*Current Research (2009) Newfoundland and Labrador Department of Natural Resources*
*Geological Survey, Report 09-1, pages 131-146*

# VOLCANIC REDBED COPPER MINERALIZATION IN THE HINDS LAKE AREA, CENTRAL NEWFOUNDLAND

G. Case and A. Zagorevski[1*]
Department of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, ON, K1S 5B6
[1] Geological Survey of Canada, 601 Booth Street, Ottawa, ON, K1A 0E8
[*] Corresponding author: azagorev@nrcan.gc.ca

## ABSTRACT

*Central Newfoundland contains a collage of Cambro-Ordovician arc and non-arc volcanic rocks that are host to numerous base-metal (Cu–Pb–Zn) deposits; most notably the volcanogenic massive sulphide (VMS) deposits of the Buchans Group. However, other types of base-metal mineralization also occur throughout the region, in a variety of different lithotectonic settings. This study focuses on an area of copper-sulphide mineralization adjacent to the northwest side of Hinds Lake. The area is underlain by volcano-sedimentary rocks of presumed Silurian age. Exposed stratigraphic sequences consist of a lower unit of a columnar-jointed basaltic flow, unconformably to disconformably overlain by a thin siltstone sequence, which is overlain by a polymictic conglomerate. The sequence is capped by a unit consisting of thick-bedded, columnar-jointed to massive, subaerial to shallow-marine felsic pyroclastic flow. The stratigraphy has been tilted and displaced by minor normal faults. The copper-sulphide mineralization is structurally and stratigraphically controlled and is hosted by calcite–chlorite veins in the upper basalt flow. The simple, copper-rich mineralogy and association with subaerial to shallow-marine volcano-sedimentary rocks, suggest that the copper-sulphide mineralization shares many characteristics with the volcanic redbed copper deposits.*

## INTRODUCTION

The central Newfoundland Appalachians comprises a collage of Cambro-Ordovician arc terranes that were successively accreted to the Laurentian margin during the Ordovician Taconic and Ordovician to Silurian Salinic orogenies. As a result, the eastern margin of Laurentia experienced significant growth. Following the Ordovician to Early Silurian tectonism, a subaerial Silurian volcano-sedimentary overlap sequence was, locally, unconformably deposited on the accreted terranes accompanied by the intrusion of consanguineous plutons (*e.g.*, Chandler *et al.*, 1987; Williams, 1995a). These were subsequently deformed during the late Salinic, Acadian, Neoacadian, and Alleghenian orogenies. The Cambro-Ordovician terranes are highly prospective for base metals and are host to several previous and current important mines, including Buchans, Rambler, Ming and Duck Pond. The Silurian overlap sequences have been the subject of uranium exploration; however, Silurian volcanic sequences have not been traditionally viewed as being prospective for base metals. In this contribution, a previously known but poorly understood copper mineral occurrence is described in detail, in hopes of stimulating further research.

The study area (Figure 1) is located about 20 km south of the town of Howley, in proximity to the hydro-electric power generation station. During construction of the generating station's emergency spillway, the copper mineralization that forms the focus of this study was uncovered, noted by the Newfoundland Department of Mines and Energy, and was subsequently staked for mineral rights (MODS Report 012H/03/002). Preliminary work and analytical determination of the sulphides was conducted (Kausch, 1981); however, property development went no further.

During the summer of 2007, as part of the Targeted Geoscience Initiative 3: Newfoundland Appalachians project, a program of geological fieldwork was conducted in central Newfoundland with the aim of expanding Canada's base-metal reserves in proximity of existing mining communities. A small aspect of the fieldwork conducted involved the investigation of the copper occurrence, which forms the focus of this paper. This paper describes the local stratigraphy, the copper-sulphide mineralization, and the host rocks in the vicinity of the Hinds Lake emergency spillway. Descriptions are supplemented by petrographic, geochemical and mineralogical work that aid in the classification of the nature and distribution of the copper mineralization.

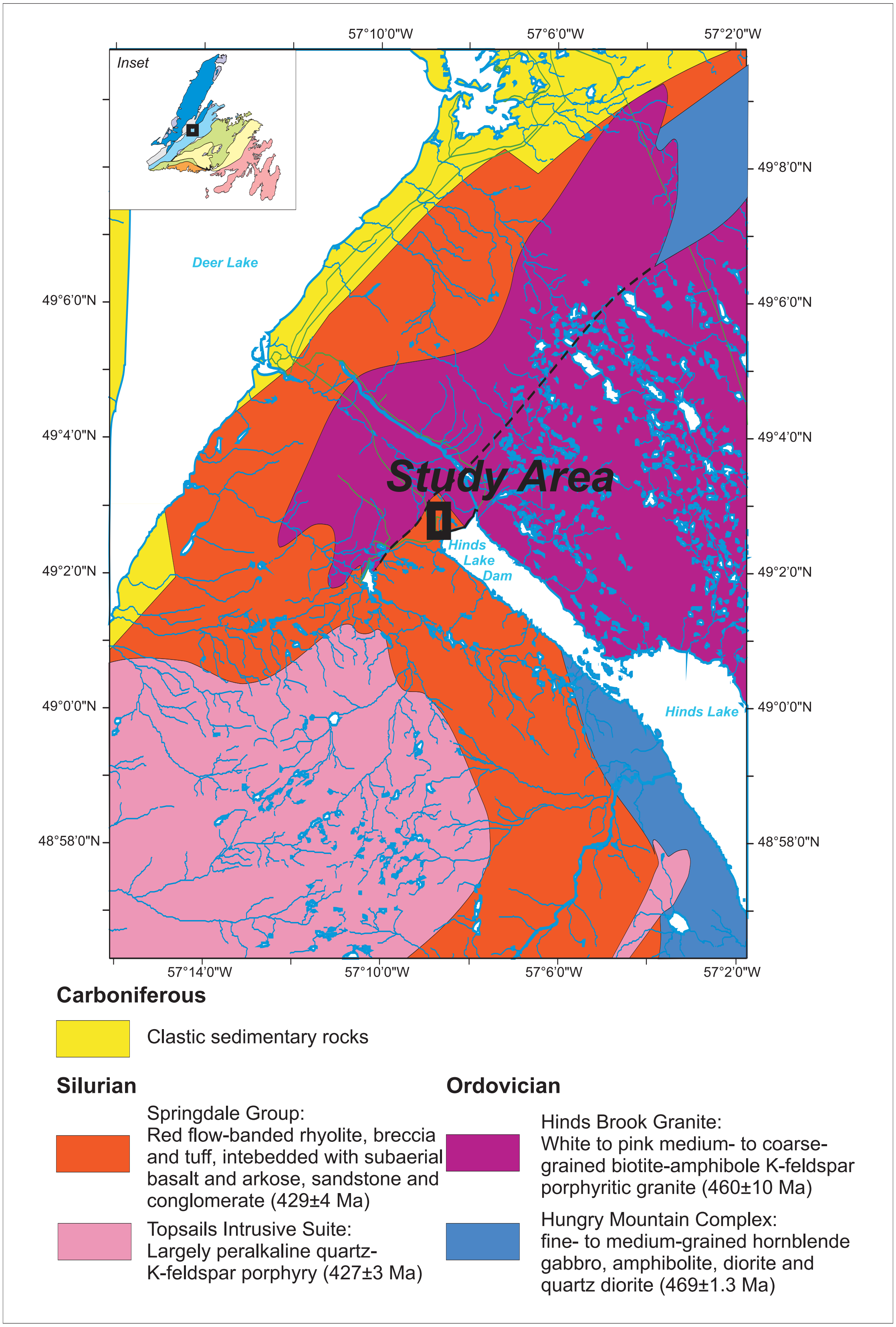



**Figure 1.** *Geology of the Hinds Lake Dam area (from Whalen and Currie, 1983). Inset: Location of the study area on the lithotectonic map of Newfoundland (Williams, 1995b).*

## REGIONAL GEOLOGY

The geology of the Newfoundland Appalachians reflects the culmination of a prolonged accretionary history. The Newfoundland Appalachians are divided into four separate and distinct lithotectonic zones, and additional subzones, based on the distribution and characteristics of the lithostratigraphic units therein (Williams, 1995a, b). These lithotectonic zones represent the products of the opening and closing of the Iapetus Ocean and its marginal basins, during which the eastern margin of the Laurentian lithospheric plate underwent considerable growth and deformation; this plate growth and deformation took place during the Taconian, Salinic, Acadian, Neoacadian, and Alleghenian orogenies (van Staal, 2005).

The study area is located within the Notre Dame Subzone of the Dunnage Zone (Williams, 1995a) and is underlain by the rocks of the Notre Dame Arc (Whalen *et al.*, 1997; van Staal *et al.*, 2007). The Notre Dame Arc comprises Middle Ordovician plutonic rocks formed as a result of several phases of arc-magmatism and slab break-off (Whalen *et al.*, 1987, 1997; van Staal *et al.*, 2007), and is extensively intruded by Silurian plutons of the Topsails Igneous Suite (Whalen and Currie, 1983; Whalen *et al.*, 1987, 2006; Whalen, 1989). The latter have been also interpreted to represent arc-magmatism followed by slab break-off (Whalen *et al.*, 2006). The supracrustal equivalents of the Topsails Igneous Suite, which are the subject of this study, include continental redbeds and the subaerial volcanic rocks of the Springdale Group (Coyle and Strong, 1987); these rocks overlie the Notre Dame Arc above a regional angular unconformity to non-conformity (Williams, 1995a).

