THE SPECTRUM OF ORE DEPOSIT TYPES, THEIR ALTERATION AND VOLCANIC SETTING IN THE PENOKEAN VOLCANIC BELT, GREAT LAKES REGION, USA

by

Patrick O. Quigley
A thesis submitted to the Faculty and Board of Trustees of the Colorado School of Mines in partial fulfillment of the requirements for the degree of Master of Science (Geology).

Golden, Colorado

Date ________________

Signed: ________________________

Patrick O. Quigley

Signed: ________________________

Dr. Thomas Monecke

Thesis Advisor

Golden, Colorado

Date ________________

Signed: ________________________

Dr. Steve Enders

Interim Department Head

Department of Geology and Geological Engineering
ABSTRACT

The Paleoproterozoic Penokean volcanic belt hosts one of the most important VMS districts worldwide. Despite the significant mineral endowment of the region, scientific understanding of the mineral deposits is limited, resulting from a relative lack of exploration and production coupled with extensive glacial deposits that cover much of the region. The current thesis presents new drill core observations, geochemistry, and petrography to supplement previous research on the most important mineral deposits in the region. A synthesis of this data provides an update to the understanding of the tectonic-volcanic setting, alteration styles, and mineralization processes for mineral deposits across the Penokean volcanic belt.

The results of the present study reveal that most of the Penokean sulfide deposits are classical VMS deposits despite a wide range of alteration and mineralization characteristics. The deposits form a bimodal distribution of Cu-type and Zn-Cu type massive sulfide deposits and, with the exception of the Lynne deposit, most of the significant deposits contain low concentrations of lead. In addition, three of the deposits, namely Back Forty, Bend, and Crandon, have elevated gold contents. The Reef Au-Cu deposit, located in the Wausau volcanic complex is a gold-rich sulfide deposit that is characterized by strongly deformed and recrystallized rocks of an unknown mafic protolith. This deposit is unique amongst the VMS deposits in the belt and appears to have formed within a distinct geodynamic environment.

The styles of hydrothermal alteration vary between deposits, with white-mica-chlorite-quartz assemblages being the most prevalent. Aluminous alteration represented by andalusite-biotite-white mica schists has been noted at Flambeau and calc-silicate mineral assemblages are present at Lynne, Ritchie Creek, and Reef. Calc-silicate mineral associations have also been observed at the Pelican River and Spirit deposits, suggesting that the volcanic host rocks were originally interbedded with limestone or carbonate-altered. Regional metamorphism varies from lower greenschist to amphibolite grade and has obscured relationships in some deposits.

All major VMS deposits of the Penokean volcanic belt occur within felsic-dominated volcanic successions and are hosted by vent-proximal volcanic facies associations. For example, the Back Forty deposit is hosted within a felsic succession comprising coherent rhyolite units and associated volcanic breccias that is at least 1200 meters thick. Some of the smaller deposits recognized, including Ritchie Creek and Bend, are characterized by a thick succession of fine-grained, bedded volcaniclastic deposits that are interpreted to represent distally derived volcanic material. Mafic-dominated host rock successions
are uncommon in the Penokean volcanic belt and the Horseshoe prospect represents the only known deposit that occurs within a dominantly basaltic volcanic succession.

The present study indicates that the Penokean VMS district is best classified as a bimodal-felsic lithostratigraphic type. Chemically, the felsic volcanic rocks hosting the VMS deposits appear to have been generated from a highly evolved source which may have included partial melting of continental crust. These data indicate that the Penokean VMS deposits formed within a rifted continental margin arc that formed along the southern margin of the Superior Craton. The data presented here provides an updated volcanological, geochemical, and genetic prospective for the formation of VMS deposits across the Penokean volcanic belt and can be used to guide future exploration and research in the region.
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LIST OF ABBREVIATIONS

GENERAL

AEM  airborne electromagnetic
AI   Ishikawa alteration index
BSE  back scatter electron (image)
CCPI chlorite-carbonate-pyrite index
cm   centimeter
CPL  crossed polarized light
Cu   copper
EDS  energy dispersive spectroscopy
g/t  grams/tonne
ICP-MS  inductively coupled plasma-mass spectrometry
km   kilometer
kV   kilovolt
LIL  large ion lithophile
LREE light rare earth element
m    meter
mm   millimeter
μm  micrometer
Ma   mega annum (million years ago)
Mt   million tonnes
N    north
NE   northeast
NW   northwest
oz/t ounces/ton
PPL  plane polarized light
ppm  parts per million
S    south
SE   southeast
SEM  scanning electron microscope
SW   southwest
t    ton
<table>
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<tr>
<th>Abbreviation</th>
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<tr>
<td>VMS</td>
<td>volcanogenic massive sulfide</td>
</tr>
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<td>XRF</td>
<td>X-ray florescence</td>
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**ELEMENTS AND MINERALS**

<table>
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<th>Description</th>
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<td>ac</td>
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<td>(Ag)gn</td>
<td>argentiferous galena</td>
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<td>andalusite</td>
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<td>mag</td>
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mel  melonite
Mg   magnesium
MgO  magnesium oxide
ms   muscovite
Na₂O sodium oxide
Nd   neodymium
pet  petzite
Pb   lead
pyr  pyrargyrite
py   pyrite
po   pyrrhotite
qz   quartz
Rb   rubidium
sp   sphalerite
ste  stephanite
syv  sylvanite
Te   tellurium
Th   thorium
Ti   titanium
TiO₂ titanium oxide
tr   tremolite
Zn   zinc
Zr   zirconium
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CHAPTER 1
INTRODUCTION

The Paleoproterozoic (ca. 1880 Ma) Penokean volcanic belt represents one of the most important orogenic belts hosting volcanogenic massive sulfide (VMS) deposits worldwide (Franklin et al., 2005). It extends for over 250 kilometers across northern Wisconsin and the southwestern portion of the Upper Peninsula of Michigan. The dominantly submarine volcanic rocks comprising the belt were formed in a suprasubduction setting at the southern edge of the Superior craton. Despite relatively minor exploration, the majority of which occurred intermittently from 1970 to 1990, approximately 110 million metric tons of polymetallic massive sulfides have been delineated across the belt. However, so far only the supergene enrichment zone of the Flambeau deposit in the western part of the Penokean volcanic belt has reached commercial production. The mined resource accounts for less than 2% of known mineral reserves, which makes the Penokean volcanic belt one of the most accessible, undeveloped, and underexplored VMS districts in the world.

Despite the significant mineral endowment of the region, scientific understanding of the mineral deposits of the Penokean volcanic belt is limited. This is, at least in part, related to the fact that the Penokean volcanic belt is extensively covered by Pleistocene glacial deposits and outcrop exposure is scarce in many parts of the belt. As such, much of the bedrock geology of the region has been inferred from geophysical data and sparse exploration drilling which limits the ability to correlate volcanic environments and stratigraphy across the belt. As there is a strong stratigraphic control on VMS deposits (Allen et al., 2002; Franklin et al., 2005), understanding the volcanic setting is crucial for the development of metallogenetic models and focused exploration in the Penokean volcanic belt. Discovery of the Back Forty deposit in 2002, which was exposed at surface, highlights the potential for additional discoveries to be made and the relative immaturity of exploration across the belt.

The current study presents new geochemical, volcanological, and petrographic data collected from the most important VMS deposits across the Penokean volcanic belt. An updated mineral inventory is provided for the known mineral deposits and a compilation of historic data is used to supplement the current study. This research documents the volcanic setting of significant VMS deposits across the belt and describes the different styles of alteration and mineralization recognized. The following discussion considers the tectonic and volcanic setting of Penokean mineral deposits, the broad spectrum of ore forming conditions recognized, and how this can be applied to future exploration and research in the region.
The Penokean orogen is bounded by the Archean Superior craton to the north and east and by younger orogenic belts, including the Yavapai and Mazatzal provinces, to the south (Fig. 2-1). The Penokean belt is covered by Paleozoic sedimentary rocks to the east where it is thought to extend to the Grenville orogen in the Lake Huron region (Sims, 1993) and is bisected by the middle Proterozoic Midcontinent Rift that formed at ~1100 Ma. The Penokean orogen has been divided into two major domains. The northern, external domain consists predominantly of foreland basin derived meta-sedimentary rocks. The southern, internal domain is primarily composed of metamorphosed submarine volcanic and plutonic rocks, representing at least two accreted terranes (Fig. 2-2).

Fig. 2-1: Basement geology of the Lake Superior region as defined from geophysical investigations (Holm et al., 2007).
2.1. External Domain

The external domain of the Penokean orogenic belt consists of a continental margin sedimentary basin assemblage formed largely from tectonic subsidence of the North American craton during arc accretion (Schulz and Cannon, 2007). Rock types are predominantly thick turbidite successions of clastic and chemical sedimentary rocks interbedded with subordinate tholeiitic volcanic rocks (DeMatties, 1994) that were deposited on Archean basement of the southern edge of the Superior craton. The foreland basin assemblage contains the classic Superior-type iron formations that have been extensively mined in the region. The foreland sedimentary rocks were incorporated in the advancing fold and thrust belt developed northward of the collision zone, resulting in metamorphic grades ranging up to amphibolites facies. The external domain is characterized by few granitic intrusions. A more detailed discussion on the geology of the northern, external domain is given by Morey (1996), Ojakangas et al. (2001), and Schulz and Cannon (2007).

2.2. Internal Domain

The ~1889–1835 Ma internal domain, also referred to as the Penokean volcanic belt or Wisconsin magmatic terrane, is a prominent volcanic belt that is variably exposed across a significant portion of northern Wisconsin, approximately 275 km along strike and 150 km wide. The true extent of the volcanic belt is likely much larger and has been interpreted to extend westward across the Midcontinent Rift into Minnesota and eastward beneath Paleozoic sedimentary rocks where it is truncated by the Spirit Lake Tectonic Zone (Holm et al., 2007). The Penokean volcanic belt is separated from the northern continental assemblage by the Niagara fault zone, a large shear zone up to 10 kilometers in width that is interpreted as a paleosuture zone (Sims et al., 1989; Schulz and Cannon, 2007). The belt is comprised of an extensive suite of tholeiitic to calc-alkaline volcanic and plutonic rocks with subordinate associated sedimentary rocks. At least two distinct terranes have been recognized by previous workers, referred to as the Marshfield and Pembine-Wausau terranes (Fig. 2-2).
**Marshfield Terrane**

The Marshfield terrane is a poorly exposed volcanic terrane in central and western Wisconsin that is largely covered by Paleozoic sedimentary rocks. Over half of the terrane is composed of Archean gneissic rocks which are overlain by Paleoproterozoic volcanic rocks formed at about 1870–1860 Ma (Sims et al., 1989). Due to limited outcrop exposure and complex structural overprint, information on the volcanic successions is limited. The Paleoproterozoic volcanic strata consist primarily of an interbedded succession of mafic-felsic volcanic rocks and associated sedimentary rocks. Conglomerates locally contain clasts of Archean granitic gneiss, which are evidence that the terrane was deposited on Archean crust and that this crustal material was recycled (Schulz and Cannon, 2007). Geochemical and isotopic investigations have shown that intrusive rocks in the Marshfield terrane have distinct εNd values and radiogenic Pb isotopes that separate these intrusions from those in the Pembine-Wausau terrane (Van Wyck and Johnson, 1997). The distinctive geochemical signature of these intrusions are not found...
elsewhere in the orogen, providing evidence that the underlying crust is not a rifted portion of the Superior craton and likely represents an exotic Archean micro-continent (Holm et al., 2007). The Marshfield terrane is separated from the Pembine-Wausau terrane by the Eau Pleine shear zone, which is interpreted as a paleosuture zone (Sims et al., 1989).

**Pembine-Wausau Terrane**

Rocks of the Pembine-Wausau terrane are predominantly calc-alkaline and tholeiitic volcanic rocks with primitive to evolved arc compositions (Schulz and Cannon, 2007). Rocks within this terrane are variably exposed at surface and are locally covered by up to 60 meters of Quaternary glacial deposits, leaving only certain areas with sufficient outcrop exposure to permit detailed geologic mapping and interpretation. Thus, geophysical surveys and exploration drilling across the belt have been important for the extrapolation of bedrock geology across the terrane. The Pembine-Wausau terrane has been further divided into two distinct complexes, namely the Ladysmith-Rhinelander volcanic complex in the north and Wausau volcanic complex in the southeast (Fig. 2-3).

The Ladysmith-Rhinelander volcanic complex, which forms the northern part of the Pembine-Wausau terrane, can be subdivided into two distinct domains based on structural setting, geophysical signature, and lithology (Fig. 2-3). Limited radiometric dating of volcanic rocks from these two domains suggests that volcanism in both domains was approximately contemporaneous and occurred between 1889–1860 Ma (DeMatties, 1994).

The northern domain of the Ladysmith-Rhinelander volcanic complex is comprised largely of mafic volcanic rocks that have been metamorphosed to amphibolite grade that largely destroyed primary volcanic textures. The magnetite-rich composition of these units produces distinct geophysical expressions that allows for extrapolation of these units across the belt. Thin Algoma-type oxide facies iron-formation and serpentined ultramafic rocks are common and distinctive to this domain. DeMatties (1994) interpreted this domain to represent the remnants of a volcanic arc that formed the core of the Ladysmith-Rhinelander volcanic complex. Also present, but to a lesser degree, are associated interflow sedimentary rocks that have been metamorphosed to quartzofeldspathic schists. Deformation of the volcanic rocks of the northern domain of the Ladysmith-Rhinelander volcanic complex has produced tight, steeply plunging antiforms and synforms.
Fig. 2-3: Geology of the Penokean volcanic belt (modified from DeMatties, 1994). The main base and precious metal deposits and occurrences are Flambeau (1), Bend (2), Lynne (3), Crandon (4), Back Forty (5), Eisenbrey/Thornapple (6), Ritchie Creek (7), Hawk (8), Horseshoe (9), Pelican River (10), Catwillow (11), and Reef (12).
The southern domain of the Ladysmith-Rhinelander volcanic complex has been interpreted to represent an extensional back-arc basin succession (DeMatties, 1994) composed dominantly of tuffaceous meta-sedimentary rocks that flank the main volcanic arc succession. This domain has been metamorphosed to greenschist facies, distinctly lower grade than the northern domain and volcanic textures are generally well preserved. The rocks are characterized by a weak magnetic response, which allows discrimination of this domain from the more highly magnetic northern domain. However, this domain includes distinct magnetic features that have been defined by drilling as mafic to intermediate volcanic and plutonic units.

Distinct features associated with the southern domain include 1) a series of linear electromagnetic features related to carbonaceous, sulfidic argillite formations and 2) discrete felsic volcanic centers and associated chemical sedimentary rocks. The felsic rocks in the southern domain have been variably metamorphosed to quartz-white mica+/chlorite schists and volcanic facies recognized range from volcanic breccias to coherent, flow-banded rhyolite domes. Their geophysical signature is defined by a weak magnetic signal which makes it difficult to discriminate them from other units in the domain and thus, their true spatial extent is unknown.

**Wausau Volcanic Complex**

Calc-alkaline andesite, dacite, and rhyolite are abundant in the southern portion of the Pembine-Wausau terrane in Marathon County, north of the Eau Pleine shear zone (Fig. 2-3). These volcanic rocks are interpreted to be younger than the Ladysmith-Rhinelander volcanic complex to the north due to their different structural style and generally lower metamorphic grade (LaBerge and Meyers, 1984), although this has been disputed (Maas et al., 1985). At one locality these rocks have been documented to lie unconformably atop granodiorite and tonalite intrusive rocks that have been dated at 1850–1837 Ma (Sims et al., 1989), which substantiates a younger age for at least some of these volcanic rocks. Although poorly constrained by radiometric dating, these volcanic rocks appear to have been deposited between about 1835–1845 Ma. Geochemically, the Wausau volcanic complex appears to be distinct from the calc-alkaline suite in the Ladysmith-Rhinelander complex with a more enriched LREE and LIL element signature. This may reflect geographic compositional zoning of the Pembine-Wausau terrane or more significant crustal contamination, which is further supported by the relative abundance of felsic volcanic rocks within this terrane (Sims et al., 1989). The Wausau volcanic complex was intruded by the large Wolf River batholith and the Wausau syenite-granite plutonic series which represent anorogenic,
Mesoproterozoic (~1470 Ma) intrusive complexes that are distinctive to the southern Pembine-Wausau terrane (Sims et al., 1989).

2.3. Mineral Deposits of the Penokean Volcanic Belt

Recognition of a greenstone belt in northern Wisconsin belt in the 1960’s led to an extensive exploration effort in the region and the eventual discovery of over 13 volcanogenic massive sulfide deposits and occurrences (Fig. 2-3). Despite the significant resources identified, the belt remains almost entirely undeveloped, largely under explored, and poorly studied due to thick glacial deposits that cover the bedrock and an unfavorable socio-political climate in Wisconsin that has effectively prevented exploration and development over the past several decades. However, the discovery of the Back Forty deposit in 2002 and recent permitting activities may be an indication of a renewed interest in the belt.

A detailed account of the early exploration history in the Penokean volcanic belt is given by Mudrey et al. (1991) and Babcock (1996). According to these authors, similarities of the volcanic rocks in northern Wisconsin to those in the Canadian shield led early workers to recognize the economic potential of the Penokean volcanic belt in the late 1960’s. Concurrently, important advances in the understanding of the VMS deposit model were made and new airborne electromagnetic methods were developed. The advanced airborne electromagnetic technology was ideally suited for exploration in the Penokean volcanic belt, which is largely covered by thick glacial deposits. Early geophysical surveys targeted the western side of the belt where altered and weakly mineralized felsic volcanic rocks had been identified. Subsequent drilling of an electromagnetic anomaly near the town of Ladysmith returned 14.5 meters of 9.25% copper and 1.7 g/t gold (May and Dinkowitz, 1996) and led to the discovery of the Flambeau VMS deposit in 1970.

The Flambeau discovery triggered an exploration boom in northern Wisconsin, marking the first effort of this kind in the region. As a result, large portions of the belt were covered by airborne geophysical surveys and countless electromagnetic anomalies were identified and drilled. However, with the exception of Flambeau only small non-economic deposits were discovered until the announcement in 1976 of the world-class Crandon discovery. This discovery revived exploration efforts in the region but also marked a shift in the social and political attitude towards metallic mining in the state of Wisconsin. Despite growing concerns regarding the regulatory framework, exploration continued at a high level and over the next 15 years the majority of known deposits in the belt were identified. Significant discoveries include the Bend deposit in 1986 and the Lynne discovery announced in 1990. Despite these successes, a
continued decline in the socio-political climate in Wisconsin compounded with historically low metal prices effectively terminated exploration across the region.

Exploration markedly diminished over the subsequent years and no new discoveries were made until the serendipitous discovery of the Back Forty deposit in 2002. Reports of a water well intersecting massive zinc-rich sulfide led to fieldwork that identified a small precious metal-rich gossan outcrop. Ground electromagnetic and gravity surveys were implemented and subsequent drilling encountered 37 meters of massive sulfide (9.2% Zn and 6.5 g/t Au) overlain by a hematitic gossan (3 meters of 23.7 g/t Au; Mahin, 2004). The Back Forty is now recognized as the second largest deposit in the Penokean belt and highlights the significant exploration potential in the region.

