portage occurrence returned assays up to 2.70% Ni, 0.58% Cu and 0.25% Co and channel sampling returned 0.99% Ni, 0.22% Cu and 0.05% Co over 3 m (Royal Roads Corporation, Press Release, October 28, 2009). Grab samples from the Range occurrence returned values up to 1.77% copper (Royal Roads Corporation, Press Release, September 14, 2009). Subsequent diamond drilling at the two occurrences throughout 2009–2011 met with mixed success. Early drilling at the Portage occurrence successfully intersected mineralized gabbro in three of four diamond-drill holes, with the best assays returning 1.36% Ni, 0.36% Cu and 0.039% Co over 1-m-core length (Royal Roads Corporation, Press Release, November 18, 2009). However, diamond drilling (2011) along strike from the occurrence returned much lower grades, suggesting a limited strike extent. Diamond drilling at the Range occurrence provided good initial results. The mineralized horizon gave average assays of 0.39% Cu and 0.032% Co over 29.2 m, with negligible nickel assays, in diamond-drill hole LR-09-02; but three other drillholes failed to intersect it (Royal Roads Corporation, Press Release, November 3, 2009). Interpretation of the orientation of the target zone was revised, and additional diamond drilling in 2011 successfully intersected and extended the mineralized horizon over a minimum strike length of 200 m having similar grades and widths as those from the 2009 drilling (Buchans Minerals Corporation, Press Release, April 20, 2011). The extent of mineralization in the Range occurrence remains open to the east and west.

## REGIONAL OVERVIEW

The Portage and Range mineral occurrences are located within the Notre Dame Subzone of the Dunnage Zone of the Newfoundland Appalachians (Figure 1). The rocks in this area formed along the peri-Laurentian margin of the ancient Iapetian ocean (Williams, 1995), and are predominantly composed of rocks of the continental Notre Dame arc (Whalen *et al*., 2006), remnant ophiolitic rocks, and Ordovician–Silurian plutonic rocks (*e.g*., Currie and van Berkel, 1989; Lissenberg *et al.*, 2006; Whalen *et al.*, 2006; van Staal *et al.*, 2007). The Notre Dame arc is postulated to have formed on a rifted portion of the Laurentian margin, referred to as the Dashwoods microcontinent (*e.g.*,Whalen *et al.*, 1997; Waldron and van Staal, 2001), which was separated from the remainder of the Laurentian margin by the Humber seaway. The closure of the Humber seaway, *via* east-directed subduction beneath the Dashwoods microcontinent, led to Early Ordovician arc magmatism within the Notre Dame arc. The subsequent collision of the Dashwoods microcontinent with the Laurentian margin led to arc shut-off (*e.g*., van Staal *et al*., 2007), and the subsequent progression of west-directed subduction beneath the Laurentian margin (Lissenberg *et al*., 2005; van Staal *et al*., 2007). The latter west-directed subduction was responsible for several episodes of arc development and plutonism, including voluminous tonalite plutonism *ca.* 466–459 Ma, synchronous with the Range occurrence host rocks and mineralizing event (*see* below), as well as ophiolite accretion to the Laurentian margin (*e.g*., Lissenberg *et al*., 2006; Whalen *et al*., 2006). Closure of the Iapetus Ocean culminated during the Cardoc (*ca*. 455–450 Ma; Whalen *et al*., 2006), which resulted in the juxtaposition of the peri-Laurentian rocks with those of peri-Gondwanan affinity (*e.g*., Victoria arc, Zagorevski *et al*.,

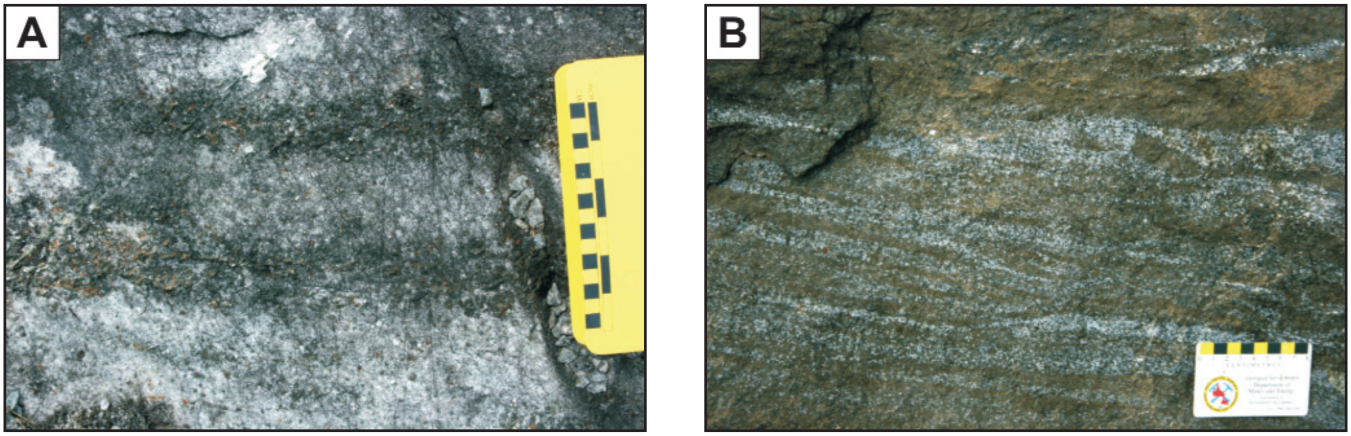



**Plate 1**. *A) Cumulate layering defined by layered olivine and plagioclase in an olivine gabbro, northern portion of the Puddle Pond complex. B) Cumulate layering defined by layered olivine and plagioclase in troctolite, central portion of the Puddle Pond complex in the vicinity of the Smith showing.*

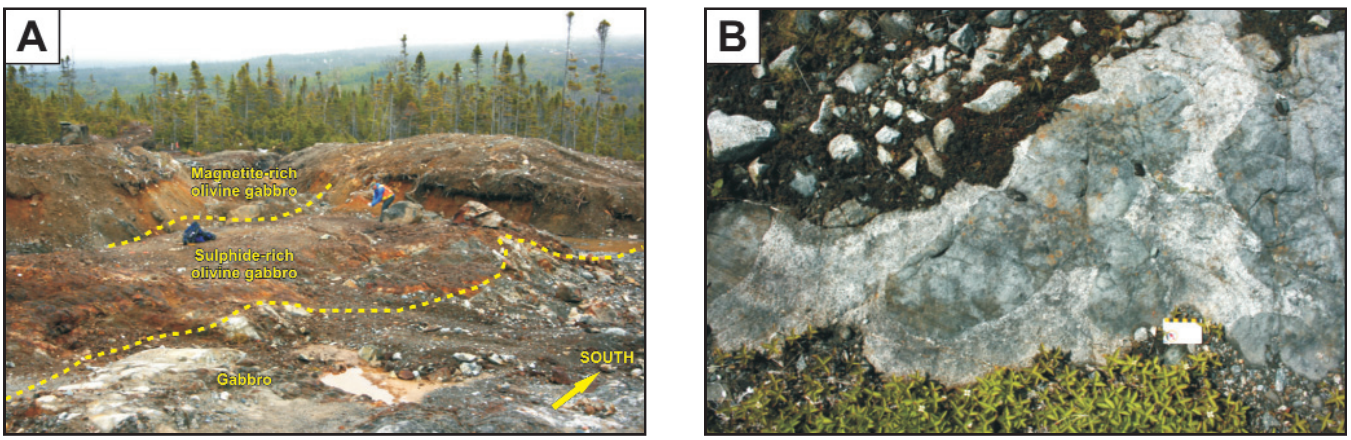



**Plate 2.** *A) Main trenched and stripped area of the Portage occurrence illustrating co-intrusive magma pulses. B) Multiple magma phases indicated by co-mingling of melanocratic and leucocratic gabbro.*

2007). Continued accretion of outboard terrains (*e.g.*, Ganderia along the Dog Bay Line) *via* west-directed subduction coincided with the waning stages of the Notre Dame arc; eventually culminating with widespread Silurian magmatism that is synchronous with the intrusion of the host rocks of the Portage occurrence and the mineralizing event. Some of the magmatism, including portions of that which produced the Puddle Pond complex, which hosts the Portage occurrence, are characterized by non-arc lithogeochemical signatures, leading to the postulation that the magmatism is related to primitive upwelling asthenospheric melts generated through the process of slab break-off (*e.g.*, Whalen *et al.*, 2006). Lissenberg *et al.* (2006) conducted petrographical studies of Silurian mafic intrusions, including the host rocks to the Portage occurrence, which in conjunction with the results of Bath (2010), are used to complement the work from this study in the descriptions below.