## LOCAL GEOLOGY

The basement rocks comprise Ordovician plutonic rocks of the Hungry Mountain Complex and Hinds Brook Granite (*ca.* 467 Ma, Whalen and Currie, 1983) and Silurian plutonic rocks of the Rainy Lake Complex (ca. 435 Ma, Whalen *et al.*, 2006). The Silurian plutonic rocks of the Topsails Igneous Suite intrude the basement, and locally form subvolcanic intrusions (*ca.* 427 Ma, Whalen and Currie, 1983) to supracrustal sequence of subaerial basalt flows, red flow-banded rhyolite, and pyroclastic volcanic rocks, which are regionally intercalated with redbed arkose, conglomerate and siltstone (*ca.* 429 Ma, Whalen *et al.*, 1987). The Topsails Igneous Suite volcanic rocks are correlative with several coeval volcano-plutonic complexes in Newfoundland including the Springdale Group, Cape St. John Group, Micmac Lake Group, King's Point Complex and other occurrences of subaerial volcano-sedimentary rocks in central Newfoundland (*e.g.*, Hibbard, 1983; Chandler *et al.*, 1987; Coyle and Strong, 1987).

The Springdale Group represents one of the subaerial volcano-sedimentary sequences that is comagmatic with the Topsails Igneous Suite (Whalen and Currie, 1983; Whalen, 1989). The stratigraphic thickness of the Springdale Group can be highly variable but is locally in excess of 2500 m. The rocks of the Springdale Group are interpreted to have been deposited in an epicontinental-type caldera setting (Coyle and Strong, 1987). The rocks consist of a series of subaerial rhyolitic flows, sills, tuffs, and volcaniclastic rocks with subordinate basalt and andesite, that are intercalated and overlain by a redbed sequence of conglomerate, sandstone, and siltstone (Chandler *et al.*, 1987; Coyle and Strong, 1987). Coyle and Strong (1987) and Whalen *et al.* (1987) documented a bimodal mafic and dacite–rhyolite chemical distribution for the volcanic rocks of the Springdale Group.

### TECTONIC SETTING OF SILURIAN VOLCANIC ROCKS

The study of Silurian volcanic and plutonic rocks in central Newfoundland suggests a rather complex tectonic setting and history. The oldest igneous rocks of the Topsails Igneous Suite indicate formation in a continental arc-like setting (*ca.* 440 Ma, Whalen *et al.*, 2006), whereas subsequent magmatism displays characteristics of non-arc environments including A-type granites and crustal partial melts. The diversity of magmas, as well as the time-span of magmatism, led Whalen *et al.* (2006) to propose that the post-435 Ma volcanic rocks formed as a result of slab break-off following the closure of Iapetan marginal basin.

## STRATIGRAPHY

The following discussion is based on the mapping in the Hinds Lake emergency spillway (Figures 1 and 2). Examination of the various rocks and structural features indicate that the area consists of an upright stratigraphic succession of basalt, siltstone, conglomerate and felsic pyroclastic rocks that have been tilted, and locally offset by brittle faults (Figure 2). The structural features will be dealt with in a separate, later section. However, it should be noted that faulting repeats the lithostratigraphic units along the strike of the spillway as distinct fault-bound blocks (Figure 2 and Plate 1A). The lithological descriptions of the stratigraphic units are augmented by the results of optical microscopy and electron microprobe analysis.

### BASALT

The lowermost exposed unit is a massive, dark-grey basalt that forms a columnar-jointed flow, at least 50 m thick (Figures 2 and 3). The basalt appears aphanitic with local small (~2 mm) amygdules, and rare, larger amygdules (up to

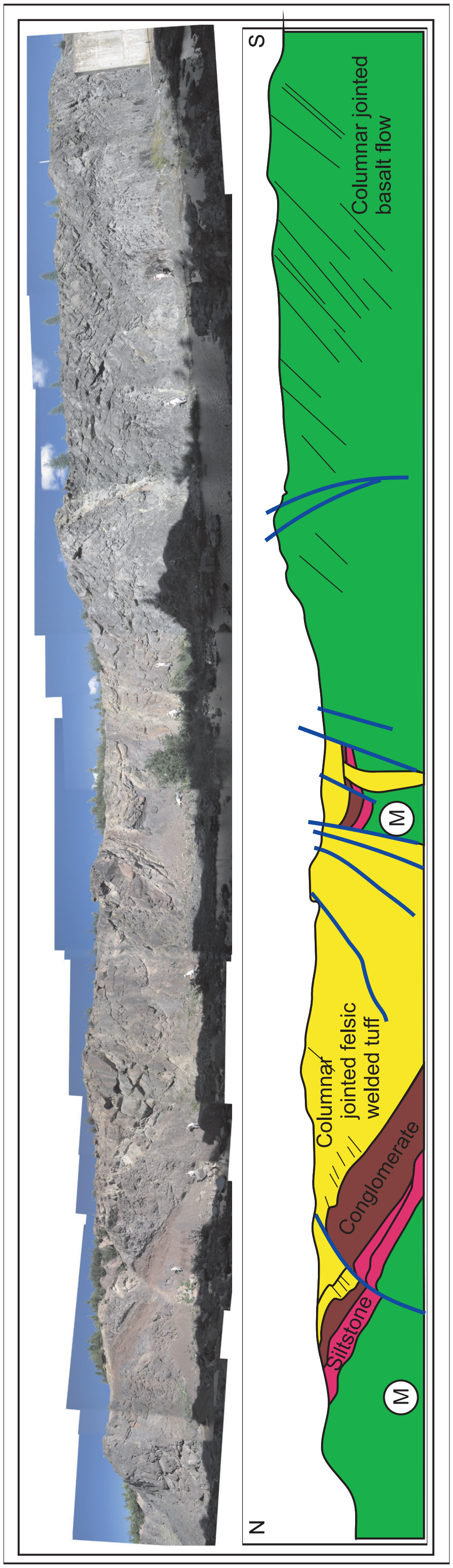



**Figure 2.** (opposite) *Composite image and geological interpretation of the Hinds Lake Dam geology (reader is looking northeast). M - mineralized veins occur at the base of the spillway. See Figure 3 for the schematic stratigraphy and description of the units.*

10 cm in length). Petrographically, the basalt has a well-developed trachytic texture, defined by the alignment of plagioclase microlites and phenocrysts, with interstitial clinopyroxene comprising the predominant groundmass mineral. Locally, clinopyroxene also occurs as microphenocrysts.

The basalt displays several styles of weathering and alteration. Weathering of the surfaces produces a dull grey appearance, and in some areas reddish hematitic alteration occurs along faults and fractures. Another prominent feature is the concentric liesegang banding, which may, in part, outline columnar joints in the stratigraphically uppermost exposures of the basalt flow (Plate 1B). The uppermost section of the basalt also hosts several sets of sulphide-carbonate veins (*see* page 135).

## SILTSTONE

The basalt unit is overlain by a sequence of dark grey and red siltstone (Figures 2, 3, and Plate 1A). The dark grey siltstone immediately overlies the basalt flow and has a bluish-grey tint. Due to its inherent friability, this lower siltstone does not preserve a well-developed bedding, although there is a <1 cm thick bed of beige–grey bentonite. The dark grey siltstone is transitional into red to purplish red, thin-bedded siltstone and fine-grained sandstone. The thickness of the siltstone unit is between 1 and 4 m.

## CONGLOMERATE

Overlying the siltstone unit is a polymictic, clast-supported, poorly sorted lens of conglomerate up to tens of metres thick (Figures 2, 3 and Plate 1A). The clasts range from pebble-size to boulder-size and include both mafic and felsic igneous components together with siltstone and sandstone. The conglomerate is clearly incised into the underlying siltstone unit and is interpreted to represent a channel-type deposit. The thickness of the conglomerate unit changes noticeably across faults (Plate 1A).

## FELSIC VOLCANIC ROCK

The conglomerate is overlain by a felsic pyroclastic flow having a minimum thickness of 20 m (Figures 2, 3, and

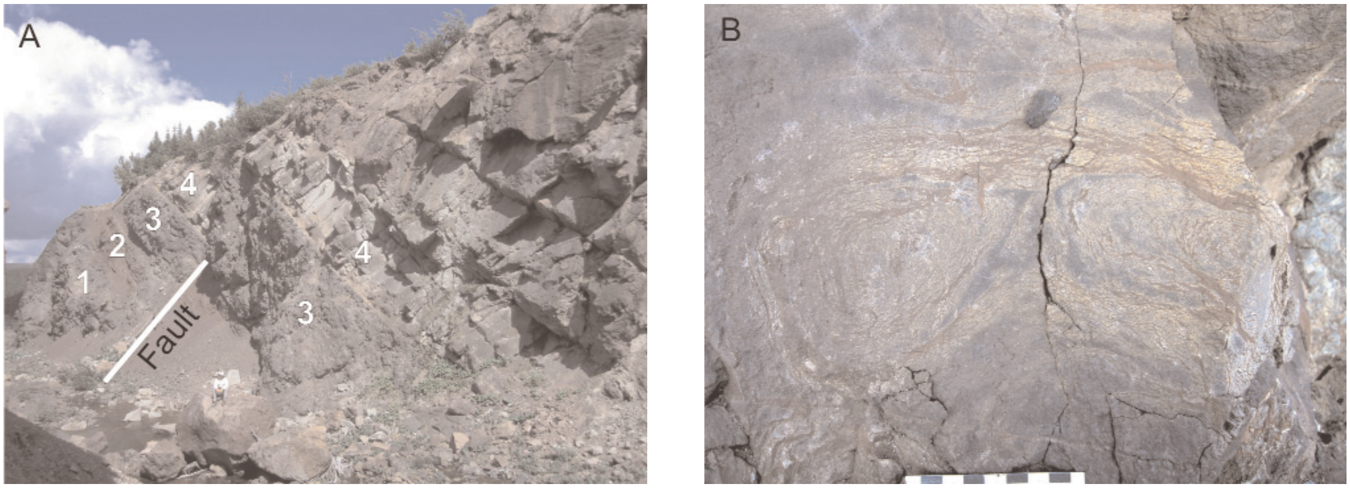



**Plate 1.** *Representative field relationships. A) Complete stratigraphy preserved in one fault block; 1 - basalt, 2 - siltstone, 3 - conglomerate, 4 - felsic volcanic. The stratigraphy is offset along a fault (trace of the fault is marked on the photo). Note the thickness variation in conglomerate across the fault and the dense columnar jointing at the base of felsic volcanic. B) Well-developed liesegang alteration in basalt.*