An updated mineral inventory for volcanic-associated mineral deposits in the Penokean volcanic belt includes over 100 million tonnes of ore-grade massive and semi-massive sulfides (Table 2-1). The majority of this metal endowment is contained within five potentially economic deposits, namely, the Back Forty, Bend, Crandon, Flambeau, and Lynne deposits.

Table 2-1: Grade and tonnage table for Penokean VMS deposits. Note that the origin of the Reef deposit is uncertain.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Size (Mt)</th>
<th>Cu (%)</th>
<th>Pb (%)</th>
<th>Zn (%)</th>
<th>Au (g/t)</th>
<th>Ag (g/t)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Forty</td>
<td>17.5</td>
<td>0.33</td>
<td>0.23</td>
<td>2.94</td>
<td>2.04</td>
<td>24.75</td>
<td>Martin et al. (2014)</td>
</tr>
<tr>
<td>Bend</td>
<td>3.9</td>
<td>1.87</td>
<td>-</td>
<td>-</td>
<td>3.14</td>
<td>13.26</td>
<td>DeMatties and Rowell (1996)</td>
</tr>
<tr>
<td>Catwillow</td>
<td>2.6</td>
<td>1.50</td>
<td>-</td>
<td>2.60</td>
<td>0.69</td>
<td>15.43</td>
<td>DeMatties (1994)</td>
</tr>
<tr>
<td>Crandon</td>
<td>65.8</td>
<td>1.04</td>
<td>0.48</td>
<td>5.56</td>
<td>1.20</td>
<td>42.86</td>
<td>DeMatties (1994), Mudrey et al. (1991)</td>
</tr>
<tr>
<td>Flambeau</td>
<td>~5.9</td>
<td>4.10</td>
<td>-</td>
<td>1.00</td>
<td>2.91</td>
<td>30.17</td>
<td>DeMatties (1994)</td>
</tr>
<tr>
<td>Hawk</td>
<td>1.4</td>
<td>0.80</td>
<td>-</td>
<td>2.70</td>
<td>-</td>
<td>-</td>
<td>DeMatties (1994)</td>
</tr>
<tr>
<td>Horseshoe</td>
<td>0.7</td>
<td>2.45</td>
<td>0.90</td>
<td>5.35</td>
<td>2.06</td>
<td>36.00</td>
<td>DeMatties (1994)</td>
</tr>
<tr>
<td>Lynne</td>
<td>5.1</td>
<td>0.47</td>
<td>1.71</td>
<td>9.27</td>
<td>0.72</td>
<td>81.60</td>
<td>Adams (1996)</td>
</tr>
<tr>
<td>Pelican River</td>
<td>2.1</td>
<td>1.00</td>
<td>-</td>
<td>4.50</td>
<td>-</td>
<td>17.49</td>
<td>Bowden (1978); DeMatties (1994)</td>
</tr>
<tr>
<td>Reef</td>
<td>0.4</td>
<td>0.28</td>
<td>-</td>
<td>-</td>
<td>10.56</td>
<td>~8.57</td>
<td>Kennedy and Harding (1990)</td>
</tr>
<tr>
<td>Ritchie Creek</td>
<td>0.8</td>
<td>2.11</td>
<td>-</td>
<td>0.37</td>
<td>0.34</td>
<td>-</td>
<td>DeMatties (1994)</td>
</tr>
<tr>
<td>Thornapple/</td>
<td>2.7</td>
<td>1.50</td>
<td>-</td>
<td>~3.50</td>
<td>-</td>
<td>-</td>
<td>DeMatties (1994)</td>
</tr>
<tr>
<td>Eishenbrey</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Various classification schemes have been derived to group VMS deposits based on their metal content, tectonic setting, and their host-rock composition. Classifications used for this study include that by Large (1992) using the base metal content of the deposits (Fig. 2-4) and Mercier-Langevin et al. (2011) to quantify the gold endowment (Fig. 2-4). The majority of Penokean deposits are divided into Cu-type and Zn-Cu-type massive sulfide deposits with only two deposits containing sufficient lead to be classified as Zn-Pb-Cu-type (Fig. 2-4). Of the potentially economic massive sulfide deposits, Bend and Flambeau are classified as Cu-type, Crandon and Back Forty are Zn-Cu-type, and Lynne is classified as a Zn-Pb-Cu-type.

The gold endowment of Penokean sulfide deposits is provided in Figure 2-4. Bend represents the only deposit previously recognized as containing a significant gold-enrichment. However, the newly compiled resource data for the deposits of the Penokean volcanic belt suggest that Crandon and Back Forty contain “anomalous” amounts of gold with estimates of these deposits containing >31 t of gold. In addition, Reef is classified as an auriferous deposit due to its gold enrichment. However, Reef has been variably classified as a disseminated volcanogenic sulfide deposit (Scott, 1988) or a structurally controlled Au deposit (Kennedy and Harding, 1990; DeMatties, 1994).
Fig. 2-4: Classification diagrams for the Penokean VMS deposits based on metal content. A. Base metal classification (after Large, 1992). B. Classification based on gold grade and content (after Mercier-Langevin et al., 2011). Note that the origin of the Reef deposit is uncertain.
CHAPTER 3
MATERIALS AND METHODS

The present thesis describes the characteristics of the VMS deposits in the Penokean volcanic belt and is based on new field and analytical work as well as a review of existing literature. The majority of fieldwork and data collection occurred over the course of 10 weeks during the summer of 2014. However, several trips were made back to the field area over the course of a three-year period and an estimated total of at least 20 weeks were spent in the belt collecting data for the present study. Fieldwork was focused primarily on drill core logging and sampling of representative drill holes from Back Forty, Bend, Flambeau, Horseshoe, Lynne, Reef, and Ritchie Creek. In all cases, drill holes were chosen that intersected as much of the volcanic stratigraphy and mineralized interval as possible. However, the quality and quantity of available drill core and drill hole data is highly variable as no exploration has been conducted on some of these deposits during the past decades. For some deposits, such as Crandon and Pelican River, drill core is no longer available.

Drill core logging was completed at several localities. Aquila Resources Inc. provided access to their core logging facilities in Daggett and Carney, Michigan, where core from Back Forty and Reef were analyzed and also their core facility in Medford, Wisconsin, where drill core from the Bend deposit and Horseshoe prospect were studied. Drill core from Flambeau and Ritchie Creek are housed at the Wisconsin Geological and Natural History Survey and drill cores were inspected at their facility in Mt. Horeb, Wisconsin. Drill core from Lynne was inspected in Duluth, Minnesota, where a number of drill cores are stored at the National Resources Research Institute.

Compilation of historic data, both published and unpublished company data, was an important first step to select representative drill holes. Where possible, a drill hole was selected along a cross section with published information to complement historic data and to allow for integration of this study with previous work. In many cases, a number of drill holes were inspected and logged but typically only one representative drill hole from each deposit was selected for geochemical sampling and petrographic analysis. Geochemical samples were taken at regular intervals throughout the volcanic stratigraphy. Geologic contacts between different volcanic units and miscellaneous features such as quartz veins were avoided to assure a representative rock analysis. Rocks containing a significant amount of sulfides (>5%) were also avoided. In most cases, thin section billets were collected from the same interval for the petrographic investigations. In addition, thin sections billets were collected within the massive sulfides
and associated alteration zones to help understand the mineralogy of these zones. A list of drill holes, geochemical samples, and thin sections is provided in Table 3-1.

Geochemical samples were crushed and pulverized at Minerals Processing Corporation laboratory located in Carney, Michigan. For active exploration projects, namely Bend, Back Forty, and Reef, the drill core had previously been sampled and the preexisting pulps were used. These pulps were then sent to SGS Laboratories or ACTLABS in Ancaster, Ontario, where they were analyzed for major elements determined by XRF and trace elements by ICP-MS following four-acid digestion. Thin sections billets were prepared either at facilities provided by Aquila Resources Inc. or at the Department of Geology and Geological Engineering, Colorado School of Mines. The billets were then sent to Spectrum Petrographics in Vancouver, Washington, where polished thin sections were prepared.

Following petrographic analysis, some of the thin sections were selected for backscatter electron imaging (BSE) and energy-dispersive X-ray spectroscopy (EDX) analysis on a scanning electron microscope (SEM). These investigations were performed on a TESCAN MIRA3 field emission SEM at the Department of Geology and Geological Engineering, Colorado School of Mines. Operating parameters used were 15 kV with a beam intensity of 11 yielding a spot size of approximately 50 nanometers. The working distance was 10 millimeters.

**Table 3-1:** Compilation of drill holes, geochemical samples, and thin sections used for this study.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Drill hole</th>
<th>Length logged (m)</th>
<th>Number of geochemistry samples</th>
<th>Number of thin sections</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Forty</td>
<td>LK-473</td>
<td>LK-473: 0-198.2 = 198.2</td>
<td>provided by AQA (n = 28)</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>LK-501</td>
<td>LK-501: 170-411 = 241</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>LK-81</td>
<td>LK-81: 0-276.5 = 276.5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bend</td>
<td>B12-01</td>
<td>0-231.4 = 231.4</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>Flambeau</td>
<td>22-71</td>
<td>134.1-212.5 = 78.4</td>
<td>5</td>
<td>14</td>
</tr>
<tr>
<td>Horseshoe</td>
<td>HS94-4</td>
<td>0-281.1 = 281.1</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>Lynne</td>
<td>LYN90-16</td>
<td>0-168.6 = 168.6</td>
<td>12</td>
<td>29</td>
</tr>
<tr>
<td>Reef</td>
<td>R12-40</td>
<td>0-139.6 = 139.6</td>
<td>16</td>
<td>10</td>
</tr>
<tr>
<td>Ritchie Creek</td>
<td>RC-5</td>
<td>0-214.6 = 214.6</td>
<td>7</td>
<td>14</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td></td>
<td>1829.4</td>
<td>87</td>
<td>125</td>
</tr>
</tbody>
</table>
CHAPTER 4
RESULTS

The aim of the present study is to provide details and descriptions of the volcanic setting, alteration, and ore mineralogy of volcanic-hosted base and precious metal mineralization for significant mineral deposits across the Penokean volcanic belt. For each deposit discussed, with the exception of Crandon where no drill core is available, one or more representative drill holes from each deposit were used to collect data necessary to comment on these characteristics.

Based on geologic observations from drill core and incorporation of previous relevant research, a schematic stratigraphic column was created to summarize the volcanic setting of each deposit (Fig. 4-1). The exception is that of Crandon where the stratigraphic column was based on descriptions of the volcanic stratigraphy by Lambe and Rowe (1987). Where possible, a more detailed description of the host rocks and their chemistries are provided in a series of downhole geochemical plots which display the major and trace elements of the representative drill holes for each deposit. In addition to chemistries obtained from this study, historic assay data was included in these plots if available. The purpose of these plots is to provide information on the chemistry of the host rocks, chemical effects of hydrothermal alteration, and metal content of ore mineralization for each deposit studied. Immobile element discrimination diagrams are a useful tool to help determine protolith where major elements no longer reflect primary compositions due to hydrothermal alteration. A series of immobile element discrimination diagrams from Pearce (1996) are provided in Figure 4-2.

Alteration indices, namely the Ishikawa alteration index (AI) and the chlorite-carbonate-pyrite index (CCPI), are included in the downhole geochemical plots. These indices are useful in characterizing the nature and degree of alteration associated with VMS hydrothermal systems (Large et al., 2002). The AI quantifies the intensity of white mica and chlorite alteration through the breakdown of feldspars and volcanic glass and their replacement with white mica and chlorite. The CCPI is useful in quantifying Mg and Fe enrichment associated with Mg-Fe chlorite, Mg-Fe carbonate, and iron sulfides and/or oxides. In addition, Rb/Sr ratios are plotted and indicate the level of K-enrichment relative to Ca depletion. Hence, this ratio describes the replacement of feldspars and other calcic minerals with potassium bearing phases, such as white mica. Equations for the AI and CCPI alteration indices are provided below:

\[
\text{AI} = 100 \frac{(K_2O+MgO)}{(K_2O+MgO+Na_2O+CaO)}
\]

\[
\text{CCPI} = 100 \frac{(MgO+FeO)}{(MgO+FeO+Na_2O+K_2O)}
\]
Fig. 4-1: Schematic stratigraphic columns for VMS deposits of the Penokean volcanic belt
Fig. 4-2: Immobile element discrimination diagrams of Pearce (1996) for volcanic host rocks of Penokean VMS deposits. All data shown is collected from this study with the exception of Back Forty, which was company data supplied by Aquila Resources Inc., and Crandon which was taken from Lambe and Rowe (1987).
In addition to volcanological and geochemical examination, petrographic research was undertaken to help characterize hydrothermal alteration and ore mineralogy and a series of core photos and photomicrographs are provided for each deposit discussed. All of the deposits have undergone varying degrees of post-mineralization deformation and metamorphism. Thus, mineralogical descriptions reflect the metamorphic mineral assemblages and are not necessarily equivalent to the original syn-volcanic mineralogy.

4.1. Back Forty

The Back Forty deposit is the most recently discovered and second largest massive sulfide deposit in the Penokean volcanic belt. Current mine recoverable resource estimates include 17.5 Mt grading 2.9% zinc, 0.3% copper, 0.2% lead, 2.04 g/t gold, and 24.75 g/t silver (Martin et al., 2014). The massive sulfides occur along at least two distinct stratigraphic positions and are enveloped by intensely altered and mineralized felsic volcanic host rocks. Approximately 67% of the planned recoverable resources at Back Forty are within the massive sulfide ore, while the remaining occurs as disseminated to stockwork and oxide ore. The large volume of mineralized rock proximal of the massive sulfide bodies is unique compared to other VMS deposits of the Penokean volcanic belt.

Based on contained metal, the Back Forty deposit is classified as a zinc-copper type massive sulfide deposit and is considered anomalous with respect to its gold content (Fig. 2-4). The ore body is localized within a westerly plunging antiform where massive sulfides attain thicknesses up to 75 meters in
the hinge of the fold resulting in a bulbous morphology to the main ore body. Massive sulfides that occur higher up in the stratigraphy are contained in a tabular, sheet-like ore body (Fig. 4-3). The ore interval has been defined over a strike length of approximately 1.1 kilometers and has been intersected at depths greater than 700 meters below the surface and remains open in this direction.

The volcanic succession hosting the deposit strikes nearly east-west and dips steeply to the south. An east-west fault truncates the ore body to the north and the orientation of the host rocks are poorly constrained north of this fault. South of the fault, stratigraphic tops face to the south as indicated by graded beds. Metal zonation within the ore body is consistent with this younging direction. Regional metamorphism has reached lower greenschist facies and volcanic textures are generally well preserved outside zones of intense alteration. The ore body occurs along the western limit of Paleozoic cover rocks which was likely important for the preservation of supergene enrichment from recent glaciations.
Volcanic Stratigraphy

The Back Forty deposit is hosted by a thick succession of pervasively altered felsic volcanic rocks. The true thickness of the felsic volcanic pile is unknown but drilling indicates a thickness of at least 1200 meters. Lithofacies recognized include volcaniclastic rocks, volcanic breccias, coherent flows and/or domes, and laminated tuffaceous sedimentary rocks. Chemically, this succession is comprised of rhyolite to rhyodacite and is cut by syn- to post-volcanic dikes of intermediate to mafic composition (Fig. 4-2). With the exception of these intrusive units, only felsic volcanic rocks have been encountered in the immediate deposit area. The extent of the felsic volcanic pile and the lithofacies recognized suggest that the Back Forty deposit is located in a vent proximal setting within a large felsic volcanic center. The volcanic host rocks at Back Forty can be divided into a lower rhyolite, an upper rhyolite, and a package of siliceous volcaniclastic and chemical sedimentary rocks.

The lower rhyolite occupies the stratigraphic footwall to the main ore body at Back Forty and also contains a poorly delineated massive sulfide body deep within the volcanic pile that may represent a separate ore interval (Fig. 4-3). The lower rhyolite is comprised largely of a coherent quartz-porphyritic rhyolite and its proximal volcaniclastic equivalents. This unit contains 15-25% quartz phenocrysts and quartz crystal fragments within a fine-grained white mica-pyrite+/-chlorite groundmass (Fig. 4-4A). Volcanic facies of the lower rhyolite changes over short distances and are hard to reconstruct at the drill core scale. Geochemical analyses of this unit confirm that the diverse volcanic facies recognized are related to a single volcanic event. The upper rhyolite occurs stratigraphically above the lower rhyolite and cannot be distinguished macroscopically from the lower rhyolite. This unit, however, contains an abundance of volcaniclastic rocks, suggesting derivation from a more distal source than the lower rhyolite unit. The volcanic clasts are mostly angular and quartz-phyric and vary from a few millimeters to several centimeters in size (Fig. 4-4B). Chemically, the lower rhyolite can be distinguished from the upper rhyolite by slight variations in immobile element ratios, suggesting they represent two distinct volcanic events. A thin, discontinuous argillaceous unit located between the lower and upper rhyolite marks the stratigraphic position of the main ore body. This unit is almost entirely altered to white mica-chlorite-pyrite, but microscopically small rounded quartz grains can be recognized in thin beds suggesting a volcaniclastic protolith (Fig. 4-4D). Near the top of the upper rhyolite a large volume of volcaniclastic rocks contain economic concentrations of disseminated-stockwork sulfides. Stratigraphically above the upper rhyolite is a succession of thinly bedded, fine-grained siliceous volcaniclastic and chemical sedimentary rocks (Fig. 4-4C). Beds within this unit are comprised mostly of chert and fine-grained volcanic material. Chemically, these rocks do not appear to be related to the underlying rhyolite units and
are thus interpreted to represent distally derived volcanic material and likely indicate a local period of volcanic quiescence. A thin massive sulfide body occurs at the contact of the upper rhyolite and the silicic volcaniclastic package.

Fig. 4-4: Core photographs and photomicrographs of volcanic host rocks of the Back Forty deposit. A. Coherent quartz-porphyry of the lower rhyolite. LK501-256.7 m. B. Outcrop of volcanic breccia facies of the upper rhyolite. C. Thinly bedded silicic volcaniclastic unit. 108445-168.2 m. D. Very fine-grained, highly altered argillite or ash tuff with thin bed containing rounded quartz grains. LK473-169.8 m. PPL. E. Massive, aphyric rhyolite. 108449-34.6 m. F. Feldspar-phyric porphyry dike. LK81-156 m.
South of the immediate deposit area, a large aphyric rhyolite unit is interpreted to represent a felsic dome that truncates the volcanic succession to the south (Fig. 4-3). This rhyolite is chemically distinct and is interpreted to post-date the lower and upper rhyolite. The extent of this unit is unknown and rocks occurring stratigraphically above this unit are yet to be identified. A series of hypabyssal feldspar porphyritic volcanic rocks cut the volcanic succession and have a predominant east-west orientation that is parallel to the regional fabric. These dikes are interpreted to be synvolcanic and locally contain significant precious metal-enrichment along their margins and sometimes within their interiors. The only mafic rocks identified in the immediate deposit area is a north-south trending mafic dike that cuts and displaces the volcanic succession and the massive sulfide lens.