## PORTAGE Ni–Cu OCCURRENCE

### LOCAL GEOLOGY AND MINERALIZATION

The Portage Ni–Cu mineral occurrence is hosted by the *ca*. 432 Ma Puddle Pond complex that outcrops over an area of approximately 15 by 3 km (van Staal *et al*., 2005). The complex, although dominated by gabbro, encompasses a range of rock types that includes quartz diorite, hornblende gabbro, olivine gabbro, olivine gabbronorite, troctolite, and minor wehrlite. Most rock types contain igneous biotite or phlogopite. Although cumulate layering is locally observed in outcrop in the northern and central portions of the complex (Plate 1A ,B), the rocks are more commonly heterogeneous, with multiple magmatic phases (Plate 2A, B). Pegmatitic segregations are common (Plate 3), with individual plagioclase crystals locally reaching up to 10 cm in length.

**Plate 3.** *Pegmatitic pod within gabbro in vicinity of the Portage occurrence.*

Rocks are generally fresh and commonly lack a strong penetrative fabric; although local weak foliations are observed.

Mineralization at the main Portage occurrence is hosted by hornblende gabbro, gabbro, and olivine gabbro and troctolite. Sulphides are dominated by pyrrhotite, with lesser chalcopyrite, pentlandite and pyrite. Oxides consist of magnetite and ilmenite. Visual estimation of sulphide content ranges from approximately 2–5% for disseminated mineralization, up to 10–20% for highly mineralized samples (Plate 4A, B). At the main trench area, in addition to the disseminated sulphide, there is also a 10–15-cm-thick semi-massive sulphide band, which returned the highest assays. Grab samples returned up to 5.30% Cu, 1.13% Ni, and 0.04% Co, and a channel sample returned 2.18% Ni, 0.19% Cu, and 0.11% Co over 1 m (Royal Roads Corporation, Press Release, October 28, 2009).

Two diamond-drill holes (LR-09-03 and LR-09-04) were logged as part of this project. Contact relationships between rock types range from gradational to abrupt and sharp, with no obvious chilling effects observed. Most intrusions appear to have occurred synchronously; however, local examples of crosscutting fine-grained mafic dykes (Plate 5A), and the presence of fine-grained dark gabbroic xenoliths within medium-grained leucogabbro (Plate 5B) suggest multiple pulses of magma over time.

Textural relationships between the sulphides and silicates vary. Commonly 2–10% disseminated sulphide patches occur interstitially amongst silicates in gabbro, norite and olivine gabbro (Plate 4A). Sulphide patches commonly partially surround or invade along plagioclase laths, essentially resulting in the detachment, and incorporation, of the silicate minerals in the sulphide. In rocks with higher proportions of sulphide mineralization, the sulphides commonly form larger (5–10 cm) patches (Plate 4B), and commonly contain silicate inclusions. Locally, such patches form net-textured sulphide.

## PETROLOGY

Primary igneous minerals in all rock types at the Portage occurrence are well-preserved and fresh (Plate 6A–D). The mineral assemblage consists of medium-grained plagioclase, pyroxene (ortho- and clinopyroxene), hornblende, and olivine. Crystals are subhedral to euhedral except for olivine, which is anhedral. Other minerals in most rock types include igneous amphibole, biotite, a bright red mica (tentatively identified as phlogopite), and quartz. Gabbroic rocks commonly display an ophitic to subophitic texture with pyroxene enclosing plagioclase laths (*e.g.*, Plate 6B), whereas other rock types commonly display cumulate textures with olivine, pyroxene and plagioclase forming cumulate mineral phases.

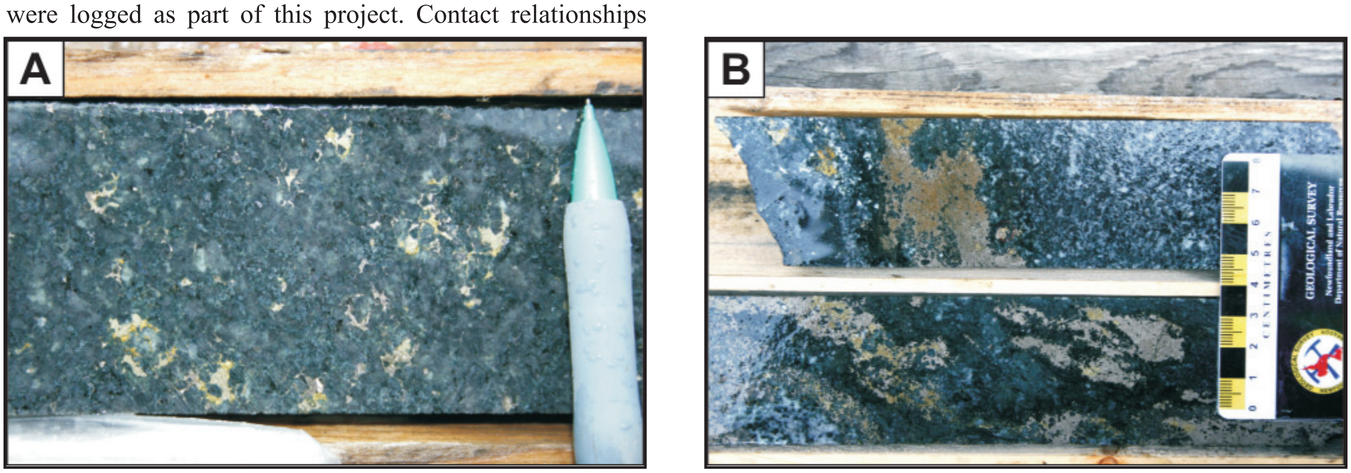



**Plate 4.** *A) Disseminated and interstitial magmatic sulphide dominated by pyrrhotite and lesser chalcopyrite and pentlandite in gabbroic host (DDH LR-09-05 @ 7 m). B) Larger patches of sulphide dominated by pyrrhotite and lesser chalcopyrite and pentlandite in gabbroic host (DDH LR-09-03 @ 23.5 m).*

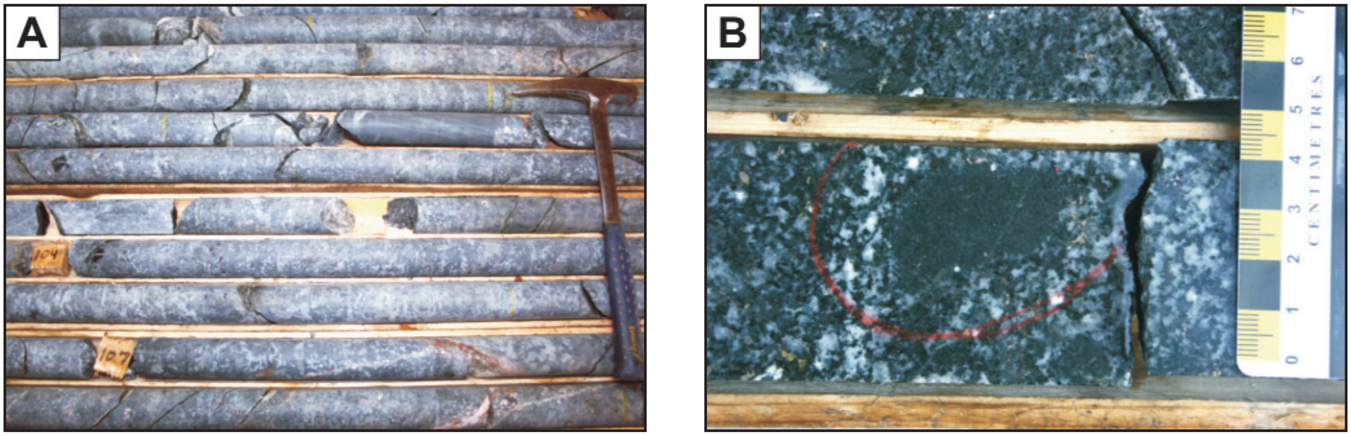



**Plate 5.** *A) Fine-grained mafic dyke crosscutting coarse-grained ophitic gabbro (DDH LR-09-03 @ 100 m). B) Fine-grained gabbro xenolith in a medium-grained gabbro (DDH LR-09-03 @ 21 m).*