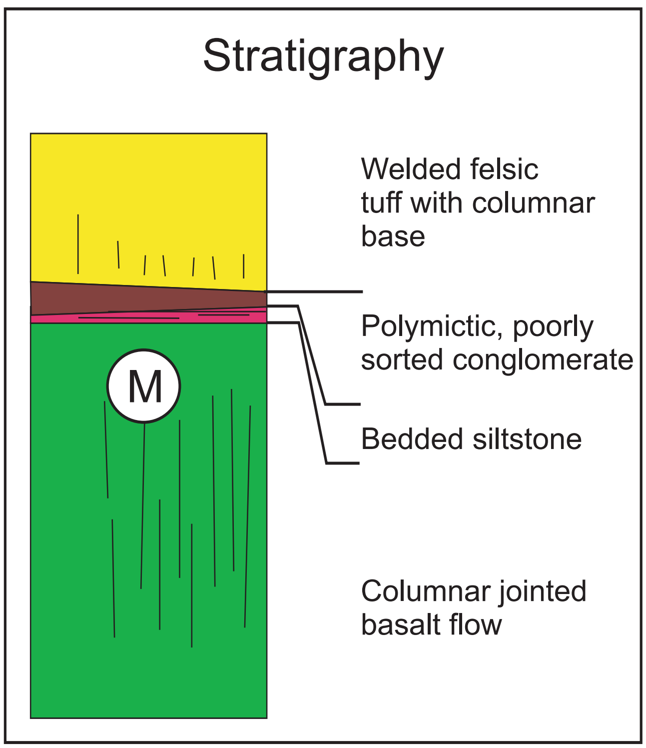



**Figure 3.** *Schematic stratigraphy of the area. Colour scheme is the same as in Figure 2.*

Plate 1A). The pyroclastic flow exhibits a distinct internal zonation: the lower zone (~2-3 m thick) contains lithic fragments, 1- 4 mm in size, and is a pale pinkish beige. This zone contains well-developed columnar joints (Plate 1A). The upper zone is considerably thicker (>15 m), darker red, and contains fine-grained (~1 mm) lithic fragments. Flattened cuspate glass shards define an eutaxitic texture, and when combined with the columnar joints, indicate hot emplacement, which suggests that the felsic volcanic rock is a welded ignimbrite flow (*e.g.*, Freundt *et al.*, 2000).

### DYKE

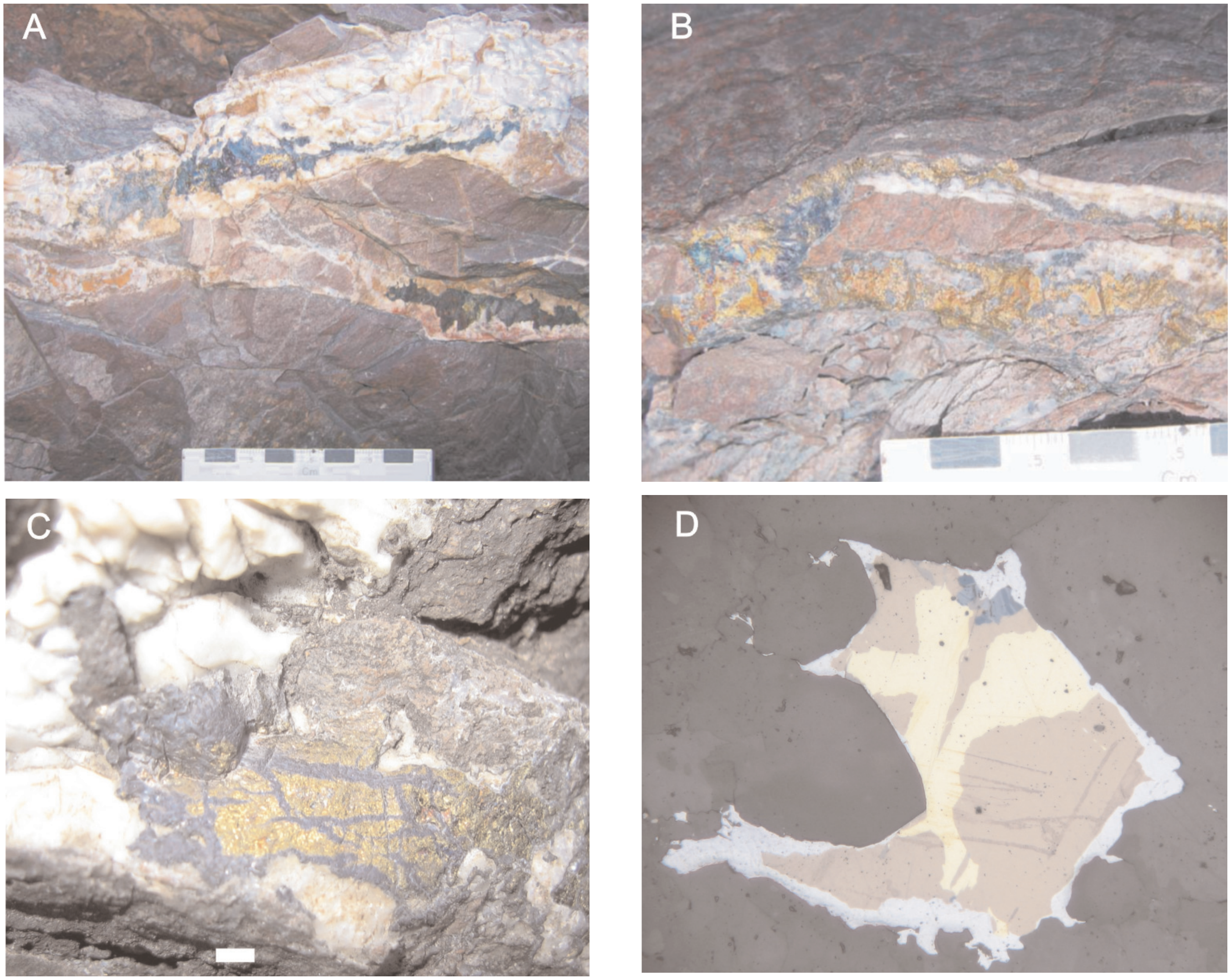
A relatively late amygdaloidal mafic dyke cuts the basalt unit. This dyke is fresh, has a glassy, dark grey to black matrix, and a dirty-brown-weathered colour. Amygdules are very small (~1 mm) and the dyke locally contains disseminated pyrite.

## COPPER MINERALIZATION

The upper section of the basalt flow, just beneath the contact with the siltstone unit, is host to a series of sets of copper-sulphide–carbonate and sulphide-barren carbonate veins. These veins are prominently exposed on the floor of the spillway (Figure 2; Plate 2). The major silicate mineral phase present in the veins is calcite, which is accompanied by minor amounts of quartz, feldspar, chlorite, and a variety of copper-sulphide minerals. As calcite is the major gangue mineral, the veins are a distinctive white to pinkish-white. The veins cut the liesegang alteration in the host basalts.

### COPPER-BEARING CARBONATE VEINS

The copper mineralization, comprising a variety of copper-sulphide and copper-oxide minerals, is restricted to a subset of the carbonate veins that are characterized by a preferred orientation (see later section on structure, page 137). The mineralized veins range from a few millimetres to ten centimetres in width, and are visible on both sides of, and on the floor of the spillway. The copper mineralization in the



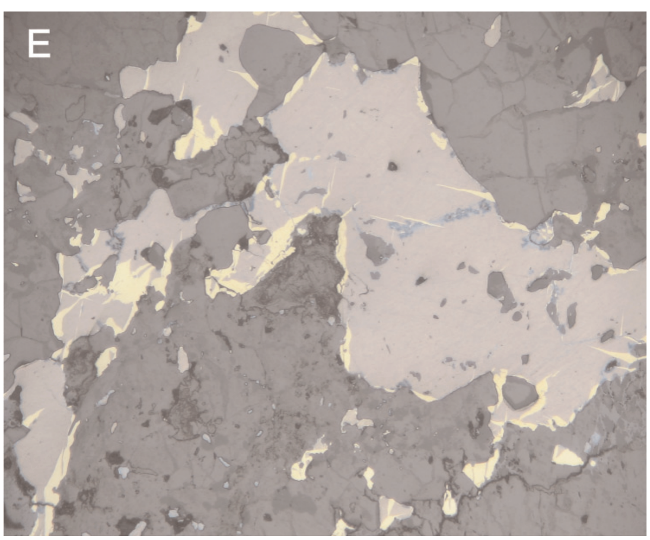




**Plate 2.** *Outcrop and reflected light photomicrographs representative of the relationships between wallrock, veins, and gangue and sulphide minerals in veins. A and B) Calcite-calcopyrite-bornite veins cutting strongly hematized basalt. C) Bornite replacing chalcopyrite. D) Bornite replaces chalcopyrite with a rim of covellite, digenite and trace galena, see Figure 5 for SEM image. E) Bornite with chalcopyrite exsolution lamellae.*