**Alteration**

The felsic volcanic host rocks of the Back Forty deposit were subjected to intense hydrothermal alteration (Fig. 4-5). With the exception of cross-cutting intrusive rocks, no unaltered or least-altered volcanic rocks have been recognized. This contrasts from other deposits studied in the Penokean volcanic belt, where a discrete change in alteration intensity is recognized from rocks that occur in the footwall versus those in the immediate hanging wall. The apparently large size of the alteration halo at Back Forty is likely related to the occurrence of multiple ore intervals at different stratigraphic positions and may reflect the longevity of the hydrothermal system.

Pervasive white mica-quartz-pyrite alteration is the dominant style of hydrothermal alteration recognized at the Back Forty deposit (Fig. 4-6A). This style of alteration has resulted in strong sodium and calcium depletion, which correlates with high AI values that commonly approach 100 (Fig. 4-5). CCPI values are consistently elevated for the rhyolitic host rocks and are mostly related to widespread disseminated sulfides throughout the volcanic pile. Although spheroidal chlorite alteration “spots” are a commonly recognized feature found throughout the volcanic succession (Fig. 4-6D), the extent of pervasive chloritic alteration is limited to two zones. The first occurs in the lower rhyolite associated with stockwork ore where chlorite forms thin halos around sulfide veins (Fig. 4-6B). The second zone occurs within the upper rhyolite as a broad semi-conformable halo beneath the upper massive sulfide interval. Here chlorite has selectively replaced volcanic clasts and produced a distinctive texture (Fig. 4-6C). Silicification appears to have been a pervasive style of alteration at Back Forty, however, the lack of unaltered volcanic rocks prohibits the quantification of this style of alteration. The use of alteration indices, such as AI values, is limited due to the widespread white mica-quartz-pyrite alteration halo.
However, Rb/Sr ratios appear to correlate with proximity to the main massive sulfide body and are interpreted to reflect strong K-enrichment and Ca-depletion surrounding this ore lens (Fig. 4-5).

**Fig. 4-5:** Down hole geochemical plot for a representative drill hole from the Back Forty deposit (drill hole LK-81). Colors and symbols from Figure 4-1.
Mineralization

The Back Forty deposit contains several different styles of ore, including massive to semi-massive sulfide ore, disseminated to stockwork ore, and precious metal-enriched oxide ore. The oxide ore type was not studied in detail but comprises two gossanous bodies above the massive sulfide ore. The west gossan forms a small outcrop comprised dominantly of hematite and magnetite (Fig. 4-7A) and overlies supergene enriched copper sulfide ore above hypogene massive sulfide ore. The mineral resource for this zone is estimated to contain approximately 180,000 tonnes grading 7.08 g/t Au, 78.2 g/t Ag, and 0.7% Cu. The east gossan, concealed underneath a thin veneer of Cambrian sandstone, is comprised dominantly of hematite. This gossan is more gold-rich relative than the western gossan and contains a resource of approximately 95,000 tonnes of 16.88 g/t Au and 5.44 g/t Ag. Although these two oxide bodies are spatially separate, the current interpretation is that they overlie the same massive sulfide lens despite their differing mineralogy and precious metal contents.

Massive sulfides occur along at least two discrete stratigraphic positions (Fig. 4-3). The majority of the economic resource at Back Forty is contained within pyritic massive sulfide that occurs at the contact between the lower and upper rhyolite. Economic minerals within this massive sulfide lens are predominantly sphalerite with lesser chalcopyrite and galena. Sphalerite is typically dark purple in color and coarse grains within irregular bands (Fig. 4-7B). Primary marcasite is a relatively common accessory mineral found at Back Forty and limited SEM-EDS analyses on polished ore samples routinely identified stannite. The precious metal contents within the massive sulfides average approximately 1.84 g/t Au and 19.0 g/t Ag. This massive sulfide lens shows weak metal zonation with a more copper-rich base and a zinc-rich top.

Higher in the stratigraphy, a second lens of massive to semi-massive sulfide occurs at the contact between the upper rhyolite and the siliceous volcaniclastic and chemical sedimentary rocks. This ore zone is a thin, sheet-like massive sulfide body that is comprised of sphalerite and galena with lesser pyrite and chalcopyrite. Precious metals contained within this lens are 1.49 g/t Au and 78.0 g/t Ag. A third body of massive sulfide occurs stratigraphically below the main massive sulfide lens, at depths below 250 meters. This massive sulfide body is mostly pyritic with local enrichments of copper and/or zinc. Limited information regarding this zone prohibits the recognition of a third stratigraphic interval along which massive sulfides accumulated.
Fig. 4-6: Alteration styles observed at the Back Forty deposit. A. Pervasive white mica-quartz-pyrite alteration of felsic volcaniclastic rock. LK473-137.8 m. B. Chlorite alteration selvage on a pyrite-chalcopyrite vein in a stockwork ore zone. LK473-159.3 m. C. Chlorite-altered angular volcanic clasts within a fine grained quartz-white mica-pyrite altered groundmass of the upper rhyolite. 108418-94.4 m. D. Chlorite alteration “spots” within a zone of pervasive white mica-quartz alteration. 108428-284.5 m.

In addition to massive sulfide ore, a significant portion of the mineral resource at Back Forty is contained within stockwork and disseminated ore zones. Stockwork ore occurs in a well-defined zone below the lower and upper rhyolite contact and is comprised of pyrite-chalcopyrite veins that cut the rhyolitic host rocks (Fig. 4-6B). Additionally, a wide zone of heavily disseminated sulfides occurs within a semi-conformable zone below the upper massive sulfide lens. The most abundant sulfide minerals within this zone are pyrite, sphalerite, and galena. The variation between these ore styles is thought to have been controlled by the volcanic facies in which they formed. The lower stockwork ore occurs within the lower rhyolite which is predominantly a coherent felsic body, whereas the disseminated ore occurs near the top of the upper rhyolite within a dominantly volcaniclastic host. The semi-conformable morphology to this zone is interpreted to represent lateral fluid flow through highly permeable or poorly consolidated volcaniclastic material. This is further supported by textural evidence indicative of sub-
seafloor replacement that includes selective replacement of the fine-grained volcanic groundmass with sulfides (Fig. 4-7C).

Precious metal-bearing ores contribute significantly to the mineral resource at Back Forty. Gold and silver occur throughout the deposit and are included within all ore types recognized. In addition, precious metals occur within discrete zones where gold+/−silver are the only metals of economic significance and sulfides are relatively sparse. Much of the complexity surrounding gold-enrichment at Back Forty is not well understood and only a brief summary of the precious metal ore zones at Back Forty are provided here. A significant zone of precious metal enrichment occupies the same stratigraphic position as the upper massive sulfide lens and these two zones appear to grade laterally into one another. The overall sulfide content of this zone is low and gold and silver are primarily associated with galena and arsenopyrite. Gold occurs as electrum, whereas silver occurs within a wide range of sulfide minerals and sulfosalts; namely, argentopyrite, pyrargyrite, stephanite, and freibergite (Fig. 4-7D). Sulfide phases tend to occur within thin brittle fractures in the siliceous volcaniclastic rocks, and thus, are speculated to have been introduced subsequently to base metal mineralization (Fig. 4-7E). A second zone of precious metal enrichment occurs along the margins of, and occasionally within syn-volcanic feldspar+/−quartz porphyry dikes (Fig. 4-3). Gold-enrichment within this zone can exceed 100 g/t and is associated with galena and chalcopyrite. The highest gold values within this zone appear to be where the dike is in contact with massive sulfides (Fig. 4-7F). A third zone of precious metal enrichment occurs on the west end of the ore body within enigmatic, strongly deformed and sheared rocks of unknown nature. This zone is characterized by a very low abundance of sulfide minerals and at present is poorly understood.

4.2. Bend

The Bend deposit contains approximately 3.9 Mt of ore with average grades of 1.9 % copper, 3.1 g/t gold, and 13.3 g/t silver (DeMatties and Rowell, 1996). As no significant zinc or lead enrichment has been identified, the deposit is classified as a Cu-type massive sulfide deposit (Fig. 2-4A). Based on the classification of gold-rich VMS deposits by Mercier-Langevin et al. (2011), Bend is considered an auriferous deposit due to its relatively high gold grades (Fig. 2-4B). The deposit comprises sub-vertically dipping, tabular massive to semi-massive sulfide lenses enveloped in a pyritic alteration halo. The ore bodies have a maximum strike length of approximately 550 meters and vary from 3 to >20 meters in thickness (DeMatties, 1994). Massive sulfides have been intersected at greater than 900 meters down dip and the deposit remains open in this direction. The volcanic succession hosting the deposit strikes nearly east-west and dips sub-vertically to the south (Fig. 4-8). Stratigraphic tops face to the south as evidenced
by graded bedding within volcaniclastic rocks and the asymmetric nature of the alteration halo surrounding the ore body. Regional metamorphism has reached lower greenschist facies and volcanic textures are generally well preserved.

**Fig. 4-7:** Photographs and photomicrographs of base and precious metal ores from the Back Forty deposit. A. Outcrop of the west gossan. B. Sphalerite-rich massive sulfide. LK-176-156 m. C. Replacement style mineralization as evidenced by sulfides surrounding angular volcanic clasts. LK-473-79.5 m. D. Electrum (el) associated with a Sb-bearing mineral assemblage of pyrargyrite (pyr) and stephanite (ste) from a zone of precious metal-enrichment. LK-473-41.8 m. BSE. E. Precious metal ore zone as photo D, note sulfides minerals infilling brittle fractures. LK473-42 m. F. Coarse native gold within margin of cross-cutting feldspar-porphyry dike. LK80-233 m.
The volcanic stratigraphy of the Bend deposit is comprised largely of volcaniclastic rocks with subordinate coherent basaltic and rhyolite units and minor clastic-chemical sedimentary rocks (Fig. 4-1). Chemically, the host rock succession is dominated by rocks having basaltic and rhyodacitic compositions (Fig. 4-2). The immediate stratigraphic footwall of the Bend deposit is comprised of fine-grained, thinly bedded to laminated volcaniclastic rocks (Fig. 4-9A) that are intercalated with quartz-phyric volcaniclastic rocks. This unit is best described as a quartz-mica schist due to the high degree of alteration and well developed foliation produced during deformation and metamorphism related to the Penokean orogeny. Step-out drilling to the north of the deposit encountered a thick succession of mafic volcanic rocks that apparently represent a footwall succession and suggest that the dominantly felsic volcanic and volcaniclastic rocks hosting the Bend deposit are confined to the immediate deposit area.

The ore is hosted by a quartz-phyric volcaniclastic unit that contains 15-30% quartz phenocrysts and quartz crystal fragments within a fine-grained phyllosilicate+/-pyrite matrix. The quartz phenocrysts often have a distinctive blue color (Fig. 4-9B). This unit varies in thickness from <20 to >120 meters and thickens down-dip (Fig. 4-8). The quartz-phyric volcaniclastic unit has been pervasively altered and primary volcanic textures have largely been obscured. However, discontinuous domains of varying proportions of quartz and mica as seen in Figure 4-9B are interpreted to represent compacted porphyritic pumice fragments. The lack of bedding and homogeneity of the unit are consistent with this interpretation. The quartz-phyric volcaniclastic unit is overlain by a thin, discontinuous unit of argillaceous and cherty sedimentary rocks which locally contain thin intervals of banded magnetite and clastic sulfides (Fig. 4-9C,D). The finely laminated volcaniclastic rocks and chemical sedimentary rocks suggest deposition during a period of relative volcanic quiescence and thus mark an important stratigraphic time interval during which mineralization occurred.

The hanging wall stratigraphy consists of a thick succession of sedimentary and volcaniclastic rocks that give way up section to an intermediate-felsic flow and dome complex of unknown dimensions. In general, rocks at the base of the hanging wall consist of fine-grained, bedded volcaniclastic rocks that become coarser and more thickly bedded higher in the stratigraphy. Graded beds and sedimentary structures are generally well preserved (Fig. 4-9E). Some units are composed of rounded lithic clasts within a calcareous groundmass and are interpreted to represent deposits originating from a shallow marine environment (Fig. 4-9F).
Fig. 4-8: Geologic cross-section of the Bend deposit, looking west (modified from DeMatties and Rowell, 1996).

Alteration

Hydrothermal alteration at Bend is typified by an assemblage of white mica, quartz, and chlorite. Alteration was most intense below and within the ore interval. The stratigraphic hangingwall of the massive sulfide horizon was only weakly altered (Fig. 4-10). The stark contrast in alteration intensity across the ore horizon indicates hydrothermal activity ceased immediately after the main ore-forming event. The abundance of phyllosilicate minerals in the most altered zones allowed development of a pronounce foliation during deformation (Fig. 4-9A). Recrystallization of sulfide minerals was common within these highly strained zones and pyrite grains often show quartz pressure shadows (Fig. 4-11A).
Fig. 4-9: Core photographs of host rocks from the Bend deposit. A. Fine-grained, finely bedded volcaniclastic rock of the footwall. B12-01-226.7 m. B. Quartz-phyric volcaniclastic unit of the ore interval. Note the blue quartz phenocrysts and crystal fragments. B12-01-131.2 m. C. Laminated chemical sedimentary rocks comprised of banded chert and magnetite within the ore interval. B12-01-112.5 m. D. Clastic massive sulfides of the ore interval that are interpreted to be reworked. B12-01-112.1 m. E. Interbedded sandstone and argillite with normally graded beds and small offset syn-sedimentary faults. B12-01-87.4 m. F. Rounded lithic clasts within a calcareous matrix. B12-01-63.1 m.
White mica alteration is the most prominent style of hydrothermal alteration at Bend. Pervasive white mica alteration has resulted in a net loss in Na$_2$O and CaO and a net gain of K$_2$O, which corresponds to increasing Al values (Fig. 4-10) consistent with the replacement of feldspar and volcanic glass by white mica. Chlorite alteration is less prominent but is locally well developed within tabular, stratiform zones within the quartz-phyric volcaniclastic unit (Fig. 4-11B) and is recognized by an increase in CCPI values and corresponding decrease in K$_2$O for samples directly below the ore interval (Fig. 4-10). This is consistent with proximal chlorite enrichment. Silicification occurs as a pervasive style of alteration as well as within discrete zones related to stockwork sulfide mineralization where primary volcanic textures have been destroyed and are almost entirely replaced by quartz (Fig. 4-11C). Pervasive silicification is not easily recognized macroscopically, but can be identified chemically. DeMatties (1994) reported an increase of up to 20% SiO$_2$ within silicified rocks of the footwall.

The spatial distribution of different alteration styles and intensities has not been well documented at Bend. However, it is apparent that a discrete, cross cutting chlorite-rich alteration pipe is not present. Instead, alteration at Bend appears to have formed as a semi-conformable, tabular halo stratigraphically below the massive sulfides. This morphology is interpreted to represent lateral fluid flow through highly permeable volcaniclastic rocks of the ore interval and footwall. The thickness and lateral dimensions of the alteration halo are unknown and no significant change in alteration intensity has been noted down-dip and along strike within the immediate deposit area.

Mineralization

The Bend deposit contains a copper-rich core of massive sulfides that gives way along strike and down dip to pyritic and variably gold-rich massive to semi-massive sulfides. Sulfides and ore minerals are predominantly pyrite with lesser chalcopyrite (Fig. 4-11D) and minor tetrahedrite-tennantite, arsenopyrite, and pyrrhotite. Whereas copper is largely confined to the massive sulfide lenses at Bend, gold is more widely distributed and may be enriched within both copper-rich and pyritic massive sulfide. Lower gold grades (~1 g/t) occur throughout the altered quartz-phyric volcaniclastic unit of the footwall. Controls on gold mineralization are poorly understood and it is macroscopically impossible to distinguish gold-bearing from gold-barren zones. Locally, sylvanite is easily recognized within quartz-carbonate veins where assay values can exceed 100 g/t and appear to be associated with dikes that cut the stratigraphy. Silver concentrations are generally very low with an average grade of ~13g/t and a Ag:Au ratio of approximately 4:1, which makes Bend one of the most silver-poor deposits within the Penokean volcanic belt. Anomalous levels of tellurium, up to several thousand parts per million, generally correlate
with elevated sulfide abundance. Telluride minerals identified in this study include, in order of relative abundance, altaite, native tellurium, sylvanite, and frohbergite (Fig. 4-11E). In addition, fluorite was also recognized within mineralized areas containing telluride-enrichment.

Fig. 4-10: Down hole geochemical plot for a representative drill hole from the Bend deposit (drill hole B12-01). Colors and symbols from Figure 4-1.
The absence of appreciable levels of zinc and lead at Bend prohibits the recognition of metal zonation typical for VMS deposits. DeMatties and Rowell (1996) described an increase in copper content at higher stratigraphic levels due to upward zone refining. In addition, the available data suggest that economic levels of copper are confined to the center of the deposit and decrease along strike and down dip. Gold concentrations remain constant and in some cases appear to increase towards the periphery and beyond the copper zone.

Mineralization at Bend shows evidence of having occurred both on the seafloor as well as by sub-seafloor replacement. The occurrence of re-deposited clastic sulfides intercalated with chemical sedimentary rocks (Fig. 4-9C, D) is clear evidence that sulfide formation was, at least locally, occurring on the paleoseafloor. Down dip, the ore interval is located within the quartz-rich volcaniclastic unit (Fig. 4-8) and clasts of silicate host rock commonly occur within a massive sulfide matrix, indicating that much of the deposit formed through subseafloor replacement (Fig. 4-11F). It appears likely that sulfides were deposited on the paleoseafloor while mineralizing fluids simultaneously moved laterally through and replaced the porous volcaniclastic strata.

4.3. Crandon

The Crandon deposit has recoverable reserves of 61 Mt averaging 1.1% copper, 5.6% zinc, 0.5% lead, 37 g/t silver, and 1 g/t gold (Lambe and Rowe, 1987), making it the largest and most economically important deposit discovered in the Penokean volcanic belt to date. Based on its metal content, Crandon is classified as a Zn-Cu type massive sulfide deposit (Fig. 2-4A) that has an anomalous gold content, with nearly 2 Moz of contained gold (Fig. 2-4B). The ore consists of massive zinc-rich sulfides underlain by a copper-rich quartz-sulfide stockwork zone. The ore body extends approximately 1500 meters along strike and at least 800 meters down dip. The host rock succession and the massive sulfide ore body are north facing, strike nearly east-west and dip 70-90 degrees to the north. The rocks have been metamorphosed to lower greenschist facies and volcanic textures are generally well preserved. The immediate deposit area is covered by extensive glacial deposits and, therefore, available geologic information is based on drill core observations. The following description is based on Lambe and Rowe (1987) as exploration drill core is no longer available.
Fig. 4-11: Core photographs and photomicrographs of alteration styles and sulfide-enrichment at the Bend deposit. A. Fine-grained white mica alteration with recrystallized pyrite and quartz within pressure shadows of quartz phenocrysts. B12-03-155.6 m. CPL. B. Wispy chlorite alteration of the quartz-phyric volcanioclastic unit of the ore interval. B12-01-125.1 m. C. Intense silicification associated with a pyritic stockwork zone. B12-09-365 m. D. Pyrite, chalcopyrite-rich massive sulfide. B12-01-114.6 m. E. Sylvanite accompanied by native tellurium within massive sulfides. B10-412.9 m. BSE. F. Pyrite, chalcopyrite-rich massive sulfide replacing argillaceous beds (right) and beds of the quartz-phyric volcanioclastic unit (left). B12-01-116.8 m.
Volcanic Stratigraphy

The Crandon massive sulfide deposit is hosted by a succession of coherent flows, volcaniclastic rocks and chemical sedimentary rocks that have been divided into two informal members: the Hemlock Creek and the younger Swamp Creek members. The base of the Hemlock Creek member consists of porphyritic basalt flows that are overlain by a thick succession of predominantly volcaniclastic and lesser chemical sedimentary rocks. The volcaniclastic rocks vary from fine-grained to lapilli tuffs and overall grade upward into a series of volcanic debris flows that comprise the stratigraphic footwall to the ore interval. The massive sulfides of the Crandon deposit as well as laterally equivalent pyritic mudstone, pyritic tuff, and minor dolomitic sedimentary rocks are located within this succession of volcaniclastic rocks. Stratigraphically above the ore interval the Hemlock Creek member contains chert, mudstone, and calcareous volcaniclastic rocks, recording a period of relative volcanic quiescence.