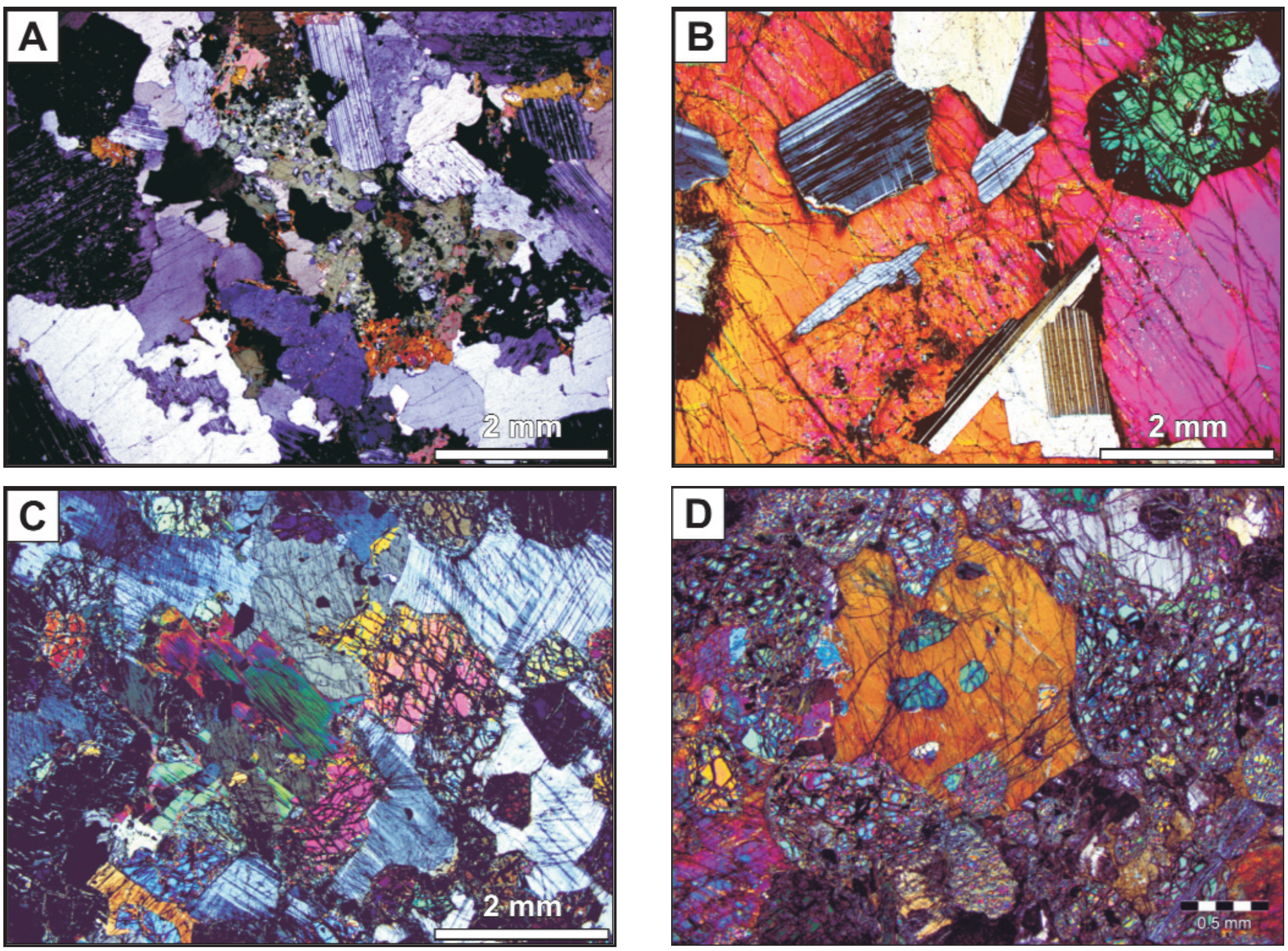



**Plate 6.** *Relatively unaltered minerals in rock types at the Portage occurrence. A) Hornblende gabbro (DDH LR-09-03 @ 39 m). B) Olivine gabbro (DDH LR-09-03 @ 102.5 m). C) Olivine gabbro to troctolite (main stripped area at the Portage occurrence). D) Wehrlite (main stripped area at the Portage occurrence).*

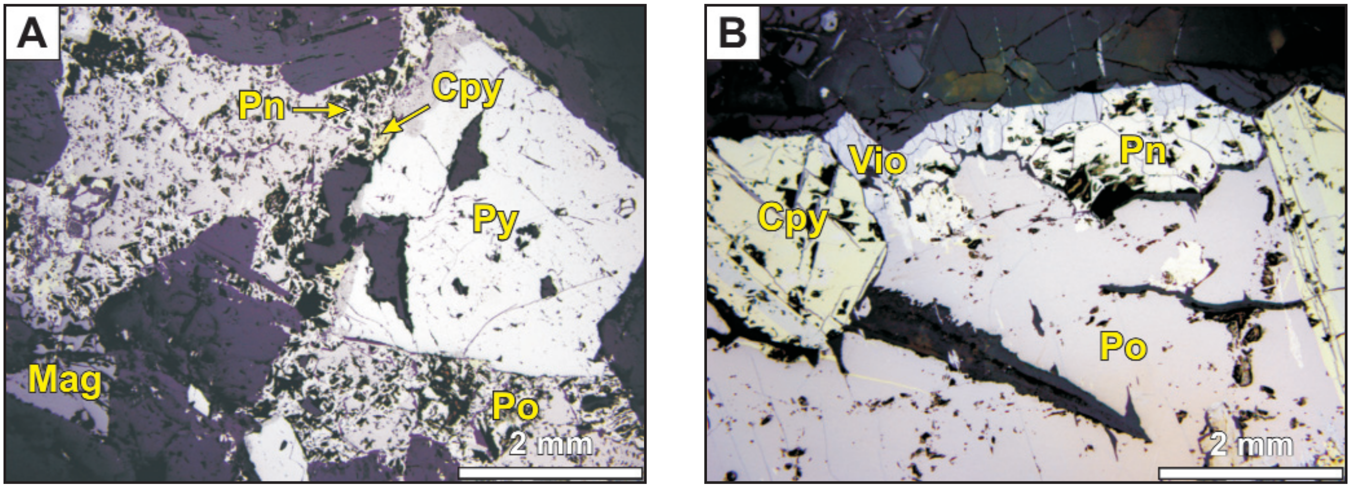



**Plate 7.** *A) Interstitial magmatic sulphide-oxide patch with pyrite (Py), pyrrhotite (Po), pentlandite (Pn), chalcopyrite (Cpy) and magnetite (Mag) (DDH LR-09-04 @ 21.5 m). B) Close-up of magmatic sulphide patch with pyrrhotite (Po), chalcopyrite (Cpy) along pyrrhotite rims, pentlandite (Pn) blebs and exsolutions from Po, and secondary violarite (Vio) after pentlandite (main stripped area at the Portage occurrence).*

Minor amphibole (dominated by actinolite–tremolite–hornblende assemblages), epidote, and chlorite occur as alteration products after primary pyroxene, whereas olivine is commonly partly altered to iddingsite and serpentine. Plagioclase, although typically relatively fresh, commonly exhibits minor sericite alteration.

Sulphide textures indicate early crystallization of pyrite that has subsequently been partially resorbed by pyrrhotite. Chalcopyrite occurs along the rims of relict pyrite crystals and along fractures within pyrrhotite, and pentlandite occurs as fracture fillings and exsolutions from pyrrhotite (Plate 7A, B). Surface samples from exposed trenches commonly contain secondary violarite replacing pentlandite (Plate 7B).

### SULPHUR ISOTOPE ANALYSIS

Sulphur isotopic analysis was carried out on one sample from the Portage zone. Analysis was done *via* Secondary Ion Mass Spectrometry (SIMS) at the Creait Research Facility at Memorial University, and the laboratory website provides particulars on instrumentation and capabilities (http://www.mun.ca/research/ocp/creait/maf/SIMS.php).

The sample chosen for sulphur isotope analysis (JHC-11-034) was from 15 m depth in DDH LR-09-03 and is a mineralized hornblende gabbro. Five SIMS spot analysis of pyrite, five analysis of chalcopyrite, and six analysis of pyrrhotite were conducted (Table 1). Results, reported in $\delta^{34}$S per mil, from the pyrite analysis range from +3.7‰ to +4.4‰ having an average value of +4.0‰. Chalcopyrite results range from +3.8‰ to +4.3‰ having an average value of +4.1‰. Pyrrhotite results range from +3.9‰ to +4.9‰ having an average value of 4.5‰. These results are all within 1 σ analytical uncertainty.