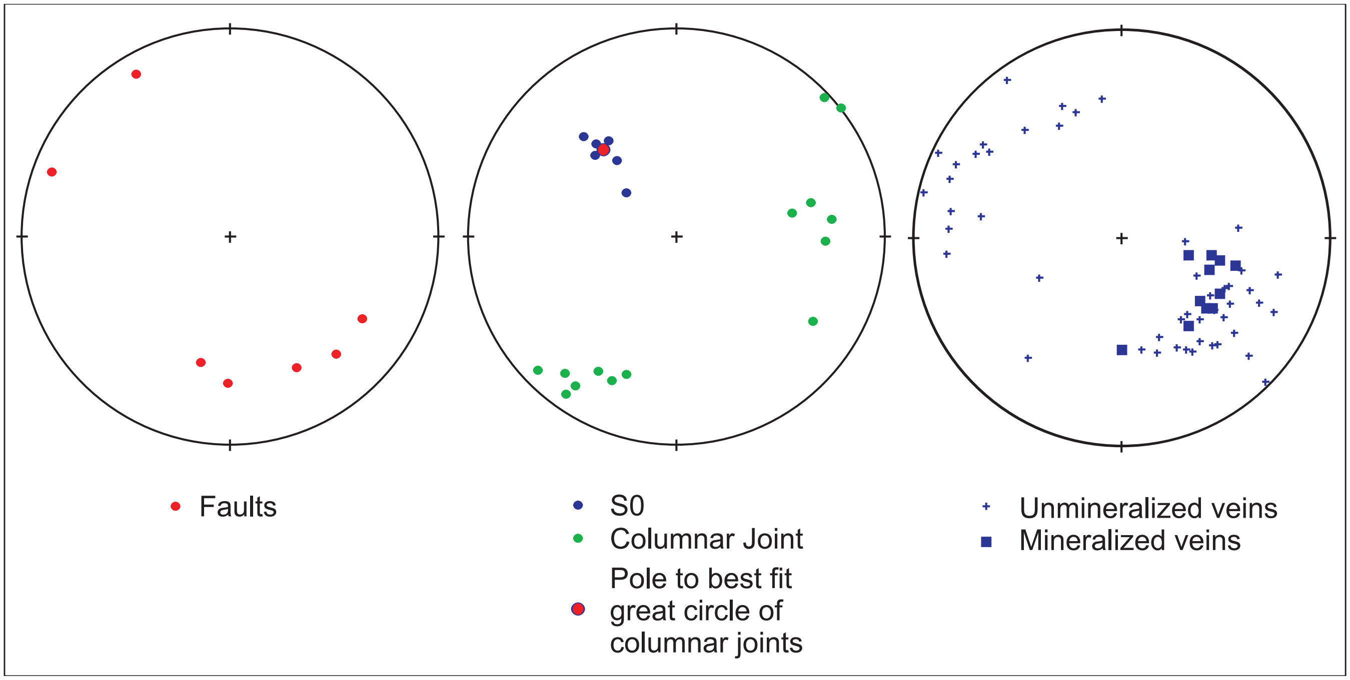



**Figure 4.** *Equal-area projection stereonets of faults, bedding (S0), columnar joints and veins. Pole to best fit great circle of columnar joints represents the average trend and plunge of the columns.*

carbonate veins is composed of a variety of sulphides, predominantly bornite and chalcopyrite, and lesser amounts of covellite, chalcocite and digenite. Malachite and azurite are also locally present as surface coatings and encrustations.

## BARREN CARBONATE VEINS

The number of carbonate veins without mineralization (*i.e.*, barren) outnumbers the mineralized veins. Although both the copper-mineralized and the barren veins share a common preferred orientation, the two groups of veins can be broadly discerned on the basis of their orientation. In addition to calcite, which is the main mineral in the veins, the barren veins also contain minor amounts of quartz, feldspar, and chlorite.

## STRUCTURAL GEOLOGY

The orientations of the bedding planes, columnar joints, faults and veins were measured and are presented in Figure 4 and described below.

## FAULTS

Previous regional mapping has revealed the presence of several sets of brittle faults (Whalen and Currie, 1983). The first set trends northeast and parallels the long axis of the Carboniferous Deer Lake Basin. The second set of faults trends northwest, with a major fault occurring immediately northeast of the study area along Hinds Brook (Whalen and Currie, 1983). The spillway exposes several steeply dipping faults that have an east to northeast-east trend. The measurement of the orientation of these faults is complicated by the irregular nature of the fault surfaces, which may account for some of the spread in the data (Figure 4).

Significant but highly variable displacement of stratigraphic unit boundaries is observed across the faults (Figure 2 and Plate 1A). Rare chlorite slickensides are locally observed and suggest a steep rake (a slickenside lineation of 63º and a direction of 310º). As such, these faults are consistent with predominantly normal motion with a potential minor component of oblique slip (Plate 1A). Minimum estimates of displacement ranges from several metres (Plate 1A) to over 28 m in the centre of the spillway (Figure 2).

## BEDDING AND COLUMNAR JOINTS

Measurements of bedding and columnar joints were taken from all fault-bound blocks and stratigraphic units. The bedding orientations are consistent between the fault blocks suggesting that the faults have produced very little rotational motion (average S0 049/50; Figure 4). The columnar joints were found to be consistently perpendicular to bedding (average column orientation 48 towards 323), and as such, they may be used as a reasonable approximation to the pole to bedding in areas of poor exposure.

**VEINS**

Two fault blocks that expose the uppermost section of the basalt flow (Figure 2) contain several distinct sets and compositions of veins. Considering that bedding and columnar joints have consistent orientations between the fault blocks, the vein sets between fault blocks are treated together. Orientations of both the copper-mineralized and barren vein types were measured (Figure 4). The orientations of all veins show a great degree of scatter; however, broadly, two groups can be discerned. The first group consists of gently (southeast-) dipping veins, which appear to be barren. The second group of veins (average strike/dip 210/40) consistently dip gently to the northwest and comprises all of the copper-mineralized veins and some of the barren veins.

## NATURE AND DISTRIBUTION OF COPPER MINERALIZATION

Copper-sulphide mineralization occurs in two fault blocks that repeat the stratigraphy (Figure 2). The copper-bearing veins occur in the poorly jointed portion of the basalt unit, just beneath the lower contact with the siltstone unit (Figure 2). The copper-mineralized veins range from a few millimetres to ten centimetres in thickness (Plate 2). They are easily recognized in the outcrop because of the presence of brightly coloured secondary copper minerals such as malachite and azurite. Bornite and chalcopyrite are the major (primary) copper-sulphide minerals present, and together with calcite, quartz, feldspar and chlorite gangue comprise an 'early stage' of vein filling. Lesser amounts of covellite, chalcocite, and digenite, comprise a late stage of sulphide formation, and typically occur as mineral replacement of or, as crosscutting fractures to the early stage bornite–chalcopyrite assemblage.

## ANALYTICAL METHODS AND RESULTS

Representative samples were collected from each lithological unit. Samples were selected to optimize the range of samples for thin-section and geochemical analyses. Selected thin sections were imaged and various silicate and sulphide phases were analyzed using a Camebax MBX Electron Microprobe. Whole-rock geochemistry samples were selected for internal homogeneity in altered and non-altered rocks and care was taken to avoid veins. The samples collected were analyzed at the Acme Analytical Laboratories, and the analytical methods used are described in Zagorevski (2008).

**MINERAL CHEMISTRY**

**Igneous Minerals**

Multiple pyroxenes were analyzed using the electron microprobe, including matrix clinopyroxene, and both the cores and the rims of phenocrysts (Figure 5); the clinopyroxene was found to be augite (Figure 5). Differences are evident from the core to rim within the phenocrystic pyroxenes, and between the matrix and phenocrystic pyroxenes. The rims and matrix grains tend to be very slightly enriched in iron relative to the cores of phenocrysts. Plagioclase occurs as phenocrysts and matrix phases. All the plagioclase observed in thin section and analyzed on the electron microprobe were found to have restricted $An^{40-55}$ compositions (Figure 5). Phenocryst feldspars exhibit zonation from labradorite core to andesine rim (Figure 5).

**Mineralized Vein Mineralogy**

***Gangue Minerals***

Chlorite was found as a minor component of the gangue mineral assemblage in the mineralized veins and plot in the ripidolite and brunsvigite fields (Hey, 1954). Carbonate was found as a significant component of the gangue mineral assemblage in the mineralized veins and is nearly pure calcite; rodochrosite is a very minor component.

***Sulphides***

The predominant sulphide mineral assemblage within the mineralized veins consists of bornite and chalcopyrite (Figure 5 and Plate 2). These two minerals seem to be coeval, displaying both chalcopyrite–bornite and bornite–chalcopyrite successions (Plate 2). Covellite was observed under microscopy, identified by its distinctive colour and pleochroism (Plate 2), and appears as a minor secondary mineral in the vein assemblage. Other sulphide minerals were found to occur as rims on pre-existing Cu-S minerals, and include chalcocite, digenite, minor amounts of galena and barite (Figure 5).