The overlying Swamp Creek member consists of a series of rhyolitic flows overlain by calcareous volcaniclastic rocks, fine-grained tuffs, and crystal tuffs that mark the last significant volcanic activity recognized within the Crandon deposit area. These rocks are overlain by turbidite deposits with poorly sorted sandstone and granitic conglomerate, which are interpreted to represent clastic rocks originating from a subaerial source. Although not mentioned in the literature, this suggests a disconformable relationship between the dominantly volcaniclastic and sedimentary succession recorded in the upper Swamp Creek member.

Chemically, the volcanic host rocks form a bimodal suite of basaltic and rhyolitic volcanic rocks (Fig. 4-2). The coherent volcanic rocks vary from high alumina basalt in the footwall to tholeiitic rhyolite in the hanging wall. A distinct gap in Zr/TiO$_2$ between footwall and hanging wall volcanic rocks indicates a shift from dominantly mafic volcanism prior to mineralization to felsic volcanism after the main ore-forming event (Lambe and Rowe, 1987).

Alteration

The host rocks of the Crandon deposit have been affected by intense hydrothermal alteration (Lavery, 1985). Alteration facies range from a chlorite-white mica assemblage that occurs distal to ore through an intermediate quartz-chlorite+/-white mica facies to a quartz-chlorite+/-white mica alteration assemblage proximal to ore. The quartz-chlorite+/-white mica facies is characterized by high quartz
content and is only found in the upper portions of the stratigraphic footwall and is often correlative with high sulfide content.

The alteration halo occurs as an irregular, semi-conformable, tabular zone that extends approximately 200 meters below the Crandon massive sulfide interval. No distinctive pipe-shaped alteration halo has been recognized. Although strong hydrothermal alteration is confined to the footwall of the deposit, rocks in the immediate hanging wall are weakly hydrothermally altered as has been documented by geochemical analysis. No hydrothermal alteration has been documented above the Hemlock Creek member (Lambe and Rowe, 1986).

Mineralization

Two distinct ore types are recognized at Crandon: a massive zinc-rich sulfide ore and stockwork copper-rich ore. The massive ore consists of laminated sphalerite-pyrite intercalated with sedimentary beds of the ore interval with relatively minor chalcopyrite and galena. Lead contents are variable and locally exceed one percent. Silver values are consistently around 40 ppm. The gold content is variable, but averages about 1.6 ppm. High gold contents apparently coincide with zones of high sphalerite content. The stockwork ore comprises chalcopyrite +/-pyrite-bearing quartz stringer veins and pyrite-sphalerite-chalcopyrite stringer veins that form a roughly tabular zone beneath the massive sulfide ore. In contrast to the massive ore, the stockwork zone contains <0.1% lead. Silver concentrations are erratic, but generally low (~10 ppm). The stockwork ore does not contain appreciable levels of gold.

The reported sulfide mineralogy of the Crandon deposit is quite simple and consists of pyrite, sphalerite, chalcopyrite, and galena, with minor amounts of arsenopyrite and tetrahedrite. Documented silver and gold bearing minerals include native silver, electrum, stephanite, polybasite-pearcite, and native gold. Additionally, supergene enrichment and an associated suite of minerals occur in the uppermost portions of the ore body.

4.4. Flambeau

The Flambeau massive sulfide deposit contained approximately 5.9 Mt of 4.1% Cu, 1% Zn, 2.91 g/t Au, and 30.17 g/t Ag (DeMatties, 1994) and is classified as a Cu-type massive sulfide deposit (Fig. 2-4). A significant zone of supergene enrichment occurred at the subsurface and was mined from 1993 to 1997 for a total of 1.6 Mt ore grading 10.3% Cu, 3.98 g/t Au, and 62.98 g/t Ag (May and Dinkowitz, 1996). The massive sulfides form a tabular, stratiform lens that has a strike length of approximately 720
meters, an average thickness of 15 meters, and was delineated to a depth of at least 240 meters below surface (May, 1977). The ore body and volcanic host rocks strike NE-SW, dip steeply to the NW and are thought to occur on the limb of a large isoclinal fold. The host rock succession has been interpreted to be overturned with stratigraphic tops facing southeast (Fig. 4-12). Regional metamorphism produced upper greenschist to lower amphibolite stable mineral assemblages (May, 1977).

**Volcanic Stratigraphy**

The stratigraphic footwall at Flambeau is comprised predominantly of phyllite and schist of an intermediate precursor composition. Metamorphic mineral assemblages include quartz-muscovite-chlorite-biotite+/−andalusite+/−garnet. Quartz occurs primarily as fine-grained recrystallized patches that could represent siliceous volcanic fragments (Fig. 4-13A). Circular-shaped clusters of quartz grains observed in thin section are thought to represent recrystallized quartz phenocrysts (Fig. 4-13B). Muscovite, with lesser biotite-chlorite is fine-grained and occurs within bands of foliated grains that

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**Fig. 4-12:** Geologic cross section of the Flambeau deposit. Section shown is 418 with the approximate location of drill hole FL-71 projected from section 422. Solid line indicates portion of drill hole examined for this study. Modified from May (1977).
surround the siliceous clasts. These bands are thought to represent the altered equivalent of a fine-grained or glassy matrix, suggesting that the protolith was volcanioclastic in nature. Biotite occurs as coarse lath-shaped porphyroblasts that both overgrow and cut foliation (Fig. 4-13C). Fine-grained chlorite occurs within bands associated with muscovite and also as coarse, radiating masses of crystals where it accompanies sulfide minerals (Fig. 4-13D). Andalusite forms coarse-grained porphyroblasts that are always strongly altered and sometimes completely replaced by fine-grained phyllosilicates that are interpreted to be products of retrograde alteration (Fig. 4-13C). These porphyroblasts occur in bands and as clusters of grains suggesting a primary compositional control on their formation (Fig. 4-13E). Garnets were not directly observed in this study, however, May and Dinkowitz (1996) reported locally abundant spessartine, correlating with a zone of manganese enrichment. Fine-grained, skeletal masses of gahnite locally present within the footwall to the ore body were initially interpreted to be garnets (Fig. 4-13F).

Rock types also reported to occur in the footwall, but not examined in this study, include a quartz-phyric schist and a massive actinolite schist which are interpreted to represent the altered and metamorphosed equivalent of a felsic quartz-crystal tuff and a dacite-andesite flow, respectively (May and Dinkowitz, 1996). Despite the hydrothermal alteration and metamorphism, relict volcanic textures are still commonly preserved in footwall rocks. The footwall rocks examined in this study are interpreted to represent fine-grained, thinly bedded volcanioclastic rocks inter-bedded with volcanic breccia. The similar compositions of the different volcanic facies indicate that they were derived from a common volcanic source.

The ore interval at Flambeau is comprised of fine-grained tuffs, cherty sedimentary rocks, and lapilli tuffs. These units have been altered and metamorphosed to quartz-phyllosilicate-pyrite schists and have been distinctly more mineralized than the encompassing volcanic strata (Fig. 4-13F). This interval has been traced along strike for 4,500 meters and is interpreted to represent a hiatus in active volcanism during which mineralization occurred (May, 1977). Despite a significant change in mineralogy, the volcanic textures and chemistries of rocks from the footwall and ore interval indicate continued deposition of intermediate-felsic volcanic material during mineralization.

Rocks from the hanging wall examined in this study consist of dark gray, fine-grained, feldspar-phryic volcanioclastic rocks that are significantly less altered and mineralized than rocks of the footwall and ore interval (Fig. 4-14). This unit contains 20-40% anhedral-subhedral altered feldspar crystals within a fine-grained quartz-mica-amphibole matrix (Fig. 4-13G) and locally contains large irregular lithic clasts (Fig. 4-13H). Chemically, this unit is andesitic in composition and has immobile element ratios that are similar to those sampled in the footwall (Fig. 4-2). This interpretation differs from the findings of previous workers (May, 1977; May and Dinkowitz, 1996) proposing a pronounced lithologic change
between footwall and hanging wall. It is suggested here that these apparent differences are related to the intense hydrothermal alteration predating the metamorphic overprint. Rocks further south of the deposit and presumably higher in the stratigraphy have been described as sedimentary in character, grading into graphitic schists interbedded with intermediate volcanic flows (May, 1977). Truncating the volcanic succession to the southwest and occupying a large area to the north of the deposit is a large tonalite or series of tonalite intrusive bodies (May, 1977), which may have caused contact metamorphism of the volcanic rocks in the Flambeau area.

Alteration

The metamorphic overprint of the hydrothermally altered volcanic rocks has resulted in complex mineral assemblages. Similarities in the immobile element ratios throughout the volcanic stratigraphy sampled suggest that the metamorphic mineral assemblages recognized in the footwall are not related to differences in the precursor volcanic composition (Figs. 4-2, 4-14). Three distinct mineral assemblages are recognized, namely andalusite-biotite, quartz-muscovite-pyrite, and chlorite-carbonate.

A thick package of andalusite-biotite bearing volcaniclastic rocks occur in the footwall and are considered a diagnostic feature of footwall alteration at Flambeau. Both andalusite and biotite occur as porphyroblasts. A decrease in the abundance of biotite-andalusite has been noted east of the deposit, with a corresponding increase in chlorite-white mica and has been used as a proxy for alteration intensity (May and Dinkowitz, 1996). The quartz-muscovite-pyrite assemblage is widespread and is most intensely developed stratigraphically below and within the ore interval and is recognized as alternating bands of fine-grained muscovite and fine-grained recrystallized quartz. The chlorite-carbonate alteration assemblage occurs within the massive-semimassive sulfide lens where chlorite occurs as feathery masses of grains and carbonate occurs as patchy zones of recrystallized dolomite-ankerite (Fig. 4-13D).

Chemically, volcanic rocks of the footwall are extremely altered with AI values approaching 100 (Fig. 4-14). A corresponding deficiency of sodium, calcium and an increase in Rb/Sr ratios is consistent with replacement of feldspars and volcanic glass with white mica. The CCPI index is also consistently high for samples within and below the ore interval and correlates with an increase in iron, magnesium, and sulfur related to an increase in sulfide minerals and chlorite. In samples collected from this study, SiO$_2$ varies from 56-70% but immobile element ratios suggest that the rocks are of similar, andesitic composition. This highlights the strong effects of silicification and the bulk chemical modification of the host rocks as a result of hydrothermal alteration.
Fig. 4-14: Downhole geochemical plot for the Flambeau deposit (drill hole FL-71). Colors and symbols from Figure 4-1. FW = footwall; HW = hanging wall.

Intense alteration at Flambeau is confined to a semi-conformable halo stratigraphically below and within the ore interval. Alteration intensity extends for a short distance into the hanging wall. This implies that the hydrothermal system shut off shortly after the main ore-forming event and could also provide evidence for replacement style mineralization. No well-defined chlorite-rich alteration pipe has been recognized (May, 1977). However, the high degree of shearing recognized from elongate siliceous clasts (Fig. 4-13) may have translated the geometry of such an alteration pipe into its present semi-conformable shape.

Mineralization

Base and precious metals of economic importance occur within both hypogene and supergene zones of mineralized rock. The focus of this study concerns the primary ore mineralogy, however, Flambeau is considered one of the most significant examples of a supergene-enriched massive sulfide deposit (May, 1977). Supergene ore occurs as a precious metal-enriched gossan (average 20.6 g/t Au) which caps a zone of supergene enriched massive sulfide comprised dominantly of chalcocite and bornite. The zone of supergene enrichment extended up to 56 meters below surface where copper grades locally exceeded 20%. For a more detailed description regarding the supergene mineralization readers are referred to May (1977) and May and Dinkowitz (1996).
Fig. 4-15: Photographs and photomicrographs of ore minerals from the Flambeau massive sulfide deposit. A. Pyrite dominant semi-massive sulfide with lesser chalcopyrite and minor sphalerite. FL71-624’. B. Chalcopyrite, sphalerite, and pyrite within the main ore lens. Note very small chalcopyrite inclusions throughout the sphalerite. FL71-560’. RL. C. Copper-bearing minerals interstitial to recrystallized pyrite. Gray bands within covellite are chalcopyrite. FL71-603’. BSE. D. Electrum surrounded by quartz. Not visible in photograph is that electrum occurs within a microfracture cutting the quartz. FL71-560’. BSE. E. Telluride minerals on pyrite grain boundaries. FL71-603’. BSE. F. Gahnite surrounded by quartz, biotite and minor pyrite and sphalerite. BSE.

Hypogene ore occurs within a tabular, stratiform lens of massive to semi-massive sulfide comprised dominantly of pyrite, chalcopyrite, and sphalerite (Fig. 4-15). Several small, discontinuous lenses of massive sulfides have been defined both stratigraphically above and below the main massive sulfide body. A disseminated pyritic halo envelopes the ore body and extends along strike for at least 1,500
meters in either direction and down dip for an unknown distance (May, 1977). No discrete zone of stockwork ore has been recognized, however, this could be attributed to the effects of regional deformation. The ore body is chemically zoned with a chalcopyrite-rich base grading into a more sphalerite-rich top that has led to the interpretation that the ore body is overturned (May, 1977; May and Dinkowitz, 1996).

Chalcopyrite is the dominant sulfide mineral and occurs within bands, interstitial to recrystallized pyrite, and also as inclusions within sphalerite (Fig. 4-15B). High concentrations of sphalerite occur toward the top of the massive sulfides and within thin lenses of massive sulfide found in the stratigraphic hanging wall (May, 1977). Chalcopyrite inclusions in sphalerite appear to be less abundant towards the top of the massive sulfide lens. Iron in sphalerite ranges from approximately 2-9 wt% which correlates to relatively low Fe/Zn ratios of 0.04-0.15. Additional sulfide minerals recognized in this study include minor amounts of galena and trace amounts of arsenopyrite, famatinite, and covellite (Fig. 4-15C).

The average precious metal grades at Flambeau are 2.9 g/t Au and 30 g/t Ag. However, the distribution of these metals within the hypogene ore has not been well documented. Widespread, low-grade gold concentrations occur within the quartz-muscovite schists of the ore interval and have been used as geochemical indicators (May and Dinkowitz, 1996). Gold has been found throughout the massive sulfide lens and occurs as native gold or electrum (Fig. 4-15D). Silver is associated with zones of high sphalerite content, typically toward the stratigraphic top of the massive sulfides (May, 1977). Silver-bearing and associated telluride minerals identified in this study include hessite, altaite, and tellurobismuthinite (Fig. 4-15E).

4.5. Horseshoe

The Horseshoe prospect is classified as a zinc-lead-copper type massive sulfide occurrence (Fig. 2-4) and contains an estimated resource of 670,000 tonnes averaging 2.45% copper, 5.35% zinc, 0.9% lead, 2.06 g/t gold, and 36.0 g/t silver (DeMatties, 1994). The limited drilling conducted to date suggests that massive to semimassive sulfides occur within a deformed tabular zone that varies in thickness from <1 meter up to 10 meters in thickness (Fig. 4-16). The mineralized zone and encompassing volcanic strata strike east-west and dip steeply to the south. The volcanic pile in the immediate vicinity of the Horseshoe prospect has been interpreted to be overturned, however, owing to a general lack of stratigraphic indicators this is speculative. The mineralized zone has been defined over a strike length of approximately 500 meters and to a vertical extent of approximately 300 meters. The metamorphic grade appears to have
reached upper greenschist facies as indicated by the presence of garnets within the ore interval. Volcanic textures of the surrounding host rocks are generally well preserved.

**Volcanic Stratigraphy**

The Horseshoe prospect is unique amongst the massive sulfide deposits of the Penokean volcanic belt in that the host stratigraphy is dominated by mafic volcanic flows. However, the ore interval is hosted by felsic volcanic rocks, highlighting the bi-modal nature of volcanism in the area (Fig. 4-2). Mafic volcanic rocks of the hanging wall and footwall consist of amygdaloidal and porphyritic flows (Fig. 4-17A,B). The apparent thickness of these flows varies from <5 meters to >50 meters. Basal foliation and flow top breccias are common features recognized for individual flows and distinct curviplanar zones of intense alteration are thought to represent altered pillow selvages. In addition, thin interflow sedimentary deposits occur locally and graded bedding within these units suggests that stratigraphic tops face to the north (Fig. 4-17C).

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**Fig. 4-16:** Simplified geologic cross section of the Horseshoe prospect. Looking west, modified from unpublished data provided by Aquila Resources Inc.
Fig. 4-17: Photographs and photomicrographs of volcanic host rocks to the Horseshoe prospect. A. Irregularly shaped quartz filled amygdule within amphibole-rich mafic volcanic flow. HS94-4-105.1 m. CPL. B. Massive, porphyritic mafic volcanic flow. HS94-4-80.7 m. C. Interflow sedimentary deposit showing graded beds, arrow indicates direction of fining upward. HS94-4-171 m. D. Monomict rhyolite breccia. HS94-4-244.2 m. E. Flow banded rhyolite. HS94-4-228.5 m. F. Coherent rhyolite with least-altered feldspar phenocrysts. HS94-4-214.1 m. CPL.

Felsic volcanic rocks at Horseshoe consist of a massive rhyolite unit and associated proximal volcaniclastic deposits. Volcanic facies recognized include volcanic breccias (Fig. 4-17D) and flow-banded rhyolite (Fig. 4-17E), that occur outward of a massive rhyolite body (Fig. 4-17F). Although the geometry of the felsic volcanic facies association is not well constrained, the ore interval appears to occur at the top of the felsic volcanic rocks. The felsic interval and the ore zone occur amongst a thick succession of mafic volcanic flows which suggests that these felsic rocks had a close temporal association.
to the formation of massive sulfides. In addition to these main volcanic units, several thin mafic dikes cut the volcanic stratigraphy. The ore interval at Horseshoe is comprised of a chlorite-biotite-quartz+/-garnet schist with variable sulfide content. Quartz occurs as elongate re-crystallized grains, which may represent flattened felsic volcanic fragments. In addition to sulfides, the ore interval is marked by intense chlorite alteration and is distinctly more foliated and sheared than the surrounding host rocks.