## RANGE Cu–Co OCCURRENCE

### LOCAL GEOLOGY AND MINERALIZATION

The Range Cu–Co occurrence is hosted by the *ca.* 463 Ma Southwest Brook complex; 3 km east of the Portage occurrence (Figure 1). An age of 463 Ma was obtained by van Staal *et al*. (2005) for rocks of the complex from a sample located in the vicinity of Silver Pond (Figure 1). An identical age of 463 ± 4 Ma was obtained from altered and mineralized metatonalite as part of this project (*see* below). The Southwest Brook complex includes a diverse and complex range of rock types, exemplified by van Staal *et al's*. (2005) lengthy description of the host unit:

> "OSBTG: Generally well foliated, white, medium- to coarse-grained, mainly biotite – and/or hornblende-bearing, tonalite and/or granodiorite. Includes minor quartz-diorite. Commonly contains abundant mafic enclaves or schollen of diorite, amphibolite, and hornblendite. Mafic enclaves or schollen are locally so abundant that the rock appears agmatitic. The mafic enclaves/schollen in part probably represents relict co-mingling structures largely destroyed by continuous veining by tonalite. Commonly displays epidote alteration. Locally include crosscutting pink muscovite-bearing aplite granite and pegmatite dykes of the Lake of the Hills suite (SLH) and gabbro or diorite of the Puddle Pond Complex (SPMI)".

The geology in the vicinity of the Range occurrence is very complex and is made more so by hydrothermal alteration and subsequent metamorphic overprinting. The outcrop density in the vicinity of the occurrence is sparse, but

**Table 1.** Summary of sulphur isotopic data ($\delta^{34}S$) from the Portage and Range occurrences

| | ***JHC-11-034 : Portage*** | | ***JHC-11-007c : Range*** | | ***JHC-11-031 : Range*** | |
|---|---|---|---|---|---|---|
| | **$\delta^{34}$S** | **±1δ** | **$\delta^{34}$S** | **±1δ** | **$\delta^{34}$S** | **±1δ** |
| ***Pyrite*** | per mil | per mil | per mil | per mil | per mil | per mil |
| | 4.0 | 0.3 | 11.7 | 0.2 | 9.6 | 0.2 |
| | 4.4 | 0.4 | 10.7 | 0.2 | 9.6 | 0.2 |
| | 4.0 | 0.2 | 10.2 | 0.2 | 8.5 | 0.2 |
| | 3.7 | 0.3 | | | | |
| | 4.1 | 0.3 | | | | |
| **Average** | **4.0** | | **10.9** | | **9.2** | |
| ***Chalcopyrite*** | per mil | per mil | per mil | per mil | per mil | per mil |
| | 3.8 | 0.3 | 11.4 | 0.3 | 9.3 | 0.2 |
| | 4.3 | 0.2 | 12.8 | 0.2 | 9.2 | 0.2 |
| | 4.0 | 0.2 | 10.9 | 0.2 | 9.1 | 0.2 |
| | 4.3 | 0.2 | | | | |
| | 3.9 | 0.3 | | | | |
| **Average** | **4.1** | | **11.7** | | **9.2** | |
| ***Pyrrhotite*** | per mil | per mil | per mil | per mil | per mil | per mil |
| | 3.9 | 0.2 | 9.0 | 0.2 | 8.1 | 0.2 |
| | 4.5 | 0.2 | 9.3 | 0.2 | 7.7 | 0.3 |
| | 4.2 | 0.2 | | | 7.3 | 0.2 |
| | 4.9 | 0.2 | | | | |
| | 4.5 | 0.2 | | | | |
| | 4.8 | 0.2 | | | | |
| **Average** | **4.5** | | **9.2** | | **7.7** | |

rock types include variably altered and metamorphosed biotite tonalite, granodiorite, hornblende gabbro, gabbro, and basalt (Plate 8 A–D). Most rocks in the vicinity of the Range occurrence are strongly foliated, with the dominant foliation trending east–west and dipping moderately to the south.

Mineralization at the Range occurrence is hosted by variably metamorphosed and altered rock types ranging from a leucocratic, cordierite–quartz-bearing rock (Plate 9A, B, C, H; *see* also Bath, 2010), to an altered mafic (gabbro and/or basalt) rock (Plate 9D–F), or metatonalite (Plate 9C). Due to the extreme hydrothermal alteration and subsequent metamorphism, it is difficult to identify the exact protolith in all cases, especially for the cordierite–quartz-bearing rocks and metatonalite. Sulphides are dominated by pyrrhotite, lesser chalcopyrite and pyrite, and trace sphalerite. Pentlandite is absent. Sulphide content varies from a few percent to massive sulphide.

Four diamond-drill holes (LR-09-02, LR-11-015, LR-11-016, and LR-11-017) were logged. The rock types observed in drillcore were all foliated and included biotite tonalite, granodiorite, diabase, hornblende gabbro, metagabbro, and metabasalt (Plate 8A–D).

Contact relationships between these rock types vary from intrusive contacts for tonalite and metagabbro, to dominantly tectonic and structural contacts for the host units to the mineralization. The mineralized horizons commonly display either faulted contacts or contacts that are marked by late diabase dykes. Inclusions of xenolithic (?) gneissic fragments are locally observed in the mineralized horizons (Plate 10A, B).

Textural relationships between sulphide and silicates vary dramatically throughout the mineralized horizon. Disseminated sulphides locally occur with occasional examples of ovoid-shaped sulphide (Plate 9C). Interstitial and net-textured sulphides are common (Plate 9A, B, E, F, G), but vein-like or stringer-style sulphides also locally occur (Plate 9H). Where sulphide content increases, semi-massive to massive sulphide dominates (Plate 9C, D). As with the Portage occurrence, pyrite appears as an early sulphide phase that was subsequently replaced by pyrrhotite and chalcopyrite.

## PETROLOGY

Primary mineralogy is variably preserved in rock types at the Range occurrence, with the best preservation in biotite–tonalite, granodiorite, and hornblende gabbro that

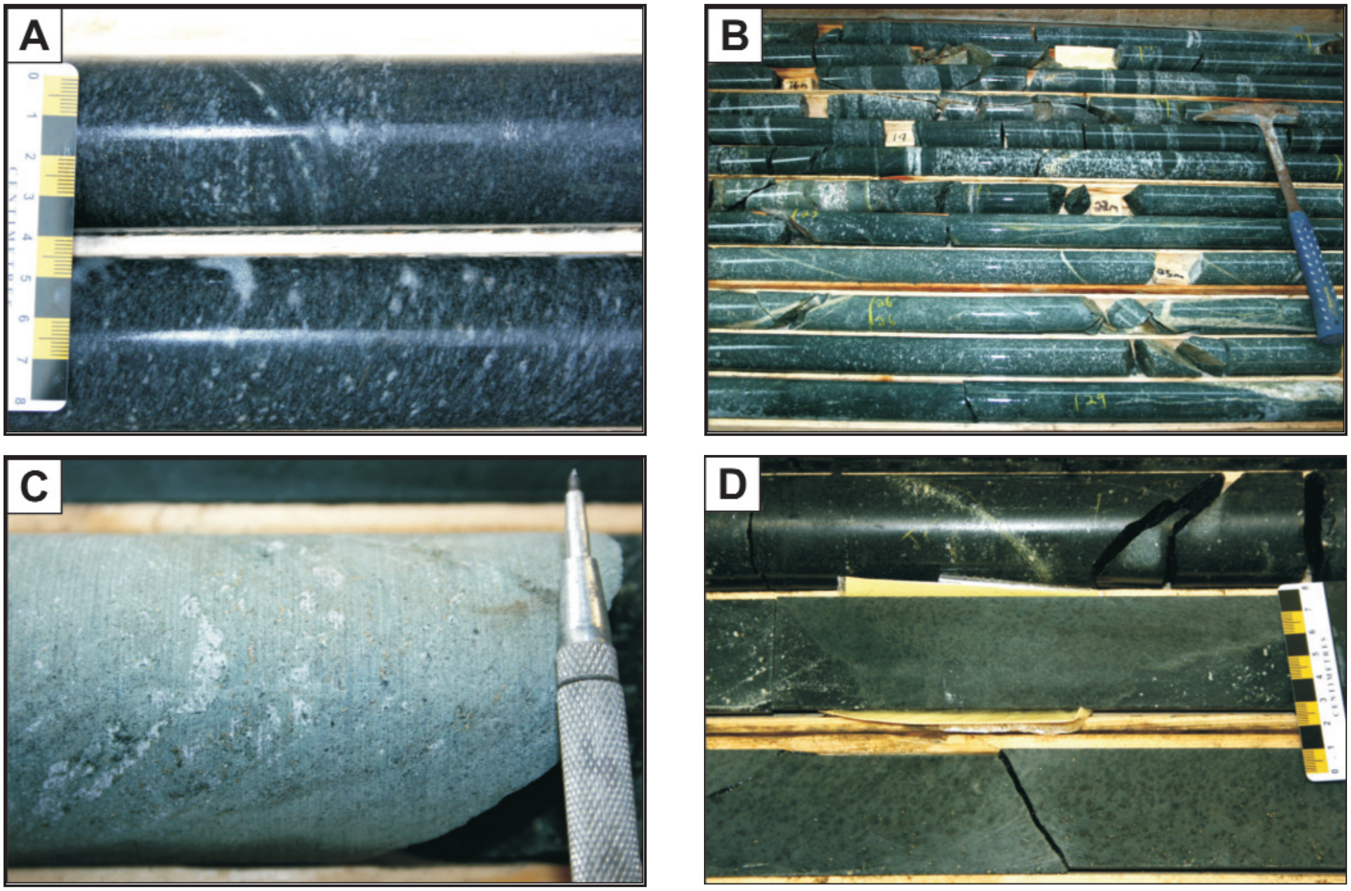



**Plate 8.** *Representative rock types at the Range occurrence. A) Well-foliated biotite–tonalite (DDH LR-11-15 @ 10 m). B) Hornblende gabbro (bottom) in contact with foliated to gneissic tonalite (top) (DDH LR-11-15 @ ~20 m). C) Plagioclase phyric basalt (DDH LR-09-02 @ 147.5 m). D) Altered basalt (bottom row and middle of center row) in contact with plagioclase-phyric gabbro (DDH LR-11-15 @ ~50 m).*