**WHOLE-ROCK GEOCHEMISTRY**

**Mafic Flow**

Samples (n=12) of the mafic flow (Table 1) were collected from several locations in the spillway. The samples range in composition from basaltic andesite to andesite on a Winchester and Floyd (1977) diagram (Figure 6). The geochemical characteristics of the samples suggest extensive major-element mobility within a single basalt flow. Si, Fe, Mg, Ca, Na, and K show a high degree of scatter relative to typically immobile elements such as Zr and Ti. Several samples were collected to assess the mobility of element within 1 m of a mineralized vein; however, they do not appear to display systematic element mobility. On MORB-normalized trace-element spidergrams, the samples show a consistent

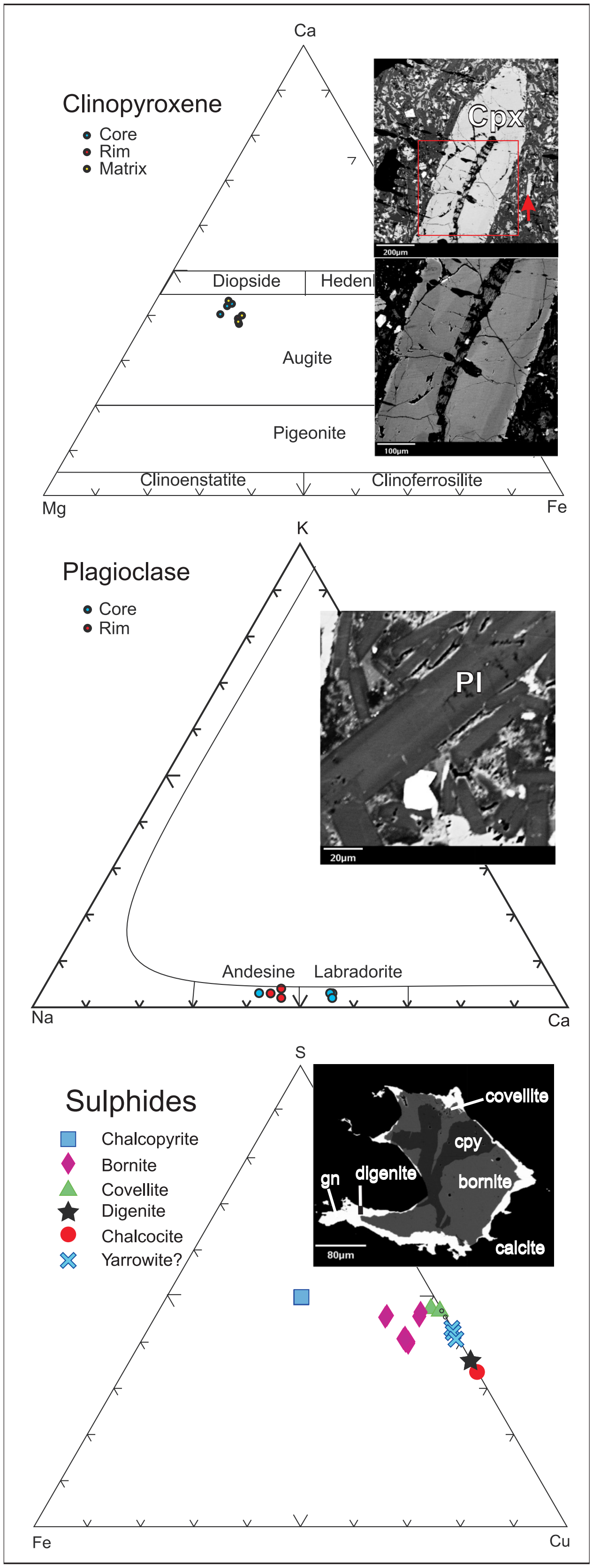



**Figure 5.** (opposite) *Summary of microprobe data for pyroxenes, plagioclase and sulphide minerals with representative SEM images (microprobe data from Case, 2008). Red arrow denotes one occurrence of matrix pyroxene adjacent to the large phenocryst. Both clinopyroxene and plagioclase display slight zoning on SEM images.*

trace-element profile with a prominent Th-Nb anomaly and a moderate to strong LREE and Th enrichment (Figure 6). They completely overlap with the previous analyses of the Topsails Igneous Suite mafic volcanic rocks (Whalen, 1989). The samples plot in the within-plate and calc-alkaline fields on tectonic discrimination diagrams.

### Felsic Volcanic Rocks

Two samples of the felsic volcanic rocks were collected from the lower and upper section of the pyroclastic flow and both samples have a rhyodacite composition (on a Winchester and Floyd (1977) diagram; Figure 6). On MORB-normalized trace-element spidergrams, the samples show a consistent trace-element profile having prominent Th-Nb and Ti anomalies, and moderately to strong LREE, Zr, Hf and Th enrichment. They completely overlap, geochemically, with the previously analyzed Topsails Igneous Suite felsic volcanic rocks (Figure 6; Whalen, 1989).

### Siltstone

Two samples of siltstone were collected (Table 1); one in close proximity to the basalt and the other from immediately below the conglomerate. The trace-element pattern of sample G-107 closely resembles the analyzed basalt (Figure 6). Sample G-108 displays marked depletion of REE, but not Nb, Zr, Hf, or Ti, relative to the first sample. The samples were plotted on a V/Nb vs. Zr diagram (Figure 7), which is a modification of a sedimentary provenance diagram of Rogers *et al.* (2003). Modification was required because Cr, which was used in the original diagram, was consistently below the detection limit (13.7 ppm). Considering the narrow range of Cr concentrations that is possible (*i.e.*, <13.7 ppm) and expectation of higher values in mafic rocks, the spatial spread of the data is likely representative of the differences that would be seen on the V/Nb vs. Zr/Cr diagram. This diagram suggests that the siltstones were mainly derived through chemical weathering of the mafic volcanic rocks, with minor contribution of felsic sources, consistent with presence of weathered mafic lithic fragments in thin section.

**Table 1.** Geochemistry of Hinds Lake area (NAD 83, UTM Zone 21)

| **Sample** | **G-101** | **G-102** | **G-104** | **G-105** | **G-106** | **G-107** | **G-108** | **G-109** |
|---|---|---|---|---|---|---|---|---|
| **Easting** | **489414** | **489411** | **489386** | **489386** | **489385** | **489409** | **489409** | **489409** |
| **Northing** | **54353254** | **5432373** | **5432418** | **5432424** | **5432456** | **5432486** | **5432486** | **5432486** |
| **Lithology** | **Mafic** | **Mafic** | **Mafic dyke** | **Felsic** | **Felsic** | **Siltstone** | **Siltstone** | **Mafic** |
| $SiO_2$ | 56.83 | 52.59 | 46.26 | 71.46 | 70.51 | 64.85 | 60.05 | 54.14 |
| $TiO_2$ | 1.34 | 1.39 | 3.25 | 0.42 | 0.36 | 0.81 | 1.19 | 1.63 |
| $Al_2O_3$ | 15.85 | 16.52 | 12.39 | 14.67 | 13.39 | 12.89 | 15.94 | 17.13 |
| MnO | 0.12 | 0.11 | 0.2 | 0.02 | 0.04 | 0.07 | 0.06 | 0.06 |
| MgO | 3.21 | 2.55 | 4.24 | 0.55 | 1.07 | 1.76 | 1.46 | 1.81 |
| CaO | 6.31 | 5.33 | 6.57 | 1.33 | 2.96 | 3.17 | 2.89 | 2.81 |
| $Na_2O$ | 3.27 | 2.53 | 2.13 | 1.69 | 0.5 | 0.2 | 0.3 | 0.22 |
| $K_2O$ | 2.05 | 2.69 | 0.69 | 3.33 | 3.27 | 2.75 | 3.34 | 3.74 |
| $P_2O_5$ | 0.354 | 0.356 | 0.676 | 0.064 | 0.056 | 0.574 | 0.106 | 0.438 |
| LOI | 2.3 | 8.5 | 9.6 | 3.6 | 6.1 | 6.5 | 7.2 | 6.5 |
| $Fe_2O_3t$ | 8.1 | 7.34 | 13.7 | 2.76 | 1.73 | 6.29 | 7.4 | 11.44 |
| Total | 99.74 | 99.94 | 99.73 | 99.85 | 99.95 | 99.82 | 99.98 | 99.92 |
| Ba | 610 | 195 | 1198 | 285 | 388 | 335 | 330 | 273 |
| Co | 20.2 | 21.5 | 30 | 1.4 | 4.1 | 17.5 | 11.1 | 25.6 |
| Cs | 0.4 | 2.6 | 1.3 | 2.8 | 3.7 | 4.2 | 3.4 | 2.2 |
| Cu | 22.1 | 38 | 22.8 | 1.9 | 2.3 | 1.6 | 2 | 0.7 |
| Ga | 18.2 | 18.4 | 19.4 | 15.7 | 15.9 | 14.9 | 17.3 | 20.3 |
| Hf | 4.1 | 4.6 | 5.9 | 9.1 | 8.6 | 3.6 | 4.1 | 4 |
| Nb | 6.9 | 7.7 | 8.5 | 13.1 | 12.8 | 6.5 | 7.7 | 7.9 |
| Ni | 7.2 | 7.1 | 12.8 | 1.1 | 1.6 | 14 | 3.7 | 4.8 |
| Pb | 6.7 | 2.5 | 3.8 | 5.8 | 5.9 | 7.4 | 8.5 | 3.3 |
| Rb | 40.1 | 92.4 | 19.2 | 87.6 | 89.1 | 75.4 | 78.3 | 88 |
| Sr | 498.8 | 114.6 | 250.8 | 108.1 | 85.7 | 100.5 | 120.5 | 67.3 |
| Ta | 0.4 | 0.4 | 0.5 | 0.8 | 0.8 | 0.4 | 0.4 | 0.5 |
| Th | 5.4 | 5.8 | 3.3 | 16.9 | 15.5 | 6.1 | 5.6 | 6.5 |
| U | 1.6 | 1.7 | 1 | 4.6 | 4.4 | 2.5 | 1.1 | 0.9 |
| V | 194 | 187 | 327 | 21 | 20 | 47 | 87 | 129 |
| Y | 25.3 | 24.7 | 49 | 34.3 | 35.3 | 29.5 | 14.1 | 21.1 |
| Zn | 57 | 67 | 89 | 6 | 11 | 29 | 21 | 43 |
| Zr | 166 | 170.6 | 232.6 | 329.5 | 315.8 | 142.7 | 156.7 | 146.5 |
| La | 22.7 | 22.4 | 21.7 | 42.9 | 37.4 | 29.9 | 15.2 | 21.1 |
| Ce | 50 | 49 | 53 | 90.4 | 78.9 | 63.8 | 37.1 | 53.4 |
| Pr | 6.21 | 6.12 | 7.5 | 10.52 | 9.39 | 7.86 | 3.73 | 6.28 |
| Nd | 24.5 | 23.9 | 33.4 | 37 | 33.5 | 29.9 | 14 | 26.1 |
| Sm | 5.25 | 5.01 | 8.38 | 6.66 | 6.4 | 6.07 | 3.02 | 5.34 |
| Eu | 1.53 | 1.41 | 3.02 | 1.23 | 1.25 | 1.73 | 0.9 | 1.44 |
| Gd | 5 | 4.74 | 9.36 | 5.89 | 5.99 | 5.95 | 2.99 | 4.75 |
| Tb | 0.79 | 0.77 | 1.53 | 0.97 | 1.03 | 0.91 | 0.5 | 0.74 |
| Dy | 4.59 | 4.42 | 8.79 | 5.52 | 5.91 | 5.04 | 2.79 | 4.13 |
| Ho | 0.92 | 0.87 | 1.81 | 1.22 | 1.25 | 1.03 | 0.56 | 0.81 |
| Er | 2.61 | 2.43 | 5.13 | 3.64 | 3.55 | 2.91 | 1.6 | 2.31 |
| Tm | 0.4 | 0.39 | 0.75 | 0.56 | 0.54 | 0.46 | 0.24 | 0.33 |
| Yb | 2.49 | 2.4 | 4.64 | 3.83 | 3.63 | 2.88 | 1.71 | 1.99 |
| Lu | 0.36 | 0.37 | 0.7 | 0.61 | 0.56 | 0.44 | 0.26 | 0.3 |