Alteration

The host rocks that encompass the ore interval at the Horseshoe prospect show no evidence for intense hydrothermal alteration (Fig. 4-18). This contrasts from other deposits of the Penokean volcanic belt that have well-developed alteration haloes and show significant variations in alteration intensity from the stratigraphic footwall to the hanging wall. Throughout the volcanic stratigraphy the host rocks have consistent AI values between 23-40 whereas CCPI values vary between 39-90, which appears to reflect compositional variations that are not likely related to hydrothermal alteration (Fig. 4-18). In contrast to the surrounding volcanic stratigraphy, rocks immediately associated with the massive sulfide lens have been subject to intense hydrothermal alteration that has been metamorphosed to a chlorite-biotite+/-garnet assemblage and is pervasive throughout the ore interval (Fig. 4-19A,B). This zone of alteration is most intense stratigraphically below the massive sulfides and is interpreted to represent a deformed chlorite-sulfide stockwork zone. In addition to chlorite alteration, patchy re-crystallized carbonate minerals occur throughout the ore interval and appear to have a direct association with sulfide abundance (Fig. 4-19C).

Mineralization

Polymetallic massive to stockwork sulfides occur within a relatively thin, deformed tabular zone. Slight copper enrichment occurs within the stockwork zone relative to the massive sulfides but generally the ore interval is distinctly polymetallic. Stockwork style sulfides occur as a semi-conformable lens stratigraphically below the massive sulfides and consist of bands of chalcopyrite and sphalerite with lesser pyrite and pyrrhotite within a chlorite-biotite-quartz+/-garnet schist (Fig. 4-19B,D). Rocks within the ore interval are strongly deformed and foliated and shear textures are common (Fig. 4-19E).

The massive sulfide lens at Horseshoe is unusual in that it is best described as a sulfide matrix-supported polymict breccia (Fig. 4-19F). Lithic clasts include highly siliceous clasts and variably altered mafic volcanic rocks. These clasts are well rounded and vary in size from <1 to >30 cm. Pyrite often occurs as discrete rounded “buckshot” grains within a finer-grained chalcopyrite-sphalerite-pyrrhotite
Fig. 4-18: Downhole geochemical plot for HS94-4 from the Horseshoe prospect. Colors and symbols from Figure 4-1.
matrix. Buckshot textures are interpreted to represent milled pyrite grains indicating recrystallization of the massive sulfides, which likely occurred during regional deformation related to the Penokean orogeny. Precious metal contents at Horseshoe appear to be significant, however, no systematic study of the distribution or mineralogy of these metals has been undertaken. Limited SEM work completed for this study found no gold- or silver-bearing minerals, and the only minor metals encountered were native bismuth and breithauptite, a nickel-antimony alloy with chemical formula NiSb.

4.6. Lynne

The Lynne massive sulfide deposit contains 5.1 Mt of ore with average grades of 9.3% Zn, 1.7% Pb, 0.5% Cu, 81.6 g/t Ag, and 0.7 g/t Au (Adams, 1996). Of the potentially economic deposits in the Penokean volcanic belt, Lynne is the only deposit that contains significant lead and is classified as a Zn-Pb-Cu type massive sulfide deposit (Fig. 2-4A). Sulfide-enrichment at Lynne is comprised of four closely stacked lenses of stratiform massive to semi-massive sulfides. These lenses appear to coalesce in the central portion of the deposit, creating a bulbous ore lens (Fig. 4-20). Mineralized strata sub-crops below 12-23 meters of glacial overburden, extends for approximately 400 meters along strike, and has a maximum aggregate thickness of 100 meters. The massive sulfides and their host rocks strike E-SE and dip 40 degrees to the northeast. Graded beds within the volcaniclastic host rocks indicate stratigraphic tops face northeast (Adams, 1996). Regional metamorphism has reached greenschist facies, however, the emplacement of a tonalite body in the immediate footwall of the deposit has resulted in higher-grade contact metamorphism. Evidence for retrograde alteration is widespread (Adams, 1996).

Volcanic Stratigraphy

The Lynne deposit is hosted by volcaniclastic and coherent volcanic rocks that dip shallowly to the northeast. Chemical sedimentary rocks (Fig. 4-1) form a distinct and important unit within the volcanic stratigraphy and are spatially associated with massive sulfides. Chemically, the host rocks are bimodal and vary from basalt to rhyolite with a notable gap of rocks with intermediate composition (Fig. 4-2). The volcanic stratigraphy of drill hole LYN90-16 is shown in Figure 4-21 and is considered to be representative of the deposit stratigraphy.

In the immediate deposit area a large tonalite has intruded the footwall and locally disrupts the ore interval (Fig. 4-20). The tonalite is composed of roughly equal proportions of coarse feldspar and quartz phenocrysts (Fig. 4-22A) and has a distinctive granophyric appearance along its outer margin. Distal to
the ore body, a lower rhyolite unit consisting of a thick succession of rhyolite lapilli tuff and rhyolite breccia that is interpreted to be associated with a rhyolitic flow-dome complex (Kennedy, 1997).

**Fig. 4-19:** Photographs and photomicrographs of alteration and ore styles at the Horseshoe prospect. A. Biotite-chlorite-quartz-garnet schist of the ore interval. HS94-4-250.7 m. PPL. B. Alteration now comprised of chlorite-biotite within stockwork sulfide zone. HS94-4-264.7 m. PPL. C. Patchy carbonate alteration within stockwork sulfide zone. HS94-4-264.7 m. PPL. D. Same image as C in reflected light showing poly-metallic sulfides: chalcopyrite, sphalerite, pyrite, and pyrrhotite. E. Deformed and sheared chlorite schist with banded pyrite-chalcopyrite. HS94-4-263.6 m. F. Matrix-supported massive sulfide breccia with large rounded mafic volcanic clasts and buckshot pyrite. HS94-4-270.1 m.
The ore interval at Lynne is comprised largely of chemical sedimentary and crystal-rich volcaniclastic rocks. Interbedded chert and carbonate rocks (Fig. 4-22B,C) are spatially associated with massive sulfides and were likely deposited in a shallow marine setting. Felsic volcaniclastic rocks are highly altered and consist of 20-30% blue quartz phenocrysts and crystal fragments within a very fine-grained micaceous matrix (Fig. 4-22D). A series of thin intermediate-mafic feldspar porphyritic rocks cross cut the ore interval and have high angle contacts and chilled margins suggest these are dikes and/or sills rather than volcanic flows (Fig. 4-22E).

The hanging wall stratigraphy is composed of interlayered crystal-rich volcaniclastic rocks (Fig. 4-22F) and rhyolite flows (Fig. 4-22G). The volcaniclastic rocks are chemically similar and have a similar appearance to those of the ore interval and generally consist of angular to sub-rounded quartz and feldspar phenocrysts and crystal fragments within a fine-grained quartz-phyllosilicate matrix. Feldspars are markedly more abundant than volcaniclastic rocks of the ore interval and are likely a product of subdued
hydrothermal alteration within the hangingwall succession. Coherent felsic rocks are coarse-grained to porphyritic with quartz and feldspar phenocrysts within a fine-grained micaceous matrix. In addition, numerous feldspar-phyric flows and/or dikes and sills (Fig. 4-22H) are interlayered throughout the dominantly felsic hanging wall stratigraphy.

Fig. 4-21: Down hole geochemical plot for the Lynne deposit (drill hole LYN90-16). Colors and symbols from Figure 4-1.
Alteration

Three distinct styles of alteration are recognized within the Lynne deposit. Phyllosilicate alteration is most evident in the volcaniclastic protolith where the destruction and replacement of feldspars by fine-grained phyllosilicates is prominent. Figure 4-23 shows the contrast of unaltered and altered volcaniclastic rocks. This style of alteration along with Al and CCPI values has a positive correlation with proximity to ore within the volcaniclastic rocks (Fig. 4-21). This style of alteration is accompanied by a decrease in \( \text{Na}_2\text{O} \) and \( \text{CaO} \), and an increase in \( \text{MgO} \), \( \text{K}_2\text{O} \), and \( \text{Rb}/\text{Sr} \) values, which are all related to mineralogical changes as a result of feldspar destruction and the addition of magnesium. An observed contrast of alteration intensity between volcaniclastic and coherent rock types which further supports textural evidence that the coherent rocks are likely post mineralization dikes/sills (Fig. 4-21). The phyllosilicate alteration zone is thought to be the metamorphic equivalent to a white mica-chlorite alteration zone.

In addition to phyllosilicate alteration, a highly magnesian mineral assemblage occurs at the base of the ore zone along the outer margins of the tonalite. The dominant mineral assemblage within this zone is talc-chlorite-tremolite that has a distinctive appearance and is mechanically soft and waxy. Volcanic textures were completely obscured within this zone of intense alteration, which is thought to represent a high temperature Mg-rich upflow zone that fed the overlying massive sulfides. The presence of calc-silicate minerals may indicate a calcareous protolith.

Calc-silicate or a skarn type mineral assemblage is also recognized at Lynne. This style of alteration is spatially associated with sulfide-enrichment and occurs within the calcareous and chert protoliths (Fig. 4-23D-F). Common minerals found in this alteration assemblage include andradite-grossular, epidote, diopside, and tremolite-actinolite. The granoblastic textures in this assemblage (Fig. 4-23F) suggest it formed as a result of post-mineral contact metamorphism of the chemical sedimentary rocks, most likely related to emplacement of the footwall tonalite.

Mineralization

Mineralization at Lynne is comprised of several massive to semi-massive lenses of base metal sulfides and associated precious metal enrichment. These lenses appear to coalesce in the center of the deposit creating a bulbous-shaped ore body. Three discrete lenses of massive sulfide were intersected in
Fig. 4-22: Core photographs rocks hosting the Lynne deposit. A. Footwall tonalite. LYN16-148.8 m. B. Chert from the ore interval. LYN16-118.4 m. C. Calcareous unit from the ore horizon. LYN16-111.1 m. D. Phyllosilicate-altered felsic volcaniclastic rock within the ore horizon. LYN16-129.6 m. E. Chilled margin of basaltic-andesite dike cutting mineralized chert at high angle. LYN16-119 m. F. Altered felsic volcaniclastic rock from the hanging wall. LYN16-80.2 m. G. Coherent felsic rock from the hanging wall. LYN16-83.8 m. H. Feldspar-phyric dike/sill within the hanging wall. LYN16-90.6 m.
Fig. 4-23: Photographs and photomicrographs of alteration styles at the Lynne deposit. A. Feldspar-rich crystal tuff with abundant coarse feldspar crystals and crystal fragments within a fine grained quartz-mica groundmass. LYN16-52.4 m. CPL. B. Highly altered quartz-crystal tuff containing large quartz phenocrysts in a fine grained micaceous matrix. Patchy style of alteration reflects altered feldspars and/or lithic clasts. LYN16-94.8 m. PPL. C. Coherent feldspar porphyry with euhedral feldspar phenocrysts within fine grained feldspar+quartz matrix. Low degree of alteration suggests this unit is a post-mineral dike or sill. LYN16-105.8 m. D. Mineralized sample with calc-silicate style alteration. LYN16-113.8 m. E. Compositionally zoned garnets within calc-silicate alteration zone. LYN16-98.6 m. BSE. F. Granoblastic texture of coarse tremolite overgrowing sphalerite mineralization. LYN16-131.5 m. PPL. G. Talcose alteration zone. LYN16-141.1 m. H. Hornfelsic-granoblastic talcose alteration zone LYN16-139.9 m. CPL.
drill hole LYN90-16 and were variably enriched in base and precious metals (Fig. 4-21). No discrete stockwork zone has been recognized. Mineralization is intimately associated with chemical sedimentary rocks and evidence of replacement style mineralization is provided by: 1) discrete alteration selvages within rocks stratigraphically above massive sulfide lenses (Fig. 4-24A) and 2) remnants of silicate minerals within a massive sulfide matrix (Fig. 4-24B). Furthermore, the lack of sulfide minerals found within volcaniclastic rocks interbedded with massive sulfides suggests that the mineralizing fluids selectively replaced the chemically reactive calcareous horizons. Late contact metamorphism has produced calc-silicate minerals that appear to overgrow the sulfide mineralization (Fig. 4-24C).

Common sulfides comprising base metal ore include sphalerite, galena, and chalcopyrite with lesser pyrrhotite and pyrite. Sphalerite varies in color from purple to light brown (Fig. 4-24D-F) which reflects variations in the iron content of the sphalerite. Overall, the sphalerite is Zn-rich with low to no detectable iron in SEM-EDS spectra. Silver contributes significantly to the economic potential of the Lynne deposit with assay values of >1,000 ppm silver not uncommon. Silver is associated with base metals and appears to be more closely associated with galena than the other base metal sulfides (Fig. 4-24G,H). Silver minerals recognized in this study are acanthite, native silver, löllingite, freibergite, argentiferous galena, and unidentified silver sulfides or sulfosalts. Overall gold is a relatively minor constituent at Lynne and no gold was found in this study. Adams (1996) reported that gold is rarely associated with base metals and is found in its highest concentrations associated with skarn style alteration and mineralization.

Previous workers have recognized a distinctive metal zonation pattern at Lynne, consisting of a chalcopyrite-pyrrhotite base, a sphalerite-rich core and lead-silver mineralization towards the top of the sulfide lenses (DeMatties, 1994; Adams, 1996). However, compilation of historic assay data reveals a more complicated distribution of metals in the deposit (Figure 4-21); there is little evidence of a copper-rich base grading upwards into zinc and lead dominated sulfide-enrichment.

4.7. Reef

The Reef Au-Cu prospect contains an estimated mineral resource of 412,500 tonnes averaging 10.6 g/t gold, 0.28% copper, and approximately 8.6 g/t silver (Kennedy and Harding, 1990). This resource was defined by a joint venture between Noranda Exploration and Amax Gold in the late 1980’s. More recently, Aquila Resources Inc. has over doubled the number of holes drilled on the property and expanded the mineral inventory, although an updated mineral resource has not been completed. At present the genesis of Au-Cu mineralization at Reef is poorly understood and the prospect has been variably
Fig. 4-24: Core photos and photomicrographs of massive sulfides at the Lynne deposit. A. Sharp contact of massive sulfide and volcaniclastic host rock with alteration extending into the host rock. LYN16-109.9 m. B. Round and recrystallized quartz fragments within massive sphalerite matrix. LYN16-125.4 m. CPL. C. Coarse laths of calc-silicate mineral overprinting massive sulfide. LYN16-131.5 m. RL. D. Massive sphalerite showing variations of grain size and color of sphalerite related to iron content. LYN16-131.2 m. E. Purple-red sphalerite containing minor iron. LYN16-98.6 m. PPL. F. Yellow-brown sphalerite with no detectable iron. LYN16-112.3 m. PPL. G. Lead and silver minerals within granoblastic calc-silicates. LYN16-113.8 m. BSE. H. Acanthite and associated minerals within high-grade silver zone. LYN16-113.8 m. BSE.
classified as a volcanogenic-related sulfide deposit and a structurally controlled, shear zone-hosted gold deposit (Scott, 1988; Kennedy and Harding, 1990; DeMatties, 1994). Metal-enrichment occurs within a series of gently dipping quartz-sulfide zones within strongly altered, metamorphosed and variably sheared host rocks (Fig. 4-25). The mineralized zones strike northeast-southwest, dip shallowly to the northwest and have been defined several hundred meters in each of these directions. Regional deformation and metamorphism along with shearing and possible contact metamorphism from the nearby anorogenic Wolf River batholith have largely destroyed primary rock textures. The abundance of amphiboles, biotite, and local garnet suggest metamorphic grades have reached amphibolites facies.

Local Geology

The Reef Au-Cu prospect is located within the Wausau volcanic complex and is situated between the inferred Eau Claire shear zone and the large, anorogenic Wolf River batholith (Fig. 2-3). Steeply to sub-vertically dipping mafic volcanic rocks constitute the majority of rock types within the deposit area and are overlain by a thick succession of felsic volcaniclastic rocks that are exposed along the Eau Claire River approximately 2.5 kilometers west of the deposit area (Kennedy and Harding, 1990). Rocks along the Eau Claire River have been variably interpreted as deformed and metamorphosed volcanic rocks (Maass, 1986) or mylonites associated with a two kilometer wide northeast trending shear zone that extends for 25 kilometers northeast (LaBerge and Myers, 1983). Kennedy and Harding (1990) interpreted this zone to comprise the axis of a major syncline, with the Reef prospect lying on the southeast limb of the fold.

Regional drill holes and outcrops from the surrounding deposit area have previously been described (Scott, 1988). These rocks display a strong metamorphic overprint, variable degrees of shearing, and an uncertain protolith. Kennedy and Harding (1990) interpreted the rocks hosting the Reef prospect to be a biotite-rich foliated to mylonitic granofelsic rock derived from a gabbro protolith. However, detailed core logging shows that the overall appearance of the granofels unit including metamorphic textures, grain size, and mineralogy is highly variable and likely reflects lithological variations in the host stratigraphy. The dominant phases of the granofels unit recognized in this study include: a medium-coarse grained granoblastic rock composed predominantly of feldspar, amphibole, and biotite (Fig. 4-26A); a finer-grained version of above that contains quartz and patchy biotite that is often proximal to the ore interval (Fig. 4-26B,C); and a coarse grained equigranular unit composed of feldspar, amphibole and magnetite (Fig. 4-26D). Despite these units being visually distinct, rock textures and mineral assemblages change rapidly and often do not have definitive contacts. Thus, despite close-spaced drilling the correlation of
these different rock types between drill holes and section lines is difficult. Distinct within this dominantly mafic host succession are discrete granophytic to porphyritic and locally aplitic felsic intrusive rocks (Fig. 4-26E) that have previously been interpreted to be related, at least spatially, to gold and sulfide enrichment (Kennedy and Harding, 1990). In addition, near the bottom of the drilled section at Reef is a large, homogeneous, coarse grained gabbroic unit that is interpreted to intrude the local section (Fig. 4-26F). The extent of the gabbro is unknown as drill holes typically end within this unit.

Detailed chemostratigraphic analysis from a representative drill hole at Reef provides further insight into the complexity of the local stratigraphy (Fig. 4-27). The host rocks are dominantly mafic in composition as indicated by Ti-Zr ratios. However, these ratios are strongly heterogeneous and vary widely throughout the stratigraphy, despite an average sample spacing of approximately 10 meters. Clearly this would not be expected if the rock type was derived from a single gabbroic protolith. In
Fig. 4-26: Core photographs and photomicrographs of rocks hosting the Reef Au-Cu prospect. A. Variably altered granoblastic rocks composed primarily of feldspar-amphibole-biotite. R12-40-63.9 m. B. Patchy biotite within fine grained quartz-rich matrix. R40-12-110.7 m. C. Photomicrograph of similar alteration style as photo B with patchy biotite within fine grained quartz-rich matrix. R12-40-96.95 m PPL. D. Coarse, equigranular amphibole, feldspar, magnetite. R12-40-81 m. E. Fine-grained altered and mineralized aplitic intrusive rock. R12-40-52.8 m. F. Coarse equigranular gabbro. R12-40-127.7 m.

addition, Figure 4-27 shows no systematic change in host rock composition relative to the ore intervals and suggests that the mineralization was not stratigraphically controlled. This differs from the VMS deposits studied, which show a consistent variation between rock types above and below the ore interval.
The protolith may have been finely bedded volcaniclastic to sedimentary rocks of variable composition that are no longer recognizable due to subsequent alteration, deformation, and metamorphism.