are not in direct proximity of mineralization. Primary minerals are poorly preserved in hydrothermally altered and metamorphosed tonalite, gabbro and basalt that host sulphide mineralization. Rock types within mineralized zones vary significantly on a scale of metres, and the details of lithological units and contacts are commonly obscured by intense hydrothermal alteration and subsequent metamorphism.

Metamorphic assemblages of quartz, cordierite, biotite or phlogopite, and amphibole (tentatively identified as anthophyllite) (Plate 11A, B) are widely developed in grey

**Plate 9.** (opposite page) *Representative examples of the variable hosts and textures of sulphide mineralization at the Range occurrence. A) Disseminated to net-textured pyrrhotite and chalcopyrite in dark grey, cordierite–quartz-bearing host (DDH LR-09-02 @ 105.5 m). B) Semi-massive pyrrhotite in biotite-rich siliceous host (DDH LR-09-02 @ 117 m). C) Massive sulphide (top) and ovoid-textured sulphide (bottom) in cordierite-bearing host (metatonalite?) (DDH LR-09-02 @ 102.3 m). D) Semi-massive sulphide (bottom) hosted by a blebby-looking mafic host. Note the similar blebby appearance of both the mafic host as well as the pseudomorphs within the sulphide. Note the coarse-grain pyrite indicative of recrystallization (DDH LR-11-15 @ ~52 m). E) Net-textured pyrrhotite and chalcopyrite in extremely altered mafic host (DDH LR-11-16 @ 79.7 m). F) Net-textured pyrrhotite and chalcopyrite in an altered blebby host. Note that the pseudo-morphology has the appearance similar to that for olivine cumulates in ultramafic rocks (DDH LR-09-02 @ 129.4 m). G) Semi-massive, interstitial pyrrhotite and chalcopyrite mineralization (DDH LR-11-15 @ ~58 m), H) 'Vein-like' or 'stringer-like' pyrrhotite and chalcopyrite in a cordierite–quartz-bearing host (DDH LR-11-15 @ ~55 m).*

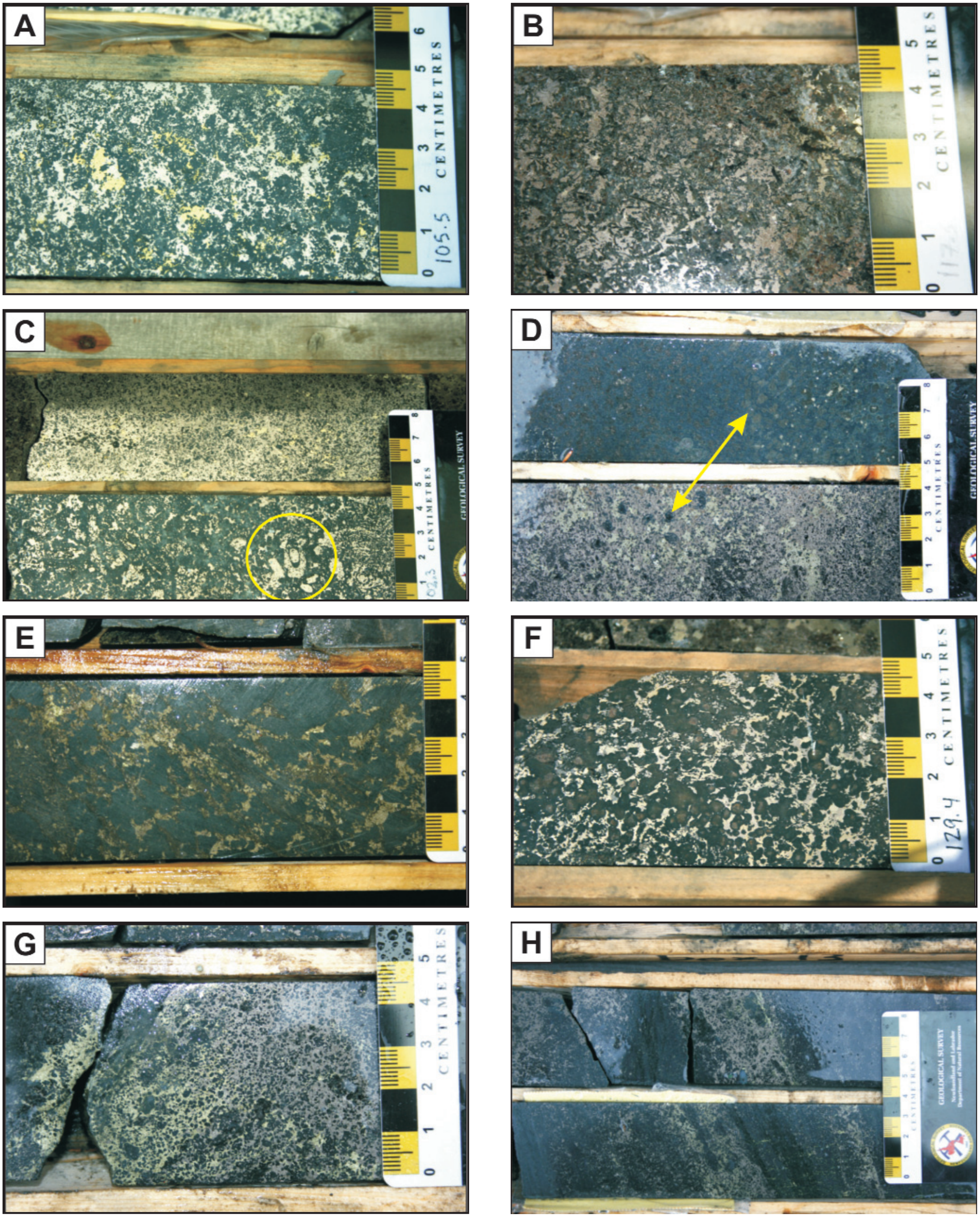



**Plate 9.** *Caption on opposite page.*

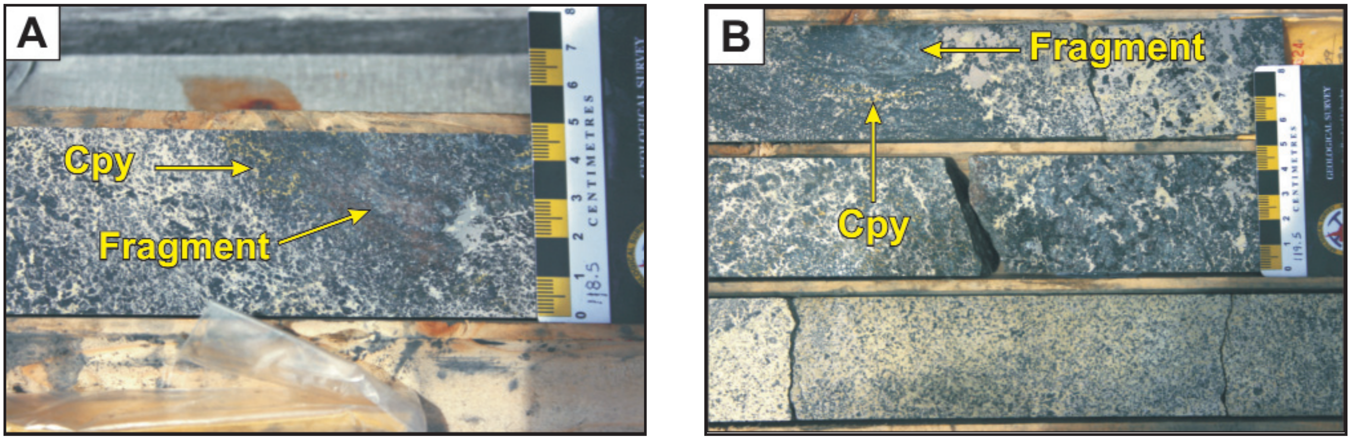



**Plate 10.** *A) DDH LR-09-02 @ 118.5 m. B) DDH LR-09-02 @ 119.5 m. Examples of felsic gneissic xenolithic (?) fragments within host rocks to mineralization at the Range occurrence. In both examples, note the increased chalcopyrite as well as the coarser grained nature of the sulphide mineralization in proximity to the xenoliths. (Cpy–chalcopyrite)*