**Table 1.** Continued

| **G-110 489406 5432544 Mafic** | **G-111 489419 5432570 Mafic** | **G-113 489442 5432655 Mafic** | **G-114 489442 5432655 Mafic** | **G-115 489484 5432735 Mafic** | **G-116 489406 5432544 Mafic** | **G-117 489406 5432544 Mafic** | **G-118 489406 5432544 Mafic** | **G-120 489406 5432544 Mafic** |
|---|---|---|---|---|---|---|---|---|
| 48.83 | 59.08 | 57.77 | 51.95 | 56.76 | 53.83 | 53.53 | 64.93 | 52.53 |
| 1.28 | 1.36 | 1.38 | 1.29 | 1.41 | 1.38 | 1.39 | 1.39 | 1.66 |
| 15.34 | 16.3 | 15.09 | 16.09 | 16.42 | 16.07 | 16.08 | 15.97 | 17.38 |
| 0.11 | 0.09 | 0.14 | 0.08 | 0.11 | 0.1 | 0.13 | 0.05 | 0.07 |
| 2.01 | 2.41 | 3.32 | 0.89 | 3 | 1.67 | 1.23 | 0.51 | 1.92 |
| 8.32 | 2.41 | 5.77 | 18.8 | 5.69 | 5.81 | 6.97 | 2.97 | 3.42 |
| 3.39 | 6.96 | 4.87 | 0.13 | 3.69 | 1.81 | 1.41 | 1.36 | 0.22 |
| 1.56 | 0.72 | 0.37 | -1 | 2.17 | 2.58 | 3.09 | 3.43 | 3.8 |
| 0.344 | 0.362 | 0.363 | 0.344 | 0.348 | 0.358 | 0.362 | 0.363 | 0.417 |
| 9 | 1.9 | 2.3 | 3.4 | 1.9 | 7.6 | 8.2 | 5.1 | 7.3 |
| 9.63 | 8.25 | 8.45 | 6.91 | 8.28 | 8.74 | 7.62 | 3.91 | 11.26 |
| 99.87 | 99.86 | 99.85 | 99.9 | 99.76 | 99.95 | 100.03 | 99.95 | 100.01 |
| | | | | | | | | |
| 158 | 297 | 107 | 10 | 718 | 223 | 236 | 229 | 292 |
| 17.9 | 18.3 | 22.8 | 15.5 | 20.2 | 23.2 | 20.4 | 3.2 | 26.2 |
| 1.9 | 0.2 | -1 | -1 | 0.5 | 2.5 | 3 | 2.4 | 2.3 |
| 2.9 | 12.2 | 134.8 | 44.3 | 24.7 | 1.2 | 1.4 | 4.4 | 1.6 |
| 19 | 17.3 | 17 | 32.9 | 17.3 | 17 | 18.1 | 18 | 19.8 |
| 4.5 | 4.3 | 5.1 | 4.4 | 4.8 | 4.8 | 4.6 | 4.5 | 4.4 |
| 9.1 | 7.8 | 8.3 | 7.6 | 8.2 | 7.3 | 7.2 | 7.2 | 7.6 |
| 7.4 | 8.2 | 7.4 | 7 | 6.9 | 7 | 7.6 | 1.8 | 5.6 |
| 4.6 | 5.6 | 12.5 | 12.8 | 4.5 | 3.4 | 3.8 | 2.1 | 3.5 |
| 40.3 | 20.5 | 11.2 | 0.3 | 51.1 | 66.3 | 79.1 | 85.6 | 93.1 |
| 110.5 | 396.1 | 341 | 488.5 | 525.2 | 103 | 112.8 | 72.9 | 75.9 |
| 0.5 | 0.4 | 0.4 | 0.4 | 0.5 | 0.4 | 0.4 | 0.4 | 0.5 |
| 5.8 | 5.9 | 5.6 | 5 | 6.3 | 6.3 | 6.4 | 5.3 | 6.8 |
| 1.7 | 1.8 | 1.8 | 1.6 | 1.7 | 1.6 | 1.7 | 1.9 | 1 |
| 195 | 189 | 193 | 188 | 194 | 190 | 192 | 181 | 140 |
| 23 | 25.2 | 26.3 | 24 | 27 | 25.1 | 26.4 | 24.2 | 22.9 |
| 65 | 68 | 64 | 22 | 56 | 47 | 33 | 8 | 48 |
| 162.1 | 168.7 | 185.1 | 160.1 | 178.9 | 172.6 | 172.3 | 169 | 157.7 |
| | | | | | | | | |
| 21.6 | 19.3 | 24.8 | 21.3 | 24.4 | 24.5 | 26.5 | 28.3 | 22.5 |
| 49.5 | 44.4 | 53.4 | 46.6 | 53.7 | 54.3 | 59 | 61.6 | 55.6 |
| 6.37 | 6.06 | 6.7 | 5.97 | 6.89 | 6.91 | 7.32 | 7.75 | 6.64 |
| 25.3 | 24.1 | 25.4 | 23.6 | 27.4 | 26.2 | 27.3 | 28.4 | 26 |
| 5.43 | 5.38 | 5.6 | 5.13 | 5.62 | 5.11 | 5.7 | 5.08 | 5.22 |
| 1.79 | 1.57 | 1.52 | 1.44 | 1.59 | 1.47 | 1.61 | 1.15 | 1.55 |
| 5.12 | 5.05 | 5.35 | 4.81 | 5.33 | 4.87 | 5.36 | 4.71 | 4.9 |
| 0.82 | 0.82 | 0.87 | 0.77 | 0.87 | 0.8 | 0.88 | 0.75 | 0.79 |
| 4.29 | 4.53 | 4.88 | 4.33 | 4.89 | 4.29 | 4.85 | 4.43 | 4.24 |
| 0.82 | 0.95 | 1 | 0.91 | 1.01 | 0.93 | 0.96 | 0.88 | 0.82 |
| 2.35 | 2.73 | 2.83 | 2.61 | 2.89 | 2.66 | 2.78 | 2.68 | 2.33 |
| 0.32 | 0.41 | 0.42 | 0.39 | 0.42 | 0.4 | 0.42 | 0.4 | 0.36 |
| 2.01 | 2.55 | 2.69 | 2.37 | 2.76 | 2.56 | 2.62 | 2.55 | 2.16 |
| 0.3 | 0.39 | 0.41 | 0.38 | 0.42 | 0.39 | 0.39 | 0.38 | 0.34 |

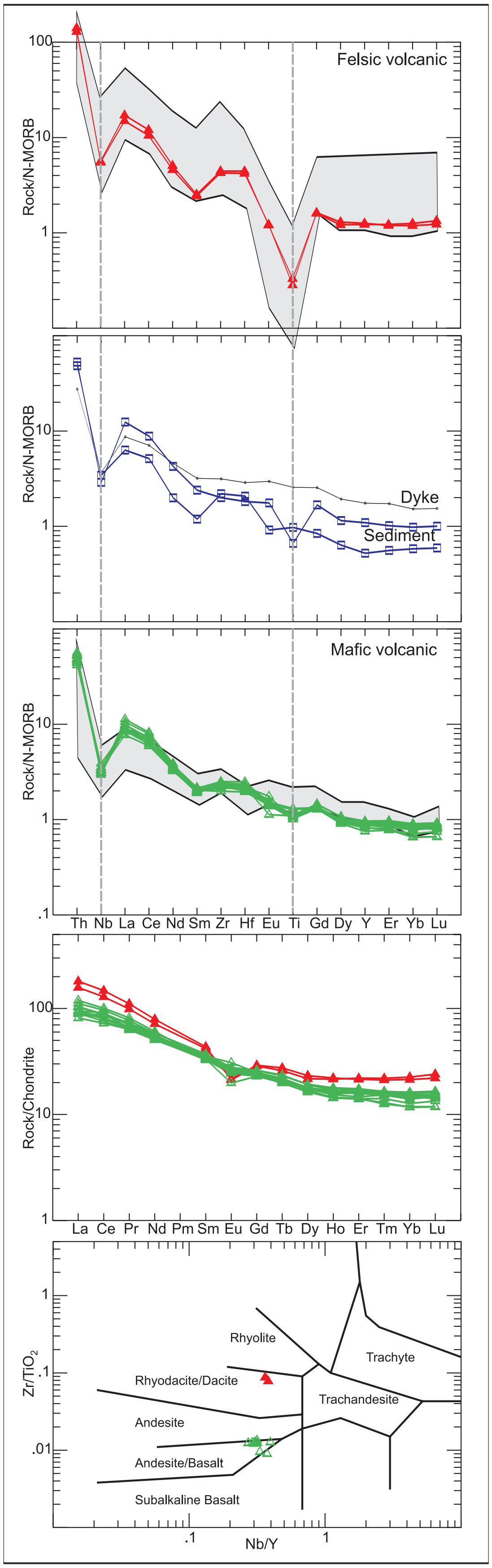



**Figure 6.** (opposite) *Geochemical characteristics of volcanic and sedimentary rocks in the Hinds Lake Dam area (N-MORB normalization values from Sun and McDonough, 1989; Nb/Y vs. Zr/TiO2 diagram from Winchester and Floyd, 1977).*