**Alteration**

As a result of strong and possibly multi-stage deformation and metamorphism, distinguishing between hydrothermal and regional alteration is difficult. However, a few common features are recognized proximal to the mineralized intervals and are likely related to hydrothermal alteration. One such feature is comprised of distinctive patchy biotite alteration (Fig. 4-26B,C) that appears to extend for a short distance on either side of the quartz-sulfide ore intervals. This biotite enrichment is recognized geochemically with a pronounced increase in K$_2$O surrounding the ore intervals (Fig. 4-27). Other alteration indices, namely AI and CCPI, do not show any consistent correlation with gold enrichment. In addition to patchy biotite, discrete zones of skarn-like mineral assemblages often occur proximal to the mineralized zones (Fig. 4-28A). These intervals are comprised of massive andradite-epidote-diopside with lesser carbonate minerals, quartz, and sulfides. Disseminated and vein confined sulfides are ubiquitous throughout the stratigraphy and do not necessarily correlate with gold enrichment. Magnetite is locally abundant and can exceed 20% but the distribution and genesis is poorly understood (Fig. 4-28B). Although a relatively minor constituent, white mica was noted along gold-rich quartz-sulfide vein selvages and supports findings of Kennedy and Harding (1990) that also reported this association (Fig. 4-28C).

**Mineralization**

Enrichment of gold and copper occur within at least seven discrete quartz-sulfide intervals that dip shallowly to the northwest. The host rock stratigraphy dips steeply to sub-vertically northwest and was interpreted by Kennedy and Harding (1990) to lie on the southeast limb of a major syncline. This contrasts from the shallowly dipping felsic intrusive rocks and mineralized intervals (Fig. 4-25), which implies a discordant relationship to the surrounding stratigraphy. Gold is largely confined to distinct quartz-sulfide intervals but occasionally extends into the surrounding host rocks. Mineralized intervals range from <1 to >15 meters in thickness and vary from massive to semi-massive sulfide (Fig. 4-28D), to dominantly quartz with only minor sulfide abundance. Quartz within the ore interval varies from being completely recrystallized to highly deformed, forming quartz ribbons that do not resemble “typical” quartz veins. In addition, massive quartz veins consisting of milky-white quartz and variable amounts of
sulfide and calc-silicate minerals are common throughout the stratigraphy but are barren in terms of gold content and are interpreted to have been emplaced post gold mineralization.

**Fig. 4-27:** Downhole geochemical plot for a representative drill hole from the Reef prospect (drill hole R12-40). Figures and symbols from Figure 4-1.
**Fig. 4-28:** Photographs and photomicrographs of altered and mineralized rocks of the Reef prospect. A. Calc-silicate style of alteration with massive garnet-epidote and minor calcite and chalcopyrite. R12-40-34.5 m. B. Host rock with abundant disseminated magnetite. R12-40-90.3 m. C. Thin gold-bearing quartz-sulfide veinlet with biotite-muscovite selvage. D. Contact of fine-grained granofelsic rock and gold-rich massive sulfide. R12-40-34 m. E. Coarse visible gold from quartz boulder associated with saprolite. F. Base and precious metal bearing minerals within the quartz-sulfide ore interval. R12-40-32.15 m. BSE.
The dominant sulfide minerals associated with gold are pyrrhotite and pyrite with lesser chalcopyrite and minor amounts of sphalerite and galena. In addition, Kennedy and Harding (1990) reported an association with cubanite and rarely molybdenite. Magnetite occurs with the sulfide assemblage but is not typically associated with gold. Visible gold has not been recognized with the exception of quartz-hematite boulders that occur on the surface associated with a zone of saprolite development (Fig. 4-28E). Within the protore, gold occurs as microscopic grains, as electrum, and within a wide range of telluride minerals (Fig. 4-28F). Gold-bearing and associated trace minerals identified in this study include calaverite (AuTe$_2$), frohbergite (FeTe$_2$), hessite (Ag$_2$Te), petzite (Ag$_3$AuTe$_2$), melonite (NiTe$_2$), muthmannite ((Au,Ag)Te), and tellurobismuthinite (Bi$_2$Te$_3$).

4.8. Ritchie Creek

The Ritchie Creek prospect is classified as a copper-type massive sulfide occurrence with an estimated resource of approximately 800,000 tonnes averaging 2.11% copper, 0.37% zinc, and 0.34 g/t gold (DeMatties, 1994). No information regarding the silver or lead content of the deposit is available. The deposit occurs as a stratiform massive to semi-massive sulfide lens that varies from <1 meter up to 17 meters in thickness and has been traced along strike for approximately 250 meters and over 350 meters down dip. The deposit and volcanic host strata strike nearly east-west, dip sub-vertically, and are locally overturned (Fig. 4-29). Regional metamorphism within the deposit area has reached upper greenschist to lower amphibolite facies (DeMatties, 1990).

Volcanic Stratigraphy

The Ritchie Creek prospect is hosted within a dominantly volcaniclastic succession with a relatively small proportion of coherent volcanic rocks. Generally, the rocks are highly foliated and deformed and thus, primary textures are not well preserved which makes interpretation of the protolith and volcanic facies difficult. Chemically, the host rocks are mostly felsic-intermediate in composition with the exception of mafic flows and associated volcaniclastic rocks in the footwall (Fig. 4-30). The ore interval is associated with a coherent to brecciated rhyolite unit that is distinctive amongst the surrounding stratigraphy. Post-mineralization mafic-intermediate dikes are common and cross cut the stratigraphy.

The stratigraphic footwall to the ore interval is comprised dominantly of quartz-feldspar-biotite-muscovite-chlorite schist. These rocks are often banded with bands containing varying mineral
compositions, often with varying grain sizes that are interpreted to reflect primary graded beds (Fig. 4-31A). Relatively minor constituents to the footwall stratigraphy are mafic volcanic flows and associated volcaniclastic rocks. These flows are typically fine-grained, massive to porphyritic with amphibole-pyroxene phenocrysts within a fine-grained quartz-biotite-chlorite matrix (Fig. 4-31B). Immediately below, and associated with the ore interval, is a distinctive coherent to brecciated rhyolite unit. This unit has been altered and metamorphosed to a quartz-muscovite schist and contains altered feldspar phenocrysts. The volcanic breccia facies of this rhyolite unit contains large, angular siliceous clasts within a quartz-muscovite matrix (Fig. 4-31C).

Massive to semi-massive sulfides within the ore interval occur near the stratigraphic top of the felsic volcanic rocks. The ore interval contains an abundance of carbonate minerals that have been
Fig. 4-30: Down hole geochemical plot for a representative drill hole from the Ritchie Creek prospect (drill hole RC-5). Colors and symbols from Figure 4-1.

variably metamorphosed into a calc-silicate mineral assemblage (Fig. 4-31D,E). The marked increase in Ca-bearing minerals associated with the ore interval represents a calcareous protolith that is interpreted to represent either a chemical sedimentary protolith, such as a limestone, or the result of semi-conformable carbonate alteration prior to mineralization.

Less information exists for lithologies of the hanging wall. Rocks observed in the present study suggest continued deposition of strata similar in composition and character to those in the footwall. These rocks are fine-grained, massive to weakly foliated, and are comprised predominantly of feldspar, quartz, and biotite with lesser muscovite and chlorite (Fig. 4-31F). Preservation of feldspar phenocrysts and a lack of sulfides coupled with low Al and CCPI values suggest that the hydrothermal system was inactive during deposition of the hanging wall strata.

Alteration

Hydrothermal alteration at Ritchie Creek has been overprinted by regional and possibly contact metamorphism. In general, it appears that significant hydrothermal alteration is restricted to the ore interval and the underlying felsic volcanic rocks. The felsic volcanic pile has been subject to strong white mica alteration which has resulted in high Al values and a decrease in Na\textsubscript{2}O (Fig. 4-30) which is consistent with the replacement of feldspars by white mica. Near the top of the felsic volcanic pile, rocks
are strongly chlorite altered with accompanying sulfides that cut the felsic rocks (Fig. 4-32A). This zone of chlorite enrichment appears to be semi-conformable beneath the ore interval and may represent the deformed equivalent of a chlorite-sulfide alteration pipe.

Rocks of the ore interval are composed of calc-silicate minerals, carbonate minerals, sulfide minerals, and chlorite. This complex mineral assemblage reflects the metamorphosed product of a hydrothermally altered and mineralized calcareous protolith. Carbonate minerals are dominantly calcite, whereas calc-silicate minerals have a wide range of compositions. The dominant calc-silicate minerals identified in this study include andradite-grossular, diopside, and tremolite-actinolite (Fig. 4-32B-D). The transition from calc-silicate to carbonate dominated mineralogy occurs over a short distance within the ore interval and is likely related to a contact metamorphic overprint from post-mineral dikes intruding the ore interval. This is supported by textural evidence of granoblastic calc-silicate minerals within this interval (Fig. 4-32B-D).

Mineralization

Sulfide enrichment at the Ritchie Creek prospect occurs as a tabular, stratiform interval of massive and semi-massive pyritic sulfides. Copper is the most important metal within this zone and only minor amounts of zinc and gold have been reported. Sulfide mineralogy is dominantly pyrite with lesser pyrrhotite, chalcopyrite, and sphalerite. Pyrite often occurs as coarse, granoblastic grains whereas the other sulfide minerals are typically fine-grained and forms the groundmass (Fig. 4-32E) interstitial to pyrite. Zones of calc-silicate alteration contain appreciable amounts of magnetite, which is consistent with the skarn-style of alteration. Assay values are not available for the ore interval and no known metal zonation exists. DeMatties (1990) reported that the highest copper values occur at the stratigraphic top of the ore interval and extend in a steeply plunging ore-shoot.

Despite the overall low gold content at Ritchie Creek, significant structurally controlled gold-bearing zones have been intersected (DeMatties, 1990). These zones appear to correlate with a major north-south fault that intersects the local stratigraphy where the highest reported gold values (>10 g/t Au) occur within a highly altered mafic dike. An increased lead content occurs within this zone of gold-enrichment and is associated with altaite and possibly gold telluride minerals (DeMatties, 1990). No significant gold-bearing zones were examined in this study, however, an abundance of accessory minerals and trace metals were identified during SEM work on polished ore sections. The majority of these minerals are bismuth tellurides such as tellurobismuthinite (Bi$_2$Te$_3$) and tsumoite (BiTe), however, several
Fig. 4-31: Photographs and photomicrographs of the host rocks of the Ritchie Creek prospect. A. Volcaniclastic rocks of the footwall, note variation in grain size of individual beds and fining upward. RC5-315’. B. Porphyritic mafic volcanic flow with coarse amphibole grains within fine-grained quartz-biotite-chlorite matrix. R5-244’. PPL. C. Clastic felsic volcanic rock with angular siliceous clasts within quartz-muscovite matrix. RC5-478’. D. Sample from the calc-silicate altered ore interval. RC5-616’. E. Coarse pyrite within carbonate-rich matrix. RC5-642’. F. Feldspar phenocrysts within fine-grained quartz-biotite matrix. Hanging wall. RC5-686.5’. CPL.
Fig. 4.32: Photographs and photomicrographs of altered and mineralized rocks from the Ritchie Creek prospect. A. Strongly chlorite-altered rhyolite. RC5-595.5' PPL. B. Calc-silicate alteration with andradite and grossular within a chlorite-rich matrix. RC5-618'. PPL. C. Diopside-rich calc-silicate alteration of the ore interval. RC5-618'. PPL. D. Granoblastic tremolite-actinolite within massive pyritic sulfides. RC5-603.5'. E. Granoblastic pyrite with fine grained sphalerite and chalcopyrite within a matrix of carbonate and chlorite. RC5-642'. RL. F. Pyrite within the calc-silicate altered ore interval. Arrows point to fine grained inclusions of a complex suite of Bi, Te, Se, and Pb-bearing minerals. RC5-618'. BSE.
selenium and lead bearing minerals were also identified. These minerals tend to occur as fine-grained inclusions within granoblastic pyrite and garnet grains (Fig. 4-32F).
CHAPTER 5
DISCUSSION

The present section summarizes the results of the present study and compares and contrasts the characteristics of the different VMS deposits in the Penokean volcanic belt.

5.1. Deposit Characteristics

The Paleoproterozoic is recognized as one of the most significant time intervals for the formation and preservation of VMS deposits in Earth’s history (Franklin et al., 2005). The relative size and grade of the Penokean VMS deposits compared to Paleoproterozoic VMS deposits and deposits of all ages are shown in Figure 5-1. The Penokean VMS deposits, despite the small population size, stand out in terms of size and average zinc grade compared with other Paleoproterozoic VMS districts (Fig. 5-1). Considering the relative lack of development and modern exploration compared with most other VMS districts worldwide, the Penokean volcanic belt clearly has the potential for additional resources that are yet to be discovered.

Penokean VMS deposits average over 9 Mt in size (Table 5.1). This number is skewed by the Crandon deposit that contains over 65 Mt of ore. However, large (>25 Mt) to giant (>100 Mt) deposits, and even super giant (>150 Mt) VMS deposits are not uncommon within major VMS districts of the world (Franklin et al., 2005). Crandon represents a world-class deposit, but cannot be considered as an outlier. It is likely that a significant number of small to medium sized deposits are yet to be discovered in the Penokean volcanic belt which would reduce the average size. This appears reasonable as exploration in the Penokean belt has been limited and is consistent with the fact that the large deposits located close to surface are commonly discovered early in the exploration of VMS districts (DeKemp et al., 2011).

Deposit Style

With the exception of Reef, all of the deposits in the Penokean volcanic belt studied are considered VMS deposits. The deposits are characterized by a stratabound accumulation of sulfide minerals at or near the paleoseafloor and all deposits formed in direct temporal and spatial association with seafloor volcanism as demonstrated by the strong stratigraphic controls on the location of the deposits. Most of the deposits form sheet-like lenses of massive to semi-massive sulfides, which supports this observation.
Table 5-1: Comparison of the size and grade characteristics of the Penokean VMS deposits with other Paleoproterozoic deposits and the global VMS inventory (data from Barrie and Hannington, 1999).

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>Total Mt</th>
<th>Avg. Mt</th>
<th>Avg. Cu %</th>
<th>Avg. Pb %</th>
<th>Avg. Zn %</th>
<th>Avg. Au g/t</th>
<th>Avg. Ag g/t</th>
</tr>
</thead>
<tbody>
<tr>
<td>Penokean VMS</td>
<td>12</td>
<td>108.8</td>
<td>9.07</td>
<td>1.13</td>
<td>0.41</td>
<td>4.63</td>
<td>1.43</td>
<td>1.07</td>
</tr>
<tr>
<td>Paleoproterozoic VMS</td>
<td>134</td>
<td>819.4</td>
<td>6.11</td>
<td>1.91</td>
<td>0.75</td>
<td>3.79</td>
<td>1.32</td>
<td>1.01</td>
</tr>
<tr>
<td>Global VMS</td>
<td>800</td>
<td>6687.6</td>
<td>8.36</td>
<td>1.43</td>
<td>1.29</td>
<td>3.86</td>
<td>1.22</td>
<td>1.52</td>
</tr>
</tbody>
</table>

Crandon represents the only deposit in the Penokean volcanic belt that has a well-developed footwall stringer zone. This stockwork zone is characterized by a distinct copper-enrichment, whereas the overlying massive sulfide lens is zinc-rich (Lambe and Rowe, 1987). In other Penokean deposits, a discordant stockwork zone is not recognized and instead, the immediate footwall is characterized by a semi-conformable halo of increased disseminated sulfide abundance and associated alteration. The sulfides largely occur within discontinuous bands that are parallel to the foliation and/or layering of the host rocks. This is interpreted to represent the deformed equivalent of a stockwork zone that has been structurally transposed into a semi-conformable halo underlying the massive sulfides or may reflect lateral fluid flow through permeable volcaniclastic strata.

Further work is required to characterize the host rocks and mineralization processes at Reef to properly classify this Au-Cu prospect. In particular, structural investigations and a better understanding of the metamorphic petrology will likely be required to help unravel the complex deposit geology. Reef represents the only documented mineral occurrence within the Wausau volcanic complex. The deposit is characterized by a strong Au-enrichment and anomalous levels of Cu, but does not contain appreciable amounts of zinc or lead. The ore zone consists of heavily disseminated sulfides within discrete quartz-rich intervals and, as far as presently known, has no associated massive sulfide accumulation. Similar disseminated to structurally controlled sulfide deposits are known from other VMS camps, such as the Mouska Au-Cu deposit in the Abitibi greenstone belt (Belkabir and Hubert, 1995) and the Henty Au deposit in the Mount Read volcanic belt in Tasmania (Large et al., 2001b). However, due to the high-grade metamorphic overprint, a different origin for the Reef deposit cannot be presently ruled.
Fig. 5-1: Size and grade characteristics for Penokean, Paleoproterozoic, and global VMS deposits (data from Barrie and Hannington, 1999).

**Base Metal Grades and Metal Zoning**

Most Penokean VMS deposits are composed predominantly of pyrite, with subordinate sphalerite, chalcopyrite, and minor galena. The only potentially economic deposits that contain appreciable levels of galena are Lynne and to a lesser extent, Back Forty and Crandon (Fig. 2-4A). Common accessory minerals noted in this study include pyrrhotite, arsenopyrite, tetrahedrite-tennantite and in some deposits, magnetite. Primary marcasite is relatively common at the Back Forty deposit and has also been described at Crandon (Lambe and Rowe, 1987). A list of ore minerals of the Penokean sulfide deposits is provided in Table 5-2.

The VMS deposits of the Penokean volcanic belt typically show metal zoning. At Flambeau, sphalerite has been noted to increase towards the top of the massive sulfide lens and discontinuous lenses of massive sulfide that occur stratigraphically above the main lens are zinc-rich (May, 1977). Crandon consists of a copper-rich quartz-sulfide stockwork zone beneath a zinc-rich lens of massive sulfides
At Back Forty, the lower massive sulfide lens is predominantly zinc-rich pyritic massive sulfide and the upper sulfide lens is relatively enriched in zinc-lead-and silver; at present no copper-rich zone has been recognized. The massive sulfide lens at Bend is characterized by a chalcopyrite-rich top that is underlain by a pyritic core.

The observed ore mineralogy of the Penokean deposits is consistent with other VMS deposits worldwide (Large, 1992; Ohmoto, 1996; Franklin et al., 2005) as well as modern analogues forming on the seafloor (Hannington et al., 2005; Monecke et al., 2016). However, regional and in some cases contact metamorphism in addition to deformation has resulted in extensive recrystallization and local remobilization of the ore minerals as suggested by the textural relationships observed. Metal zoning of the Penokean VMS deposits is consistent with the process of zone refining (Knuckey et al., 1982; Eldridge et al., 1983; Ohmoto, 1996). This process is a result of sustained high-temperature fluid flow through a growing sulfide mound or subseafloor sulfide accumulation, causing dissolution of earlier formed sulfide minerals and replacement by minerals in a thermally intensifying regime. Over time, most Zn and Pb is stripped from the high-temperature interior of the massive sulfides and reprecipitated in the cooler outer zones, leaving a high-grade Cu-rich core behind. Continued refining is known to result in the formation of barren pyrite zones (Eldridge et al., 1983; Ohmoto, 1996) and may be responsible for the metal zonation pattern recognized at the Bend VMS deposit.