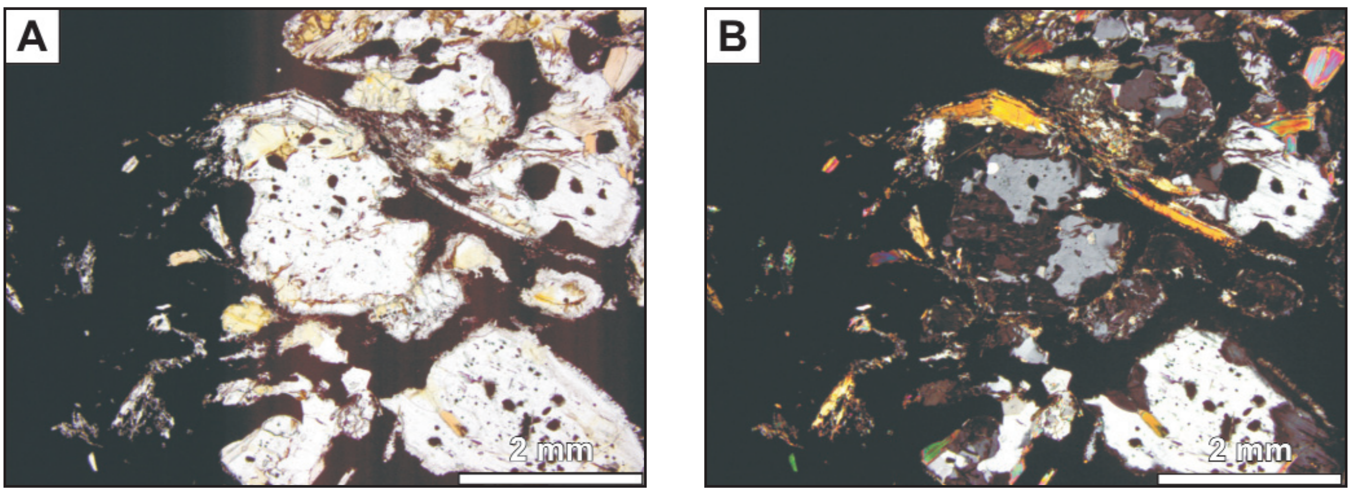
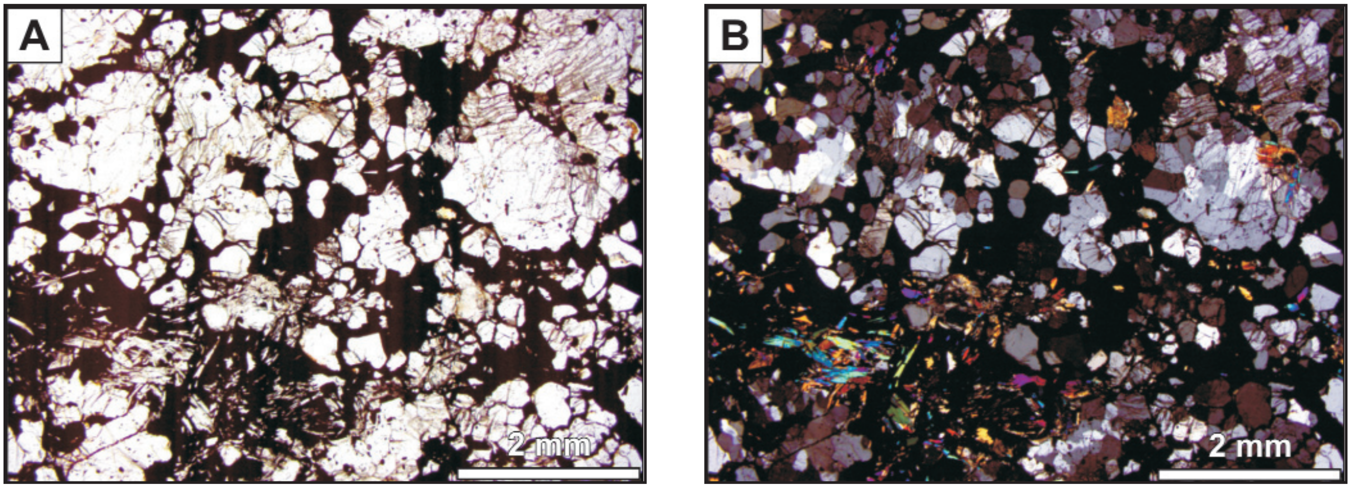



**Plate 11.** *A) Plane transmitted light photomicrograph of cordierite, quartz, biotite (or phlogopite (?)), and amphibole metamorphosed and altered leucocratic host rock at the Range occurrence. Note the yellow serpentine after cordierite (DDH LR-11-15 @ 54.6 m). B) As in A except with cross-polarized transmitted light.*

host rocks of uncertain parentage and metatonalite. Silicates commonly display polygonal grain boundaries, indicative of metamorphic textures. Cordierite is variably altered to serpentine (Plate 11A, B), pinnite and chlorite. To date, cordierite has only been identified in rocks in proximity to mineralization. Hydrothermal alteration is most intensely developed in direct contact with the sulphides, with amphibole commonly occurring around or within sulphide (Plate 12 A–C). Sulphide habit ranges from disseminations, to veinlets, to net-textured and interstitial masses.

The main host to sulphide mineralization at the Range occurrence is an altered and metamorphosed mafic rock type that contains rounded to blocky shaped silicate mineral pseudomorphs (Plate 13A, B). In some examples, this material is dominated by variably altered and resorbed (?) cordierite masses with local occurrences of a blue-green spinel (Plate 14A, B). Based on petrography, as well as mineral liberation analysis by Bath (2010), which indicated a Fe–Zn spinel, the spinel is tentatively interpreted as gahnite. In other examples, the host rock consists of variable amounts of chlorite, sericite, and amphibole (Plate 13A, B). Sulphide mineralization in the altered mafic host is commonly net-textured and is composed of pyrrhotite, pyrite, chalcopyrite and minor sphalerite (Plate 12A–C). Pyrrhotite and chalcopyrite are commonly observed as crosscutting replacements of earlier pyrite (Plate 15). Hydrothermal alteration of silicate minerals is most intensely developed in spatial proximity to sulphide mineralization. Although this rock type is interpreted as originally basaltic, definitive identification is not possible without additional lithogeochemical data and petrographic examination. There may be more than one original host rock involved.



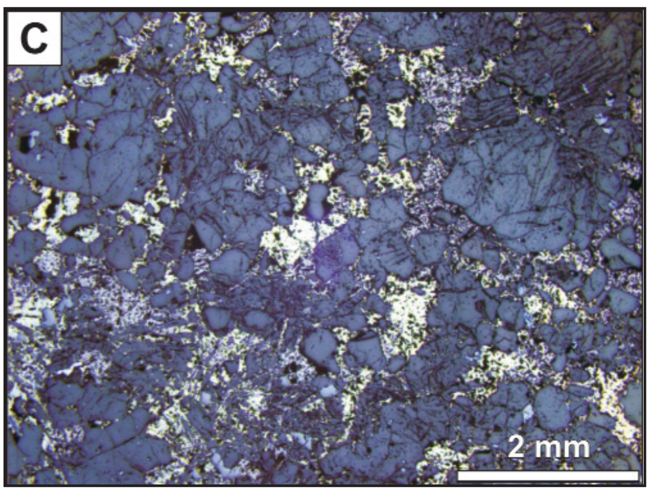




**Plate 12.** *A) Cordierite, quartz, and amphibole-bearing mineralized leucocratic rock from the Range occurrence (DDH LR-09-02 @ 119 m). B) Same as in A except in cross-polarized transmitted light. Note that most of the amphibole is entrained within the sulphide. C) Same as A and B except in reflected light. Sulphide mineralization is net-textured and dominated by pyrrhotite and chalcopyrite.*