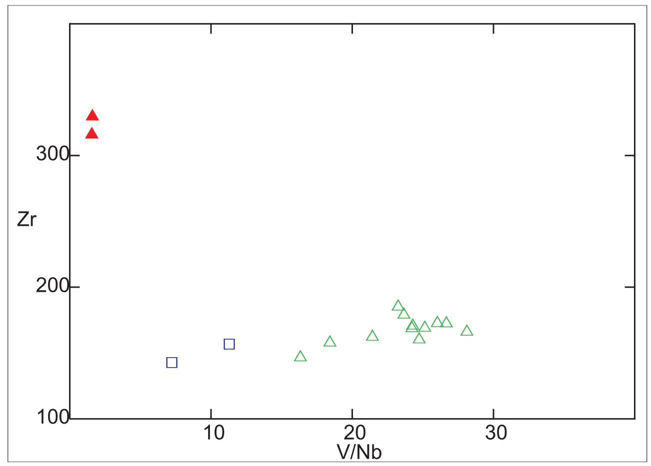



**Figure 7.** *Assessment of the provenance of sedimentary rocks on the basis of V/Nb vs Zr diagram (modified from Rogers* et al., *2003 due to Cr concentration below detection limit).*

## DISCUSSION AND INTERPRETATION

The mafic volcanic rocks form a thick, columnar jointed flow. The lack of pillow structures and the presence of well-developed columnar joints suggest that the flow erupted subaerially or in shallow-marine environment. The basaltic flow-top breccia does not appear to be preserved; hence the deposition of the siltstone was probably preceded by a short period of erosion. The siltstone indicates a period of volcanic and tectonic quiescence, interrupted by a distal volcanic eruption (bentonite layer). The deposition of siltstone and preservation of delicate bentonite layer may suggest a lacustrine or fluvial setting, but requires further investigation. Following the deposition of siltstone, there was an increase in the energy of the environment, marked by deposition of fluvial- or shallow-marine conglomerates that excised the siltstone horizon. This increase in energy was followed by the eruption of a thick proximal welded ignimbrite felsic flow. The eutaxitic textures and columnar joints associated with these felsic volcanic rocks are also consistent with a subaerial- to shallow-marine depositional environment (Freundt *et al.*, 2000).

The stratigraphic relationships suggest a very dynamic environment of deposition. The conglomerate unit has different stratigraphic thicknesses in different fault blocks (Plate 1A). One possibility is that the conglomerate was deposited in channels with lens-type morphologies, which is, in part, supported by its morphology. However, faults mark significant changes in stratigraphic thickness. Since the motion on the faults does not appear to have a significant oblique-slip component, it is probable that these relationships may suggest that the faults were active during the deposition of the conglomerates and were thus, in part, syn-sedimentary. Considering an epicontinental caldera environment proposed for the Springdale Group (Coyle and Strong, 1987), the faults may represent structures related to caldera development.

The mineralization occurring in the spillway of the Hinds Lake dam is hosted by carbonate veins that have a preferred orientation. Petrographic investigation, combined with electron microprobe analysis, indicate that the copper sulphides are mainly composed of bornite, chalcopyrite and covellite. These veins appear to be stratigraphically restricted to the uppermost portions of the basalt, occurring immediately beneath the sedimentary units. This horizon is only exposed within a limited section of the floor of the spillway; however, the large areal exposure of the Springdale Group (Whalen and Currie, 1983) suggests that the mineralized zone could extend laterally over a much larger area. The presence of potential syn-sedimentary faults during deposition of the volcano-sedimentary units may have provided an important pathway for fluid migration during mineralization.

## COMPARISON TO DEPOSIT TYPES

The Hinds Lake mineralization is significantly different from the typical base-metal deposits in Newfoundland, which are predominantly volcanogenic massive sulphide deposits associated with submarine volcanic sequences (*e.g.*, Thurlow and Swanson, 1981; Evans and Kean, 2002; Squires and Moore, 2004). In contrast with the polymetallic volcanogenic massive sulphide deposits, the mineralization in the Hinds Lake area is hosted by subaerial (or shallow-marine) volcanic rocks, and is characterized by predominantly copper minerals with very minor late lead and barium, as well as a paucity of iron sulphides. The association of the Hinds Lake mineralization with subaerial volcano-sedimentary rocks suggests closer affinities to the volcanic redbed copper (VRC) deposit type (Kirkham, 1984, 1995b).

A summary of the key features of the Hinds Lake mineralization and VRC deposits is presented in Table 2 and Figure 8. The following description of VRC deposits is a summary of Kirkham (1995b). Volcanic redbed copper (VRC) deposits are widely distributed in subaerial flood basalt sequences but also commonly occur in differentiated continental and island-arc sequences. These deposits have not been important sources of copper in Canada because they are generally narrow, tabular and small. However, VRC deposits can be very prospective as exemplified by the major copper district in the Keweenaw Peninsula (Michigan, USA). These deposits are generally restricted to subaerial- to shallow-marine rocks that display evidence of oxidation, although some deposits may occur in submarine volcanic sequences (Cabral and Beaudoin, 2007).

The VRC deposits share many characteristics and commonly occur in association with the redbed sedimentary copper deposits (Kirkham, 1995a). Early oxidation of basaltic rocks is thought to liberate metals and facilitate their transport by oxidized chloride±sulphate-rich brines. These brines can either follow permeable stratigraphic horizons such as sandstone or volcanic breccia, or structures such as syn-sedimentary faults. The deposition of the metals is thought to occur as a result of reduction of sulphate to sulphide; however, the nature of the reduction process is unknown in many deposits but may have been aided by presence of carbonaceous material (Kirkham, 1995a, b). The VRC and redbed sedimentary copper deposits commonly exhibit mineral zonation comprising chalcocite to chalcopyrite and bornite to pyrite (Figure 8).

Similar to VRC deposit type, the Hinds Lake mineralization is hosted by a continental subaerial- to shallow-marine volcano-sedimentary sequence, deposited in a transitional arc to non-arc setting at low paleolatitude (Cocks and Torsvik, 2002). The basaltic rocks have been extensively oxidized prior to mineralization as indicated by the mineralized veins cutting well-developed hematitic alteration, which locally has liesegang morphology. The preservation of igneous mineralogy in the basalt, lack of systematic wall-rock alteration and restricted occurrence of sulphides in veins suggest that the mineralizing brines were not locally derived, but may have travelled along pre-existing structures such as syn-sedimentary faults.

The occurrence of the vein-hosted mineralization in the oxidized upper part of the basalt flow indicates that there is a strong structural and stratigraphic control on the deposition of the metals. Presence of redox boundary is inferred for many VRC deposits; however the reason for the deposition of metals in the Hinds Lake area is uncertain. Presence of fine-grained lacustrine or fluvial deposits in contact with redbeds has been used as exploration criteria for Kupferschiefer-type deposits (Kirkham, 1995a). Occurrence of dark siltstone above the oxidized basalt may have played a role, as the siltstone may have been reduced.

**Table 2.** Summary of volcanic redbed copper deposits (Kirkham, 1995a) and Hinds Lake area mineralization

| | **Volcanic Redbed Copper** | **Hinds Lake Area** |
|---|---|---|
| Mineral Assemblage | Simple native copper or copper sulphide; not polymetallic, low in iron sulphides | Bornite–chalcopyrite, minor covellite, trace digenite and galena, no pyrite |
| Deposit morphology | Typically disseminated or in veins characterized by quartz-carbonate gangue mineralogy | Narrow tabular zone of calcite–quartz± chlorite veins |
| Alteration | Wall-rock alteration is insignificant or absent; commonly characterized by low-metamorphic grade mineral assemblages | No systematic wall-rock alteration, prehnite-pumpellyite veins |
| Depositional environment | Rocks are deposited in a sub-aerial environment and were in an oxidized state | Sub-aerial to shallow-marine environment with extensive oxidation of upper basalt flow and deposition of redbed sediments |
| Depositional environment | Arid to semi-arid, low-latitude areas | Silurian Laurentian margin was located at ~14ºS (Cocks and Torsvik, 2002) |
| Associated deposits | Sedimentary copper deposits (i.e., redbed and Kupferschiefer-type) | None described, but there has not been any systematic exploration |

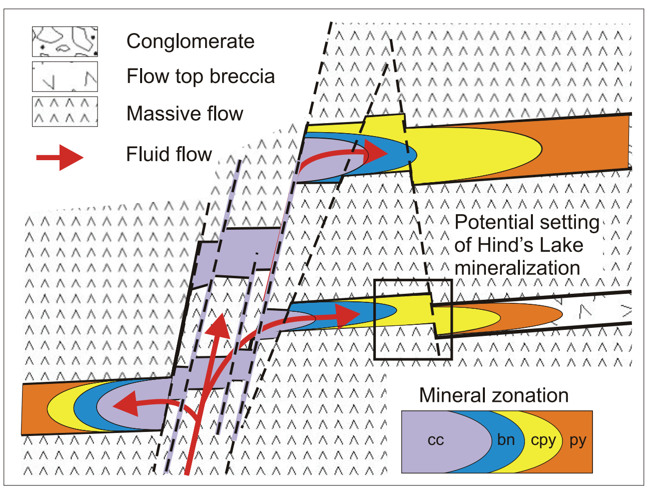



**Figure 8.** *A. Schematic diagram illustrating volcanic redbed copper mineralization and mineral zonation in a volcano-sedimentary sequence (modified from Kirkham, 1995b). Comparison to the study area suggests that Hinds Lake volcanic redbed copper mineralization may have formed in a setting similar to the peripheral cpy-bn zones. cc-chalcocite, bn-bornite, cpy-chalcopyrite, py-pyrite.*

The VRC mineralization in the Hinds Lake area does not appear to exhibit chalcocite–chalcopyrite–bornite–pyrite mineral zonation, which is commonly observed in the VRC deposits (Kirkham, 1995b). Chalcocite, a major component of many VRC deposits (Figure 8), has been identified as a late phase in one vein; however, it is generally absent from the studied section. Hence, the studied section may expose only the peripheral zone of a larger VRC mineralization.