Precious Metal Grades and Metal Affinity

Of the five potentially economic VMS deposits discovered thus far in the Penokean volcanic belt, Back Forty and Crandon are classified as “anomalous” in gold content as these deposits contain greater than 31 tons of gold (Fig. 2-4B). Gold-enrichment at Back Forty is poorly understood and occurred within massive-disseminated base metal sulfide ore, discrete zones of sulfide rich gold-only ore, as iron oxide (gossan) ore, and within an enigmatic zone of intense shearing that characteristically contains minor amounts of sulfides. This complex distribution of gold likely reflects complex processes of synvolcanic gold enrichment and possibly late overprinting or remobilization during orogenesis. In contrast, gold at Crandon occurs within the massive sulfide lens and has a direct correlation with zinc-rich massive sulfides with only minor amounts of gold occurring within the chalcopyrite-rich stockwork zone (Lambe and Rowe, 1987).
Table 5-2: List of ore minerals within Penokean sulfide deposits. Asterisk denotes minerals noted in other studies and were not identified in the present study. Primary ore mineralogy is listed in approximate order of relative abundance for each deposit, whereas minor ore mineralogy is alphabetical. Minor ore mineralogy is defined as minerals that are typically not recognized macroscopically and rely on petrographic identification due to fine grain size and/or low abundance.

<table>
<thead>
<tr>
<th>Deposit</th>
<th>Main</th>
<th>Accessory</th>
<th>Minor</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Back Forty</td>
<td>pyrite, sphalerite, chalcopyrite, galena</td>
<td>arsenopyrite, pyrrhotite, marcasite</td>
<td>acanthite, argentopyrite, bournonite, electrum, freibergite, gudmundite, isocubanite, pyrargyrite, stannite, stephanite</td>
<td></td>
</tr>
<tr>
<td>Bend</td>
<td>pyrite, chalcopyrite</td>
<td>tetrahedrite-tennantite, arsenopyrite, bornite*, chalcocite*</td>
<td>altaite, calaverite*, fluorite, frohbergite, krennerite*, native Te, petzite* SbBiTe&lt;sub&gt;3&lt;/sub&gt;, sylvanite</td>
<td>*DeMatties and Rowell (1996)</td>
</tr>
<tr>
<td>Flambeau</td>
<td>pyrite, chalcopyrite, sphalerite, galena</td>
<td>arsenopyrite, gahnite, bornite, covellite, pyrrhotite*</td>
<td>electrum, hessite, native Au*, tellurobismuthinite</td>
<td>*May (1977)</td>
</tr>
<tr>
<td>Horseshoe</td>
<td>pyrite, pyrrhotite, sphalerite, chalcopyrite, galena</td>
<td>pyrrhotite, arsenopyrite, magnetite</td>
<td>breithauptite, native Bi</td>
<td></td>
</tr>
<tr>
<td>Lynne</td>
<td>sphalerite, pyrite, galena, chalcopyrite</td>
<td>pyrrhotite, arsenopyrite, magnetite</td>
<td>acanthite, Ag&lt;sub&gt;2&lt;/sub&gt;S&lt;sub&gt;2&lt;/sub&gt;, argentiferous galena, freibergite, löllingite, native Ag, polybasite*, pyrargyrite*, tetrahedrite*</td>
<td>*Adams (1996)</td>
</tr>
<tr>
<td>Reef</td>
<td>pyrrhotite, pyrite, chalcopyrite</td>
<td>sphalerite</td>
<td>AuTe&lt;sub&gt;3&lt;/sub&gt;, calaverite, cubanite*, electurm*, fluorite*, frohbergite, hessite, melonite, molybdenite*, muthmannite, native Au, petzite, tellurobismuthinite</td>
<td>*Kennedy and Harding (1990)</td>
</tr>
<tr>
<td>Ritchie Creek</td>
<td>pyrite, pyrrhotite, chalcopyrite</td>
<td>sphalerite, magnetite, galena*</td>
<td>altaite*, Pb&lt;sub&gt;3&lt;/sub&gt;S&lt;sub&gt;2&lt;/sub&gt;, Pb&lt;sub&gt;2&lt;/sub&gt;Se&lt;sub&gt;2&lt;/sub&gt;, (Pb, Bi)&lt;sub&gt;2/3&lt;/sub&gt;(Te,Se)&lt;sub&gt;2/3&lt;/sub&gt;, PbBiTeSe, tellurobismuthinite, tsumoite</td>
<td>*DeMatties (1990)</td>
</tr>
</tbody>
</table>
In addition to Back Forty and Crandon, the Bend deposit is characterized by an elevated gold grade (Fig. 2-4B). At Bend, gold-enrichment occurs both within the copper-rich massive sulfide lens and within disseminated and pyritic lenses of massive sulfide in the footwall, within what appears to be a semi-conformable zone of gold-pyrite enrichment. In addition, local zones of quartz-carbonate veining associated with syn-volcanic dikes that intrude the mineralized interval host exceptionally high levels of gold-enrichment.

*Rare Metal Enrichment and Mineralogical Sequestration*

At present, little is known about the content, distribution, and mineralogical sequestration of rare metals in the Penokean VMS deposits. However, SEM-EDS analyses of polished ore samples revealed distinctive suites of rare-metal-bearing trace minerals within different deposits (Table 5-2). Observed differences in trace ore mineralogy likely reflect variations in the chemistry of the hydrothermal fluids, the processes and conditions of mineral deposition (Monecke et al., 2016), or the degree of metamorphic overprint, which can result in the formation of new trace minerals during isochemical recrystallization of the massive sulfide ores (Marshall and Gilligan, 1987, 1993; Vokes and Craig, 1993; Huston et al., 1995).

Back Forty contains a distinctive suite of antimony-bearing minerals in addition to stannite. Tin is an economic byproduct in some massive sulfide deposits (e.g., Neves Corvo, Kidd Creek; Yang and Scott, 2003) but has not previously been recognized in any of the Penokean deposits. Selenium-bearing minerals are abundant in mineralized samples inspected from Ritchie Creek and appear to be unique amongst other Penokean deposits. Tellurium minerals are abundant at the Bend deposit. Twelve ore samples of massive sulfide collected by the USGS contained an average grade of 635 g/t tellurium (Woodruff et al., 2003). A similar analog in terms of tellurium mineralization may be the Kankberg Au-Te deposit in the Paleoproterozoic Skellefte district. The USGS reported that Kankberg contains an average of 186 g/t tellurium, which currently accounts for 10% of global tellurium production (Goldfarb, 2015). Future evaluation of the Bend deposit should take into account that this element may be potentially recovered as a byproduct, adding to the overall value of the deposit.

**5.2. Hydrothermal Alteration**

The current study allows a first-order assessment of the styles of hydrothermal alteration associated with the Penokean VMS deposits. The main alteration styles recognized are white mica alteration, silicification, and chloritization.
White mica alteration is the most prevalent and widespread alteration style recognized and is a product of the chemical breakdown of feldspars and volcanic glass and the formation of white mica during fluid-rock interaction. Subsequent deformation and metamorphism of the white mica alteration zones has produced quartz-muscovite+-pyrite schists, which are common rock types within the Penokean deposits associated with felsic volcanic rocks. This style of alteration is, for example, well developed at the Back Forty deposit, where pervasive white mica alteration forms a halo around the deposit that extends for hundreds of meters into the surrounding volcanic stratigraphy.

The effects of silicification are harder to quantify as quartz is ubiquitous throughout the felsic stratigraphy at most deposits. Characterization and chemical analysis of least-altered volcanic rocks would need to be compared to silicified rocks to quantify the mass balance changes as a result of silicification. Locally, however, silicification is visually obvious, most notably at Bend and Back Forty where intense silicification is associated with pyritic stockwork zones where fine-grained quartz flooded the host rocks and destroyed primary volcanic textures.

Chlorite alteration has been recognized at all of the Penokean deposits studied although it is not as prevalent as white mica alteration and typically occurs in discrete zones associated with sulfide enrichment. A chlorite-biotite assemblage is recognized at Reef, Ritchie Creek, Lynne, Horseshoe, and Flambeau and reflects the generally higher metamorphic grade recognized at these deposits.

In addition to these common, widespread forms of hydrothermal alteration, a few of the deposits have distinctive styles of alteration. At Flambeau, a characteristic feature of footwall alteration is the presence of andalusite that occurs as coarse, granoblastic grains that are highly altered and retrograded to fine-grained phyllosilicates. Andalusite is associated with coarse biotite laths that distinctly overgrow the foliation. The metamorphic fabric suggests that formation of the andalusite and biotite may be related to contact metamorphism from proximal tonalite intrusions recognized in the area.

Another distinct feature recognized within Penokean deposits is carbonate enrichment and related calc-silicate, or skarn-style mineral assemblages that have been described at Lynne, Ritchie Creek, and Reef in this study and have also been documented at the Spirit prospect (Brink, 1991) and to some extent at the Pelican River deposit (Bowden, 1978). Calc-silicate minerals are predominantly tremolite-actinolite, grossular-andradite, and epidote. At Lynne and Ritchie Creek this mineral association forms a stratabound unit that is closely associated with massive to semi-massive sulfides and was described by DeMatties (1994) and Adams (1996) to be related to hydrothermal carbonates. In both of these deposits
the transition from calc-silicate dominant mineral assemblages to carbonate dominant mineral assemblages occurs over short distances and suggests that the calc-silicates may be a product of contact metamorphism from dikes and/or sills that cross cut the stratigraphy. Low-temperature alteration assemblages dominated by carbonate minerals near the seafloor have been documented in some regional hydrothermal systems due to precipitation from shallowly circulating seawater (Herrmann and Hill, 2001; Galley et al., 2007). A similar process may have been responsible for the accumulation of carbonate-bearing rocks prior to VMS mineralization in the Penokean volcanic belt, however the thickness and extent of carbonate rocks at Lynne is more consistent with a limestone protolith. Also unique to Lynne is a talc-rich mineral assemblage that occurs near the base of the ore interval and within the lowermost sulfide lens that is interpreted to reflect an upflow zone of extreme Mg-enrichment.

Most of the massive sulfide deposits in the Penokean volcanic belt show a distinct change in alteration intensity between the stratigraphic footwall and hanging wall, which indicates cessation of the hydrothermal system concurrent with hanging wall volcanism. Exceptions to this are recognized at Horseshoe and Back Forty. Horseshoe is distinct in this regard in that it shows no systematic or significant effects of hydrothermal alteration in either the footwall or the hanging wall stratigraphy and alteration assemblages are only recognized within the immediate zone of sulfide enrichment. The lack of alteration in the mineralized interval may be related to the mode of sulfide deposition. Horseshoe shows unusual breccia textures within the massive sulfide, possibly suggesting that this deposit is clastic in nature or has perhaps been remobilized. At Back Forty, intense alteration extends for hundreds of meters into the hanging wall of the main massive sulfide lens that is indicative of continued hydrothermal alteration after the main ore-forming event and likely reflects the longevity of the hydrothermal system.

Another distinct feature related to hydrothermal alteration in the VMS environment is the development of a chlorite-rich alteration pipe or upflow zone that commonly underlies the massive sulfide lenses (Franklin et al., 2005; Galley, 2007). Such a zone is consistently not recognized in Penokean massive sulfide deposits. However, semi-conformable chlorite-sulfide enrichment has been documented below the massive sulfide lens in several of the deposits and is likely related to lateral fluid flow through permeable volcanic strata as opposed to focused vertical fluid flow. The morphology of these zones in the Penokean VMS deposits is interpreted to reflect the predominance of volcaniclastic strata in the host rock successions recognized in most deposits. Another explanation could be the translation of a vertical chlorite-rich pipe into a semi-conformable alteration zone as a result of regional deformation during Penokean orogenesis.
Over the past decades, a significant amount of research has focused on developing alteration indices to use as guides for exploration and vectors towards ore (Large et al., 2001a,b). The most widely used of these is the Ishikawa alteration index (AI) which describes the breakdown and replacement of sodic plagioclase and volcanic glass by white mica and chlorite. This alteration process results in sodium depletion, which has been widely used as a measure of alteration intensity (Large et al., 2001a). More recently, a chlorite-carbonate-pyrite index (CCPI) has been devised to complement the Ishikawa index and was designed to quantify increases in MgO and FeO associated with Mg-Fe chlorite, Mg-Fe carbonate, and iron sulfides that typically develop within the upflow zone beneath massive sulfide deposits (Large et al., 2001a).

As part of the present study, extensive down-hole geochemical analyses of the host rock successions of selected VMS deposits have been conducted. The AI and CCPI alteration indices have been determined across the volcanic stratigraphy. In general, the Ishikawa index was found to be extremely useful in indicating sodium depletion in the stratigraphic footwall of most deposits and to measure proximity to massive sulfides. The AI values were found to generally drop off dramatically in the hanging wall, which is useful in determining the drill hole location with respect to the mineralized interval. This also indicates, in most deposits, the termination of the hydrothermal system shortly after massive sulfide deposition. In contrast, the CCPI values of the whole-rock samples were generally not found to be as useful for quantifying hydrothermal alteration in Penokean VMS deposits. Instead, these values tend to reflect the primary host rock composition more so than their degree of hydrothermal alteration and thus correlate positively with Ti/Zr ratios. An exception to this is at Flambeau, where the intermediate-felsic volcanic host rocks have consistently elevated CCPI values. As noted previously, chlorite alteration is not as prevalent as other styles of alteration in Penokean VMS deposits and tends to occur within discrete zones along with sulfide-enrichment. The location of geochemical samples taken for this study typically avoided highly mineralized areas and thus were to some extent biased against samples that would typically have elevated CCPI values.

In addition to the Ishikawa and CCPI values, Rb/Sr ratios were plotted and proved to be useful as an indicator of proximity to the massive sulfides. The ratio shows a general positive correlation with AI values. However, this ratio tends to produce very sharp anomalies with close proximity to ore, most notably at Back Forty, Ritchie Creek, and Lynne. Furthermore, there is a distinct association with Rb/Sr ratios with mineralized zones at Reef, where other alteration indices are not useful. The Rb/Sr ratio is thought to be related to mineralogical differences within an alteration halo and more specifically is related to the formation of K-bearing phyllosilicates and the substitution of K and Rb (Paulick et al., 2001).
Although the Rb/Sr ratios tend not to produce as broad of a geochemical indicator as sodium depletion reflected in the AI values, this ratio appears to be useful for deposit-scale exploration.

5.3. Tectonic Setting

The present study provides the first lithogeochemical dataset for Penokean VMS deposits and can be used to derive first-order conclusions on the tectonic setting of deposit formation. However, because most samples were collected from the immediate deposit area and have been subject to hydrothermal alteration, care must be taken when classifying these rocks geochemically due to alteration-induced elemental gains and losses (Winchester and Floyd, 1977; Floyd and Winchester, 1978). This is, in particular, an issue with the use of the total alkali-silica discrimination diagram that relies on major elements (Hastie et al., 2007). To overcome issues related to element mobility, immobile elements and immobile element ratios are used in the present thesis for rock classification and the identification of the magmatic affinities of the volcanic host rocks to the deposits.

Magmatic Affinity

The most widely used discrimination diagram using immobile element ratios is the diagram plotting Zr-Ti versus Nb-Y ratios (Winchester and Floyd, 1977; Pearce, 1996). The host rocks of the Penokean VMS deposits are sub-alkaline, with compositions ranging from basalt to rhyolite (Fig. 5-2). Figure 5-3 subdivides the sub-alkaline volcanic rocks into the tholeiitic, calc-alkaline, and shoshonitic magma series. This diagram utilizes cobalt as a proxy for SiO$_2$ and thorium as an immobile element replacement for K$_2$O (Hastie et al., 2007). The plot suggests that the host rocks of the Penokean VMS deposits are largely of calc-alkaline affinity. Rocks hosting the Reef prospect are classified as island arc tholeiites indicating a juvenile source and are markedly different than those associated with VMS deposits in the southern domain of the Pembine-Wausau terrane. Additionally, some of the host rocks, most notably the tight grouping of samples collected from the Back Forty host stratigraphy, have high-K shoshonitic affinities. High potassic volcanic rocks of the shoshonite series have been described as occurring at distinct periods within subduction driven orogenesis, namely in association with over steepening of the subducting slab, which may result in slab detachment or a polarity reversal in the subduction direction (Morrison, 1980; Pe-Piper, 2009). The presence of shoshonitic volcanic rocks within the Penokean volcanic belt has not previously been recognized and further work is needed to substantiate the data provided here to ensure that hydrothermal alteration has not significantly affected the chemistry and classification of these rocks.
Fig. 5-2: Classification of the volcanic host rocks of the Penokean VMS deposits using immobile element ratios (classification after Pearce, 1996). Colors and symbols from Fig. 4-2.

Lithotectonic Setting

VMS deposits and districts are classified based on their dominant lithologies within the host rock succession. This classification scheme was first proposed by Barrie and Hannington (1999) and subsequently modified by Franklin et al. (2005). According to these authors, VMS deposits can be grouped into five lithostratigraphic types, namely mafic, bimodal-mafic, pelitic-mafic, bimodal-felsic, and felsic-siliciclastic. The usefulness of this classification scheme is the relationship of the lithostratigraphic type to tectonic setting, which broadly correlates with primitive ophiolite settings, through oceanic rifted arc, evolved rifted arcs, continental back-arcs, to sedimented back-arcs, respectively. Galley et al. (2007) added a hybrid bimodal-felsic group to this classification scheme to account for shallow water epithermal-VMS transitional type deposits. The main difference between the classification scheme of Barrie and
Fig. 5-3: Volcanic and tectonic classification of the volcanic host rocks of the Penokean VMS deposits (classification after Hastie et al., 2007). Colors and symbols from Fig. 4-2.

Hannington (1999) and Franklin et al. (2005) is the volume of rock considered to classify these deposits and/or districts. Barrie and Hannington (1999) considered coeval volcanic host rocks that occur ~3 kilometers into the footwall succession, ~1 kilometer into the hanging wall succession, and ~5 kilometers along strike of the deposits and, as such, relied on the deposit-scale volcanic stratigraphy for their classification. This resulted in deposits hosted within the same volcanic succession to be classified differently and led Franklin et al. (2005) to include the entire volcanic host rock succession within a district which may include areas >20,000km² to more accurately reflect the geodynamic setting. Although this approach is clearly more rigorous, it is best suited for mature VMS districts where detailed geologic mapping is available across large areas.

Geochemical analyses from host rocks of Penokean VMS deposits collected for the present study has yielded 87 chemical whole-rock analyses. Because samples were collected at regular intervals from
the immediate deposit stratigraphy this data set can be used as a first-order constraint on the distribution of different rock types across the Penokean volcanic belt. Samples from the Reef prospect were excluded from this set of chemical data as they clearly reflect a different geodynamic environment than those in the southern domain of the Pembine-Wausau terrane. Of the remaining 68 samples from rocks hosting the Penokean VMS deposits, 46% are classified as felsic (rhyolite, dacite), 32% are classified as intermediate (andesite, basaltic-andesite), and 22% are mafic (basalts). This suggests that mafic volcanic rocks form a relatively small percentage of the total amount for rocks hosting Penokean VMS deposits, at least within the immediate volcanic stratigraphy. This is supported by the subdued magnetic intensity that characterizes the southern Pembine-Wausau terrane and implies that mafic volcanic rocks are not likely not as abundant as previously suggested.