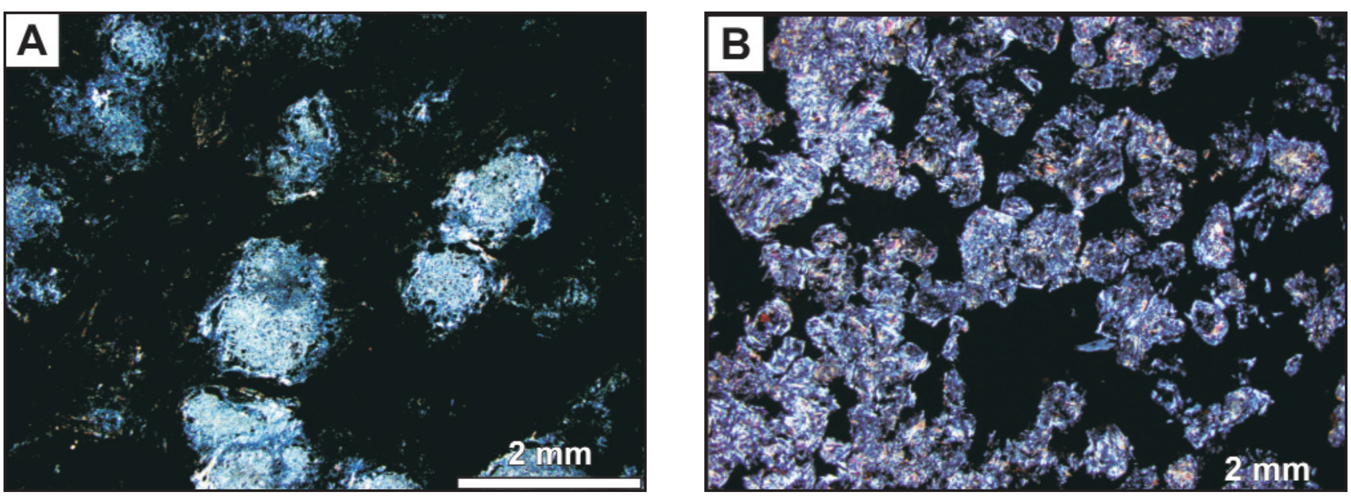



**Plate 13.** *A) DDH LR-09-02 @ 129 m. B) DDH LR-11-15 @ 59 m. Typical rounded to blocky silicate mineral pseudomorphs in the altered mafic host rock at the Range occurrence. Silicates have been intensely altered to fine-grained assemblages of white mica and chlorite.*

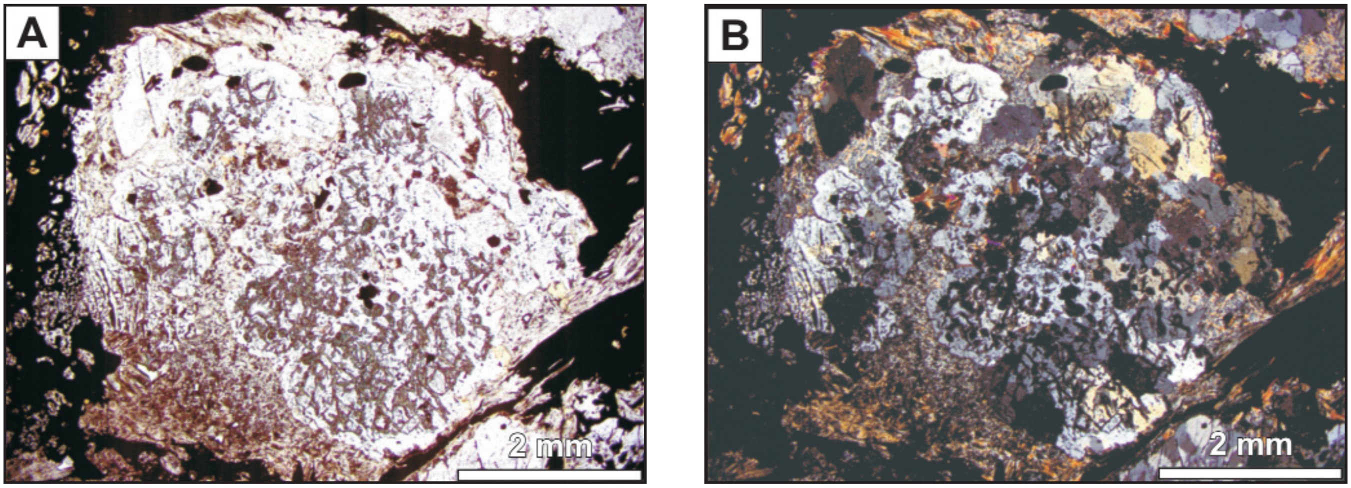



**Plate 14.** *A) Plane transmitted light. B) Cross-polarized transmitted light (DDH LR-09-02 @ 114.3 m). Close-up of one of the rounded textural features in the altered mafic host rock at the Range occurrence. Silicate mineralogy is dominated by a metamorphic assemblage of cordierite, amphibole, phlogopite, and blue-green spinel, which is opaque in cross-polarized light.*

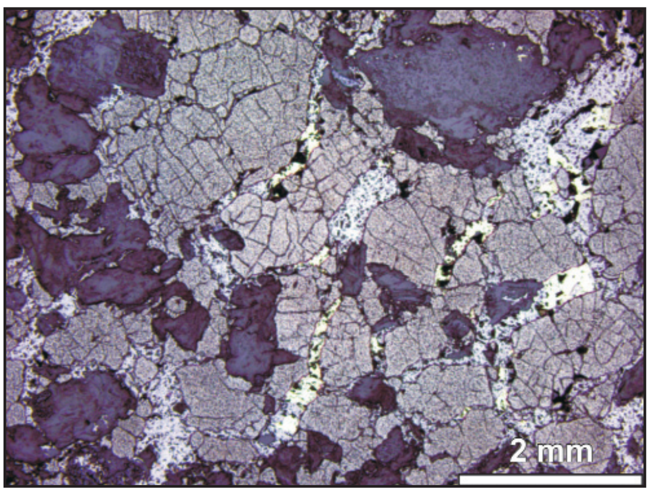



**Plate 15.** *Close-up of net-textured sulphide in the altered mafic host rock at the Range occurrence. Sulphides are dominated by pyrrhotite, chalcopyrite, and pyrite. Pyrrhotite and chalcopyrite crosscut and replace earlier pyrite (DDH LR-11-17 @ 173.7 m).*

### SULPHUR ISOTOPE ANALYSIS

Sulphur isotopic analysis was carried out *via* SIMS at the Creait Research Facility at Memorial University.

Two samples were chosen for sulphur isotope analysis, JHC-11-007c and JHC-11-031 from 59.0 m in diamond-drill hole LR-11-015 and 129.0 m in DDH LR-09-02, respectively. Sample JHC-11-007c is the altered and mineralized mafic host rock, and resembles basalt, with ghost pseudomorphs suggestive of plagioclase phenocrysts. It is intensely altered to chlorite and sericite. Sulphide mineralization consists of net-textured pyrite, pyrrhotite and chalcopyrite; with pyrrhotite and chalcopyrite replacing earlier pyrite. Sample JHC-11-031 is similar but contains the rounded to blocky pseudomorphs illustrated in Plate 13A, B. Sulphides are commonly net-textured and consist of pyrite, pyrrhotite, and chalcopyrite. Sample JHC-11-007c had eight SIMS spot analyses; two of pyrrhotite, three of pyrite, and three of chalcopyrite (Table 1). Average results from each sulphide phase, reported in $\delta^{34}S$, are: 9.2‰ from the pyrrhotite, 10.9‰ from the pyrite, and 11.7‰ from the chalcopyrite (Table 1). Sample JHC-11-031 had nine SIMS spot analyses, three from each of pyrrhotite, pyrite, and chalcopyrite. Average results from each sulphide phase, reported in $\delta^{34}S$, are: 7.7‰ from the pyrrhotite, 9.2‰ from the pyrite, and 9.2‰ from the chalcopyrite (Table 1). Values from different sulphide minerals within each sample are typically not within one $\sigma$ uncertainty of each other (Table 1).

## GEOCHRONOLOGY

van Staal *et al*. (2005) dated the Southwest Brook complex at *ca*. 463 Ma in the vicinity of Silver Pond, approximately 13 km to the west of the Range occurrence (Figure 1). Lissenberg *et al.* (2006) dated a sample of pegmatitic gabbro from the Puddle Pond complex at *ca*. 432 Ma. Due to the presence of gabbroic and other mafic rock types of uncertain age in the stratigraphy hosting the Range zone, further work was completed to date the host rocks.