## CONCLUSIONS

The Hinds Lake spillway mineralization is stratigraphically limited to the subaerial mafic volcanic rocks of the Silurian Springdale Group. The mineralization is atypical for the Central Mobile Belt within Newfoundland, in that it does not display typical mineral assemblages of volcanogenic massive sulphide deposits hosted by submarine arcs and subduction-related volcanic sequences, such as those in the Buchans Group and Victoria Lake supergroup (*e.g.*, Swinden *et al.*, 1997). Rather, it shares many features with the volcanic redbed copper deposit group (Kirkham, 1984, 1995b). The recognition of this different style of mineralization, which formed at a time that is not generally linked with base-metal mineralization in the Canadian Appalachians (for exception, *see* Cabral and Beaudoin, 2007), in itself warrants continued investigation. Given the large aerial extent of the relatively unexplored Springdale Group, and the possibility that this mineralized zone could extend beneath a thin cover of felsic volcanic rocks over a significant region, a re-evaluation of the base-metal potential of the Silurian volcanic sequences in central Newfoundland is warranted.

## ACKNOWLEDGMENTS

This project forms part of first author's B.Sc. thesis supported by the Geological Survey of Canada Targeted Geoscience Initiative 3: Newfoundland Appalachians (GSC contribution # 20080495). The manuscript has benefited from reviews by R. Taylor, N. Rogers and J. Hinchey.

## REFERENCES

Cabral, A.R. and Beaudoin, G.
2007: Volcanic red bed copper mineralisation related to submarine basalt alteration, Mont Alexandre, Quebec Appalachians, Canada. Mineralium Deposita, Volume 42, No. 8, pages 901-912.

Case, G.
2008: Nature and Distribution of Copper Mineralization in the Hind's Lake Spillway, Howley Area: Carleton University, 78 pages.

Chandler, F.W., Sullivan, R.W. and Currie, K.L.
1987: The age of the Springdale Group, western Newfoundland, and correlative rocks; evidence for a Llandovery overlap assemblage in the Canadian Appalachians. Transactions of the Royal Society of Edinburgh, Earth Sciences, Volume 78, No. 1, pages 41-49.

Cocks, L.R.M. and Torsvik, T.H.
2002: Earth geography from 500 to 400 million years ago; a faunal and palaeomagnetic review. Journal of the Geological Society of London, Volume 159, Part 6, pages 631-644.

Coyle, M. and Strong, D.F.
1987: Geology of the Springdale Group; a newly recognized Silurian epicontinental-type caldera in Newfoundland. Canadian Journal of Earth Sciences, Volume 24, No. 6, pages 1135-1148.

Evans, D.T.W. and Kean, B.F.
2002: The Victoria Lake supergroup, central Newfoundland - its definition, setting and volcanogenic massive sulphide mineralization. Newfoundland Department of Mines and Energy, Geological Survey, Open File NFLD/2790, page 68.

Freundt, A., Wilson, C.J.N. and Carey, S.N.
2000: Ignimbrites and block-and-ash flow deposits. *In* Encyclopoedia of Volcanoes. *Edited by* H. Sigurdsson. San Diego, Academic Press, pages 581-600.

Hey, M.H.
1954: A new review of chlorites. Mineralogical Magazine, Volume 224, pages 277-292.

Hibbard, J.
1983: Geology of the Baie Verte Peninsula, Newfoundland: Memoir - Government of Newfoundland and Labrador, Department of Mines and Energy, Mineral Development Division.

Kausch, E.
1981: Report on the assessment work done during 1980-1981 on ground staked licences 1726 and 1749 in the Hinds Brook area, Newfoundland. Kausch, E, Atlantic Analytical Services Limited, Bell-White Analytical Laboratories Limited, and Technical Service Laboratories Unpublished report, 14 pages. [GSB# 012H/03/0740]

Kirkham, R.V.
1984: Volcanic redbed copper. Geological Survey of Canada, Economic Geology Report, Volume 36, 37 pages.

1995a: Sediment-hosted stratiform copper. *In* Geology of Canada. Edited by O.R. Eckstrand, W.D. Sinclair and R.I. Thorpe. Geological Survey of Canada, Geology of Canada, pages 223-240.

1995b: Volcanic redbed copper. *In* Geology of Canada. *Edited by* O.R. Eckstrand, W.D. Sinclair, W. D. and R.I. Thorpe. Geological Survey of Canada, Geology of Canada, pages 241-252.

Rogers, N., van Staal, C.R., Winchester, J.A. and Fyffe, L.R.
2003: Provenance and chemical stratigraphy of the sedimentary rocks of the Miramichi, Tetagouche, California Lake, and Fournier Groups, northern New Brunswick. Economic Geology Monographs, Volume 11, pages 111-128.

Squires, G.C. and Moore, P.J.
2004: Volcanogenic massive sulphide environments of the Tally Pond Volcanics and adjacent area; geological, lithogeochemical and geochronological results. *In* Current Research. Newfoundland and Labrador Department of Natural Resources, Geological Survey Branch, Report 04-1, pages 63-91.

Sun, S.S. and McDonough, W.F.
1989: Chemical and isotopic systematics of oceanic basalts; implications for mantle composition and processes. Geological Society, Special Publications, Volume 42, pages 313-345.

Swinden, H.S. Jenner, G.A. and Szybinski, Z.A.
1997: Magmatic and tectonic evolution of the Cambrian-Ordovician Laurentian margin of Iapetus; geochemical and isotopic constraints from the Notre Dame Subzone, Newfoundland. Geological Society of America, Memoir, Volume 191, pages 337-365.

Thurlow, J.G. and Swanson, E.A.
1981: Geology and ore deposits of the Buchans area, central Newfoundland. Geological Association of Canada, Special Paper, Volume 22, pages 113-142.

van Staal, C.R.
2005: North America; Northern Appalachians. *In* Encyclopedia of Geology. *Edited by* R.C. Selley, L.R.M. Cocks and I.R. Plimer. Oxford, Elsevier Academic Press, pages 81-92.

van Staal, C.R., Whalen, J.B., McNicoll, V.J., Pehrsson, S., Lissenberg, C.J., Zagorevski, A., van Breemen, O. and Jenner, G.A.
2007: The Notre Dame Arc and the Taconic Orogeny in Newfoundland. *In* 4-D Framework of Continental Crust. *Edited by* R.D. Hatcher, Jr., M.P. Carlson, J.H. McBride and J.R. Martinez Catalan. Pages 511-552.

Whalen, J.B.
1989: The Topsails igneous suite, western Newfoundland; an Early Silurian subduction-related magmatic suite? Canadian Journal of Earth Sciences, Volume 26, No. 12, pages 2421-2434.

Whalen, J. B. and Currie, K. L.
1983: Geology of the Topsails igneous terrane, western Newfoundland, Report 923.

Whalen, J.B., Currie, K.L. and van Breemen, O.
1987: Episodic Ordovician-Silurian plutonism in the Topsails igneous terrane, western Newfoundland. Transactions of the Royal Society of Edinburgh, Earth Sciences, Volume 78, No. 1, pages 17-28.

Whalen, J.B., Jenner, G.A., Longstaffe, F.J., Gariepy, C. and Fryer, B.J.
1997: Implications of granitoid geochemical and isotopic (Nd, O, Pb) data from the Cambrian-Ordovician Notre Dame Arc for the evolution of the central mobile belt, Newfoundland Appalachians. Geological Society of America, Memoir, Volume 191, pages 367-395.

Whalen, J.B., McNicoll, V J., van Staal, C.R., Lissenberg, C.J., Longstaffe, F.J., Jenner, G.A. and van Breemen, O.
2006: Spatial, temporal and geochemical characteristics of Silurian collision-zone magmatism: an example of a rapidly evolving magmatic system related to slab break-off. Lithos, Volume 89, No. 3-4, pages 377-404.

Williams, H.
1995a: Chapter 3: Dunnage Zone - Newfoundland. *In* Geology of the Appalachian-Caledonian Orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, pages 142-166.

1995b: Chapter 2: Temporal and spatial divisions. *In* Geology of the Appalachian-Caledonian Orogen in Canada and Greenland. *Edited by* H. Williams. Geological Survey of Canada, pages 23-42.

Winchester, J.A. and Floyd, P.A.
1977: Geochemical discrimination of different magma series and their differentiation products using immobile elements. Chemical Geology, Volume 20, No. 4, pages 325-343.

Zagorevski, A.
2008: Preliminary geochemical database of the Buchans-Robert's Arm belt, central Newfoundland. Geological Survey of Canada Open File 5986, 1 CD-ROM.