Yang and Scott (2003) divided selected major VMS districts based on the trace element geochemistry of the felsic volcanic rocks occurring within the ore interval. Distinct suites of rhyolites are recognized based on their thorium contents and are divided into three groups. Low-Th rhyolites are represented by the Noranda area of the Abitibi belt that formed in a back-arc basin behind an immature island arc. Mid-Th rhyolites are represented by the Hokuroku district and some Abitibi deposits and likely formed from a moderately enriched source within a mature island arc. High-Th rhyolites form a large proportion of rhyolites from the Bathurst mining camp and the Iberian pyrite belt and are thought to have formed from partial melting of enriched, felsic-dominant continental crust. Thus, these three groups of VMS districts and their associated rhyolites resemble lithotectonic classifications of Barrie and Hannington (1999) and Franklin et al. (2005), from more primitive bimodal-mafic districts (low-Th rhyolites, Noranda-type), to more evolved bimodal-felsic districts (mid-Th, Kuroko-type), through highly evolved felsic-siliciclastic districts (high-Th, Bathurst-type).

Intermediate-felsic volcanic rocks hosting massive sulfide deposits in the Penokean volcanic belt have notable similarities to the high-Th groups of the Iberian Pyrite Belt and the Bathurst mining district (Fig. 5-4). These belts are type examples of the siliciclastic-felsic lithostratigraphic facies, which are characterized as occurring in mature epicontinental back-arcs, and are characteristically dominated by volcaniclastic and continent-derived sedimentary rocks (Franklin, et al., 2005). Yang and Scott (2003) also established a link between the different rhyolite groups and the base metal content of their associated VMS-deposits, namely an increasing lead content from VMS deposits associated with low-Th to high-Th rhyolites. The Penokean VMS deposits, however, have relatively low Pb/Zn ratios, which are similar to the more primitive Noranda and Kuroko-type VMS deposits than those of the Bathurst-type. Figure 5-4 again highlights the difference between rocks hosting the Reef prospect and those hosting the deposits in
the north. Intermediate-felsic rocks at Reef are more similar to the Abitibi field which provides further evidence that portions of the Wausau volcanic complex represent a more primitive source.

**Rhyolite Geochemistry**

A substantial amount of research has focused on distinguishing geochemical variations of rhyolites that are associated with VMS deposits versus those that are not (Hart et al., 2004 and references therein). This work has defined different groups of rhyolites, namely FI, FII, FIII, and FIV rhyolites that are distinguished based on chondrite-normalized rare-earth element discrimination diagrams and are used to establish “rhyolite fertility” (Fig. 5-5). The variation of FI-FIV rhyolites has been shown to correlate with the crustal thickness and the depth of crustal melting which allows for the stabilization of different mineral assemblages which influences the rare-earth element concentration of the magma. In general, rhyolites that fall within the FI category are not considered to be prospective for VMS deposits although
they can occur within the productive volcanic stratigraphy (Hart et al., 2004). Type FII rhyolites are abundant within the geologic record but are not typically considered as favorable as targets as the FIII-FIV rhyolites which are less abundant but are commonly associated with VMS deposits and tend to be associated with very large deposits (e.g. Kidd Creek; Hart et al., 2004).

Massive sulfide-associated rhyolites within the Penokean volcanic belt are classified as FII rhyolites and form within a restricted range within this field (Fig. 5-5). This provides insight into the extensional setting responsible for VMS formation and suggests that partial melting occurred at relatively high levels (<30 km) in the crust. The emplacement of magma within high crustal levels above the brittle-ductile transition zone (~15 km) allows for the development of hydrothermal convection circulation cells required for VMS formation (Hart et al., 2004; Franklin et al., 2005; Galley et al., 2007).
5.4. Volcanic Setting

The results of the present study suggest that the Penokean VMS deposits formed within a distinct volcanic environment. All of the main deposits are associated with felsic volcanic centers and are located in a proximal volcanic setting. This close spatial and temporal relationship to felsic volcanic centers is perhaps best exemplified by the Horseshoe prospect (Fig. 4-1) where massive sulfides are associated with a discrete rhyolitic unit within an otherwise mafic-flow dominated volcanic succession. At the deposit scale, massive sulfide deposits within the Penokean volcanic belt are commonly hosted by felsic volcaniclastic lithofacies, with a subordinate proportion of coherent volcanic rocks (Fig. 4-1). A wide range of facies characteristics are recognized within the volcaniclastic strata which vary from fine-grained, thinly bedded deposits to volcanic facies comprised of coarse, monomict, angular volcanic breccias. In general, there appears to be an association of larger massive sulfide deposits such as Back Forty, Crandon, and Flambeau with breccia deposits formed within close proximity to a volcanic edifice. This contrasts with some of the smaller deposits in the belt such as Ritchie Creek and Bend, which are hosted by fine-grained, bedded volcaniclastic successions.

Calcareous rocks and their calc-silicate equivalents have been documented at several of the massive sulfide deposits in the belt and are often spatially associated with massive sulfides, i.e. at Lynne, Ritchie Creek, Spirit (Brink, 1991), and to some extent at Eisenbrey (May, 1996). In addition, calcareous rocks have been described within the volcanic successions at other deposits, i.e. hanging wall dolomite at Crandon (Lambe and Rowe, 1987), carbonate-rich volcaniclastic rocks at Bend, discrete calc-silicate intervals at Pelican River (Bowden, 1978) and at Reef. Carbonate rocks are relatively uncommon in the VMS environment as they are thought to have formed in shallow marine settings. Extensive carbonate deposits within a VMS succession is perhaps best described for the Paleoproterozoic Bergslagen district (Allen et al., 1996). Calcareous rocks have also been documented to form as a result of regional-scale hydrothermal alteration as a result of carbonate precipitation from shallowly circulating seawater (Galley et al., 2007). The paucity of calcareous rocks recognized in the Penokean supports a hydrothermal origin. However, the thickness and extent of carbonate-rich rocks at Lynne suggests a chemical sedimentary origin, indicating that Lynne perhaps formed in a restricted, shallow marine setting. Further work, however, is required to characterize the origin of carbonate-rich strata within the Penokean volcanic belt.

Although the VMS deposits of the Penokean volcanic belt have formed in volcanically active environments, at least some of the massive sulfide lenses are located at or immediately below a paleoseafloor position marked by the occurrence of volcanic facies recording a period of volcanic
quiescence. At the Bend deposit, for instance, a thin, discontinuous banded iron formation is locally interbedded with the massive sulfides and underlies a thick package of finely bedded volcaniclastic sedimentary rocks. This indicates an abrupt change from the thick, massive quartz-phyric volcaniclastic unit that underlies the ore interval and implies relative volcanic quiescence during ore deposition. Similarly at Back Forty, the uppermost sulfide lens lies stratigraphically below thinly bedded felsic volcaniclastic rocks that have at least in part been deposited through suspension sedimentation. The main massive sulfide lens, however, shows textural evidence of sub-seafloor replacement and hydrothermal fluids may have deposited the upper massive sulfide lens at or near the paleoseafloor contemporaneously with the main sulfide lens. The extensive alteration halo recognized at Back Forty, the relative large size of the deposit and thick accumulation of massive sulfides are further evidence of replacement-style mineralization processes. At other deposits, e.g. Lynne and Ritchie Creek, calcareous rocks interbedded with massive sulfides may indicate a hiatus in volcanism during which massive sulfides formed and may have served as chemically reactive host rocks that were preferentially replaced by sulfides.

5.5. Exploration Significance

The contained mineral inventory within the Penokean volcanic belt rivals some of the largest Paleoproterozoic VMS districts, including Flin Flon, Bergslagen, and Skellefte (Syme, 1999; Allen et al., 1996; Franklin et al., 2005). The discovery of the Back Forty deposit in 2002, which was exposed at surface, highlights the significant exploration potential of the belt. Several aspects of the current study can be used to help guide exploration and future research within the Penokean volcanic belt.

The current study provides the first geochemical data set for volcanic rocks hosting Penokean VMS deposits. In general, the host rocks are dominantly of calc-alkaline affinity and some host rocks, notably those from Back Forty, appear to have a more highly evolved, high-K to shoshonitic affinity. The volcanic host rocks of the Reef Au-Cu occurrence were identified as being of a more primitive affinity, suggesting a different geodynamic setting of the Wausau volcanic complex. Based on this and previous discoveries made, the Wausau volcanic complex appears to be less favorable for significant VMS deposits. The present study also showed that the deposits of the Penokean volcanic belt are closely associated with felsic volcanic centers. Chemically, these rhyolite centers are classified as FII rhyolites and fall within a restricted range within this field, which may be used as a first-order prospectivity assessment for future exploration.
Recent research has dated several of the felsic volcanic centers that host massive sulfide deposits (Quigley, 2016). Rhyolite within the host rock successions of the Bend, Horseshoe, Lynne, and Pelican River massive sulfide deposits were formed within a discrete time interval between 1873–1875 Ma. This suggests that volcanism and associated VMS deposit formation occurred in a relatively short-lived extensional setting at the margin of the Superior craton. At present, a regional stratigraphic marker horizon has not been recognized that can be used to identify volcanic rocks of favorable age in the field, and thus, radiometric dating could be extremely useful to help identify other felsic rocks in the region that formed during this prospective time interval.

It is important to note that a younger date of approximately 1833 Ma was obtained from a zircon at the Back Forty deposit, which is a similar age to volcanic rocks from the Wausau volcanic complex. The obtained age may or may not represent the crystallization age of the felsic volcanic rock (Quigley, 2016). Additional geochronological work at Back Forty is critical for exploration as it can at present not be ruled out that there is more than one time interval within the Penokean volcanic belt that was favorable for VMS deposits.

The results of the present study coupled with the findings of Quigley (2016) can be used to synthesize metallogenetic models and derive new greenfields exploration strategies for the Penokean volcanic belt. Identification of a time interval favorable for VMS formation and the distinct geochemical signature of felsic volcanic centers hosting known deposits are important criteria that can be used to focus regional exploration.

A number of deposit-scale features were recognized during the current study and can provide insight into future exploration in the region. Vent-proximal volcanic facies, namely felsic volcanic breccias consisting of large, angular and poorly sorted volcanic deposits have been recognized at some of the larger massive sulfide deposits in the district such as at Back Forty and Flambeau, and similar volcanic-facies were described at Crandon (Lambe and Rowe, 1987). Some of the smaller deposits studied, including Ritchie Creek and Bend, appear to be characterized by a large proportion of bedded, fine-grained felsic volcaniclastic deposits. The association with vent-proximal facies and some of the larger Penokean VMS deposits may be used as an exploration tool to identify favorable environments.

The results of the present study suggest that the presence of calcareous rocks and their calc-silicate equivalents may represent a favorable stratigraphic marker along which many of the VMS deposits in the Penokean volcanic belt are located. The nature of the calcareous rocks may be related to shallow marine
conditions (e.g., Lynne) or a product of regional hydrothermal alteration, either of which appear to be associated with a period of volcanic quiescence that may be useful in future exploration efforts. The Paleoproterozoic Bergslagen belt is perhaps the most well established VMS district to have formed within a shallow marine setting (Allen et al., 1996) and could serve as an analog to better understand the metallogeny, volcanic setting, and exploration criteria in the Penokean volcanic belt. In addition, shallow marine conditions could be prospective for hybrid bimodal felsic VMS deposits.

There is a large variation in metal content recognized with Penokean sulfide deposits, from those dominated by copper (Bend, Flambeau, and Ritchie Creek) to those that contain a significant amount of lead (Lynne and Horseshoe). In addition, a number of the deposits have significant gold endowments (Back Forty, Bend, Crandon, and Reef). Despite a lack of chemical information from sulfide intervals for the various deposits, there appears to be a distinct trace element association with some of the deposits and this may have economic as well as genetic implications. Namely, tin-bearing minerals recognized at Back Forty may be of economic significance as tin is a byproduct from some world-class VMS deposits (e.g., Kidd Creek and Neves Corvo). Tellurium-enrichment at Bend is anomalous and could have a major impact on future economics of the deposit. Future exploration and evaluation of previously defined deposits in the region should consider the economic implications of trace elements at an early stage of evaluation.

Finally it is important to note that not all of the deposits in the Penokean volcanic belt are classical VMS deposits. The unusual Reef Au-Cu deposit appears to be distinct with respect to its volcanic setting, style of mineralization, and metal content. As the origin of the Reef deposit is enigmatic, exploration models for the Penokean volcanic belt need to take into account that deposits with deviating characteristics may occur within the volcanic successions of the Penokean belt. There may be significant exploration potential for synvolcanic disseminated sulfide deposits or other deposit types such as orogenic gold deposits, that occur is similar volcanic and tectonic environments and are yet to be recognized in the region.
CHAPTER 6
CONCLUSIONS

The present study utilized a combination of drill core observations, geochemistry, and petrography to supplement previous research on the mineral deposits of the Penokean volcanic belt. Detailed core logging and sampling were completed on representative drill core from seven of the most significant deposits recognized in the belt, namely Back Forty, Bend, Flambeau, Horseshoe, Lynne, Ritchie Creek, and Reef. In addition, compilation of historic data was used to summarize the Crandon deposit and was incorporated from other deposits to provide a comprehensive review and update to the understanding of the tectonic-volcanic setting, alteration styles, and mineralization processes across the Penokean volcanic belt. This work resulted in 87 new major and trace element analyses and petrographic observation of 125 thin sections from the volcanic stratigraphy as well as the mineralized and hydrothermally altered zones. In addition, a new mineral inventory is provided for the belt and is compared with other Paleoproterozoic VMS districts and the VMS deposits worldwide. The results of the study allow for the following main conclusions:

1) The Penokean volcanic belt is host to one of the most prolific Paleoproterozoic VMS districts in the world. This has been previously under-represented due to incomplete data sets, the relatively recent discovery of the Back Forty deposit, and an overall lack of published information concerning the mineral deposits of the region.

2) The mineral deposits show a wide range of metal contents from copper-dominated deposits (Bend, Flambeau, and Ritchie Creek) to zinc-copper deposits (Back Forty and Crandon) to zinc-lead-copper deposits (Lynne and Horseshoe).

3) Three of the deposits are classified based on their gold content, two of which are considered “anomalous” (Back Forty and Crandon) and are estimated to contain >31t of gold. Bend contains elevated gold concentrations and is classified as “auriferous”. The Reef deposit represents a gold-rich sulfide deposit that may be of synvolcanic origin.

4) Within the mineralized zones, the major sulfide mineralogy for the Penokean deposits include pyrite, sphalerite, chalcopyrite, and galena with some deposits (Reef and Horseshoe) containing significant amounts of pyrrhotite. Common accessory sulfides and related minerals include arsenopyrite, tetrahedrite-tennantite, marcasite, gahnite, and magnetite.
5) Several of the deposits studied appear to have distinct trace element and mineral associations that include an abundance of antimony-bearing minerals recognized at Back Forty, a distinctive suite of selenides at Ritchie Creek, and an abundance of tellurium-bearing minerals at Bend. In addition, stannite was commonly recognized from polished ore samples from Back Forty, which may be of economic significance as tin is recovered as a byproduct from some VMS deposits. The tellurium recognized at Bend is highly anomalous and may have significant economic implications.

6) A broad spectrum of hydrothermal alteration styles and intensities are recognized for the Penokean VMS deposits, with the most common including: sericitization, silicification, and chloritization and their metamorphosed equivalents.

7) A few of the deposits have distinctive alteration characteristics, which include the presence of coarse, granoblastic andalusite as a characteristic feature of footwall alteration at Flambeau, which appears to be the product of contact metamorphism. At Back Forty, the ore zone is enveloped by a massive quartz-white mica-pyrite alteration halo.

8) With the exception of Back Forty, all Penokean VMS deposits investigated in the present study show a marked decrease in alteration intensity within volcanic strata of the immediate hanging wall, which implies cessation of the hydrothermal system soon after massive sulfide deposition. The Ishikawa alteration index is particularly useful for geochemical vectoring.

9) The host rocks of the VMS deposits within the southern domain of the Pembine-Wausau terrane are dominantly of calc-alkaline affinity with some, most notably at Back Forty, having more evolved high-K to shoshonitic affinities.

10) Host rocks from the Reef Au-Cu occurrence are tholeiitic and have a more primitive chemical affinity that host rocks of the VMS deposits. This suggests that the Reef deposit, hosted by volcanic rocks of the Wausau volcanic complex, formed in a distinct geodynamic setting and perhaps a different time than the VMS deposits of the Pembine-Wausau terrane.

11) Massive sulfide deposits in the Penokean volcanic belt formed in close spatial and temporal association to felsic volcanic centers. Geochemically, the felsic volcanic rocks can be classified as FII rhyolites and fall within a restricted range within this field. This has first-order exploration
implications that can help identify prospective rhyolitic volcanic centers within the Penokean volcanic belt.

12) Intermediate-felsic rocks from the massive sulfide deposits are classified as high-Th volcanic rocks that indicate that they were generated from a highly evolved source which may have included a significant crustal component. As such, these rocks have notable similarities to those of the Iberian pyrite belt and Bathurst mining district, both of which are type examples of the siliciclastic-felsic lithostratigraphic facies, which are characterized as occurring in mature epicontinental back-arcs, and are characteristically dominated by volcaniclastic and continent-derived sedimentary rocks.

13) Results from this study indicate that the Penokean VMS district is best classified as a bimodal-felsic succession.

14) The Penokean VMS deposits are hosted by volcanic successions containing mostly volcaniclastic rocks with a subordinate proportion of coherent volcanic rocks. Horseshoe is the only exception in which the volcanic succession is predominantly basaltic flows. At least some of the massive sulfides hosted in volcaniclastic host rocks appear to have been formed through subseafloor replacement.

15) Calcareous rocks and their calc-silicate equivalents have been documented at several of the massive sulfide deposits in the belt and often have a spatial association with massive sulfides. A shallow marine setting with limestone forming the ore interval at Lynne is proposed, however the paucity of calcareous rocks recognized throughout the belt might suggest a link to regional hydrothermal alteration. More work is required to identify the origin of carbonate-rich strata in the belt, but either interpretation has exploration implications as there appears to be a close link between the occurrence of calcareous rocks in the volcanic succession and the presence of VMS deposits.

16) A number of exploration criteria are presented as a result of the present study and vary from deposit-scale features to district-wide genetic models that can aid in future exploration and research within the Penokean volcanic belt.
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APPENDIX A
SUPPLEMENTAL ELECTRONIC FILES

The supplemental file gives the complete whole rock major and trace element geochemistry results for samples collected and analyzed for this study. Company data provided by Aquila Resources Inc. and data taken from other sources is referenced as appropriate and not included in this data set.

| VMS_of_PVB_GEOCHEMISTRY_2016_PQ.xls | Whole-rock major and trace element geochemistry for samples taken for this study. |