A geochronological sample was collected from a mineralized metatonalite in outcrop at the Range occurrence. The sample collected (11JHLR-001-A01) is heavily mineralized, with pyrrhotite and chalcopyrite forming net-textured to vein-like masses. A small number of small, equant zircon grains were retrieved from the sample. Analyses were conducted under the supervision of Vicki McNicoll at the

Geochronology Laboratory of the Geological Survey of Canada *via* sensitive high resolution ion microprobe (SHRIMP II) techniques, using analytical and data reduction procedures outlined by Stern (1997) and Stern and Amelin (2003).

The SHRIMP II U–Pb analyses resulted in a single age population with a cluster of concordant, overlapping data from the sample. The weighted mean $^{206}Pb/^{238}U$ age was calculated at 463.4 ± 3.6 Ma (MSWD = 1.4, probability of fit = 0.15, n=17).

## SUMMARY AND DISCUSSION

This preliminary report discusses general characteristics of the Portage and Range occurrences. More information, including geochemistry, will later aid in understanding the relationships and results discussed here. At present, the main conclusion is that although the Portage and Range (mineral) occurrences are in close spatial proximity, they represent different types of mineralization occurring in rocks of different age.

### PORTAGE OCCURRENCE

The Portage Ni–Cu mineral occurrence displays characteristics typical of an orthomagmatic style of mineralization, most commonly associated with mafic to ultramafic intrusive rocks. Sulphide mineralization, consisting of pyrrhotite, chalcopyrite, pentlandite, and relict pyrite, occurs in a series of commonly olivine-bearing, gabbroic to troctolitic host rocks. Sulphide textures suggest an immiscible sulphide liquid in a silicate mush, which solidified as disseminated interstitial sulphide patches, and locally as net-textured sulphide surrounding silicate minerals. Hydrothermal alteration is very limited, as expected in a high-temperature orthomagmatic system in which sulphide liquids formed through exsolution processes from a silicate magma.

Sulphur isotopic data from the Portage occurrence is consistent with this interpretation. The analyses, which cluster slightly above 4 ‰ for pyrite, chalcopyrite and pyrrhotite, indicate close high-temperature equilibrium, as would be expected in an orthomagmatic system.

Although diamond drilling at the main Portage occurrence has indicated a limited strike potential for mineralization, additional occurrences and geophysical anomalies within the Puddle Pond complex are yet to be tested.

### RANGE OCCURRENCE

Understanding mineralizing processes at the Range occurrence is complicated by the intense hydrothermal alteration as well as post-mineralization metamorphism of the host rocks. The following represents a working hypothesis based on the observations and the limited data presented in this report.

Bath (2010) hypothesized that the host to the mineralization was originally an ultramafic to mafic intrusion that had assimilated pelitic paragneiss and tonalite during its ascent, and was subsequently metamorphosed. In such an interpretation, the mineralization would also be orthomagmatic. The suggestion of an ultramafic host was largely based on the presence of minor amounts of fayalite (0.25 weight percent) in one sample *via* analysis by mineral liberation analyzer – scanning electron microscope (MLA-SEM) techniques. Although some of the textural observations made during the current study, particularly the rounded and blebby pseudo-morphologies observed in drillcore (Plate 9f), could lend themselves to interpretations of an ultramafic host protolith based solely on pseudo-morphological attributes, substantiating evidence is currently lacking to support this theory. Additionally, whereas the magnesium end-member of olivine (forsterite) is a common constituent of primitive ultramafic rocks, fayalite is not commonly associated with such rocks. An alternative theory for the unusual textures commonly observed in the host rocks to the mineralization (Plate 13A, B) is that they are derived from original amygdaloidal, vesicular, or porphyritic basaltic textures, subsequently overprinted by hydrothermal and metamorphic processes.

Sulphide compositions and textures at the Range occurrence vary significantly from those observed at the Portage occurrence. There is a lack of pentlandite or any other nickel-bearing sulphide. The presence of sphalerite, albeit minor, is also distinctive. Sulphide textures at the Range occurrence include disseminations and exsolutions from silicate magmas, as well as vein-like or stringer-like habits; the latter being more typically associated with an epigenetic origin. These vein-like or stringer-like zones are more commonly observed in the metamorphosed leucocratic hosts, compared to the net-textured sulphide habit more commonly observed in the more mafic host rock. However, due to the variable and intense deformation and metamorphism imparted on the host rocks, caution in interpreting such vein-like textures in drillcore samples as being of a primary origin rather than tectonically imparted pseudo-textures is prudent.

Hydrothermal alteration of silicate minerals in the vicinity of sulphide mineralization is widespread at the Range occurrence, with chlorite and sericite commonly moderately to intensely developed. Metamorphic mineral assemblages of cordierite, amphibole (anthophyllite (?)), gahnite (tentative identification; *see* above), and quartz commonly overprint the mineralization and hydrothermal alteration.

Sulphur isotopic data from the Range occurrence show heavier average $\delta^{34}S$ values compared to the Portage occurrence. These also do not indicate high-temperature equilibrium between pyrite, pyrrhotite, and chalcopyrite in individual samples. Such discrepancy in the sulphur isotopic compositions argues against a magmatic origin for mineralization.

Geochronological data from the host metatonalite at the Range occurrence gives an age of *ca*. 463 Ma, which represents a maximum age for sulphide mineralization. However, based upon sulphide textures, which range from disseminated through to net-textured and interstitial, it is postulated that the timing of sulphide mineralization is approximately synchronous with the crystallization age of the tonalite. As such, the mineralization at the Range occurrence could be approximately 30 My older than that at the Portage occurrence. Although the exact timing of mineralization at the Range occurrence is not unequivocally known, the intense post-mineralization metamorphism observed at the Range occurrence, when compared to the non-metamorphosed and fresh appearance of host rocks at the Portage occurrence some 3 km to the west, supports a relative age difference for the two mineralizing events.

Observations and data provided in this report from the Range occurrence mitigate against an orthomagmatic origin for mineralization. In general, the features of the Range occurrence could be used to postulate a mineralizing process analogous to that for volcanogenic massive sulphide (VMS) deposits, masked, to some extent, by metamorphism. Metamorphic mineral assemblages including cordierite, anthophyllite, quartz and gahnite are common in metamorphosed VMS deposits, and are interpreted to result from the metamorphism of chlorite and sericite alteration zones within compositionally altered volcanic rocks (Upadhyay and Smitheringale, 1972; Riverin and Hodgson, 1980; Pan and Fleet, 1995; Gifkins *et al*., 2005). However, there is currently no evidence for exhalative units or definitive stockwork mineralization. More detailed work is required to assess and test the hypothesis.

## MINERAL EXPLORATION IMPLICATIONS

The Portage Ni–Cu and Range Cu–Co mineral occurrences in southwestern Newfoundland highlight the mineral potential of this under-explored area of the Province, as well as specific geological units that may have the best potential for future discoveries.

Magmatic Ni–Cu mineralization in olivine-bearing primitive rocks at the Portage occurrence further highlights the potential for such mineralization in Paleozoic intrusive rocks on the Island portion of the Province. Similar Ni–Cu mineralization occurs elsewhere on the Island (*e.g.*, in association with the Red Cross Lake Intrusive Suite in central Newfoundland, and in proximity of the Silurian Twin Lakes diorite intrusion in north-central Newfoundland (Kerr, 1999)). As depicted by Colman-Sadd *et al.* (1990), the intrusions of the Puddle Pond complex represent one of many mafic suites of Silurian age throughout central Newfoundland, many of which could merit exploration for similar style magmatic mineralization. Potential analogues also occur elsewhere in the northern Appalachians, including the St. Stephen nickel deposits of southern New Brunswick (*e.g.*, Paktunc, 1987) and mineralization associated with the Moxie and Katahdin plutons in Maine, USA (*e.g.*, Thompson, 1984).

If the Range Cu–Co occurrence indeed has some affinity with VMS-type mineralizing processes, it represents a new style of mineralization for this area. If the interpretation that some of the metamorphosed and extremely altered host rocks to the mineralization are metabasalt in composition is correct, the origin of such rocks requires consideration. They could possibly represent ophiolitic material related to the Lush's Bight oceanic tract (*e.g.*, Lissenberg *et al.*, 2006); although the maximum *ca*. 463 Ma age for mineralization at the Range occurrence is problematic, as such rocks are generally considered to be older (*ca*. 489 Ma; Dunning and Krogh, 1985; Cawood *et al.*, 1996). Alternatively, the basaltic rocks could be correlated with the Cormacks Lake Complex to the west, although the *ca*. 463 Ma age is again younger than expected, as the Cormacks Lake Complex is dated at *ca*. 489 Ma (*see* van Staal *et al.*, 2005). Regardless of its enigmatic origin, the Range Cu–Co occurrence represents a previously unrecognized style of mineralization in this part of southwestern Newfoundland, and the surrounding area may warrant further exploration for this type of target.

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