THE VOLCANIC STRATIGRAPHY AND ALTERATION OF
THE SCHIST LAKE AND MANDY MINES DEPOSITS, FLIN
FLON, MANITOBA

by

EILIDH MURRAY LEWIS

Thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Science (MSc) in Geology

School of Graduate Studies
Laurentian University
Sudbury, Ontario

©EILIDH MURRAY LEWIS, 2012
NOTICE:
The author has granted a non-exclusive license allowing Library and Archives Canada to reproduce, publish, archive, preserve, conserve, communicate to the public by telecommunication or on the Internet, loan, distribute and sell theses worldwide, for commercial or non-commercial purposes, in microform, paper, electronic and/or any other formats.

The author retains copyright ownership and moral rights in this thesis. Neither the thesis nor substantial extracts from it may be printed or otherwise reproduced without the author's permission.

In compliance with the Canadian Privacy Act some supporting forms may have been removed from this thesis.

While these forms may be included in the document page count, their removal does not represent any loss of content from the thesis.
Abstract

The Schist Lake and Mandy volcanogenic massive sulphide (VMS) deposits are located 5 km east of the town of Flin Flon in Northern Manitoba. The main goals of this thesis are to: 1) to characterise and describe the host rocks to the Schist Lake and Mandy volcanogenic massive sulphide deposits and their associated hydrothermal alteration zones; 2) to compare the host rocks and the volcanic environment of these VMS deposits to those of the main Flin Flon camp; and 3) to determine if the Schist Lake and Mandy VMS deposits are time stratigraphic equivalent to VMS deposits in the main Flin Flon camp, or to the rocks of the Hook Lake Block? These questions were tested using detailed geological mapping, logging of drill core, petrography, and lithogeochemistry.

Strata of the Schist Lake and Mandy mines area are divisible into four informal units which, from oldest to youngest include: 1) the Lower Mafic volcaniclastic unit; 2) the Middle Mafic volcaniclastic unit; 3) the Bedded Tuff unit; and 4) the Upper Mafic volcaniclastic unit. The Schist Lake and Mandy VMS deposits are hosted by a quartz porphyry with localised sericite schist within a thicker succession of mafic volcaniclastic of the Lower Mafic volcaniclastic unit. The Schist Lake deposit has an alteration zone consistent with that of typical bimodal mafic VMS deposits consisting of an inner chlorite core and an outer sericite zone with pervasive silica alteration throughout. The deposit and alteration halo have been transposed during regional deformation by deformation associated with the Mandy Road fault; the latter bisects the map area. Geochemical comparison of the Middle and Lower Mafic volcaniclastic units on either side of the Mandy Road fault indicate that there is no significant geochemical difference between the units. Therefore, the Mandy Road fault is not interpreted as a significant block bounding
structure and mafic volcaniclastic units on either side of the fault are compositionally and physically similar. This, along with the physical and compositional similarity between the Upper Mafic volcaniclastic unit and the Hidden formation, the Bedded Tuff unit with the Millrock member and the Middle and Lower Mafic volcaniclastic units with the Millrock member mafic flows and volcaniclastic rocks are consistent with the interpretation that they maybe stratigraphically equivalent to strata of the Flin Flon Block. Thus, the Schist Lake and Mandy VMS deposits are interpreted to be the stratigraphic equivalent of the Flin Flon, Callinan and 777 VMS deposits that make up the main Flin Flon VMS district.
Acknowledgements

I would like to thank my supervisors Dr. Harold Gibson and Dr. Stephen Piercey for their guidance, knowledge and support throughout the duration of the project, as well as Dr. Renee-Luce Simard who helped to edit my thesis as part of my thesis committee. Thanks also to my external reviewer, Dr. John Hinchey.

Financial and logistical support was provided by the Manitoba Geological Survey, the Geological Survey of Canada (TGI3), Laurentian University Mineral Exploration Research Centre and HudBay Minerals Ltd.

I would also like to thank my parents, Mark and Gail Cole and my husband, David Lewis, for their continued support throughout the whole process; I would not have made it this far without them.
Table of Contents

Signatures of examining committee ii

Abstract iii

Acknowledgements v

Table of contents vi

Lists of Figures and Tables x

Chapter 1 – General Introduction to the Schist Lake and Mandy Mines Project

1.1 Introduction 1
1.2 Volcanogenic Massive Sulphide Deposits 2
1.3 The Trans-Hudson Orogen 3
1.4 Geological and Stratigraphic Setting of the Flin Flon Mining Camp 5
1.5 Structural History of the Flin Flon Area 9
1.6 Historical review of the Schist Lake and Mandy VMS mines 10
1.7 Objectives of Thesis 13
1.8 Organisation of Thesis 13

Chapter 2 – The Geology of the Schist Lake and Mandy Mines Area
Chapter 4 – Alteration Geochemistry and Spatial Distribution of Elements and Minerals

4.1 Introduction 67

4.2 Alteration associated with Volcanogenic Massive Sulphide Deposits 67

4.3 Methodology and Alteration Indices 69

4.4 Results: The Spatial Distribution of Selected Elements, Oxides, Alteration Indices and Mineralogy 71

4.5 Discussion 73

Chapter 5 – Discussion and Conclusions

5.1 Discussion 86

5.2 Conclusions 94

References 104

Appendix 1 – Drill Core Logs for the Schist Lake and Mandy Mines Area 117

Appendix 2 – Detection Limits for Geochemical Whole Rock Major and Trace Element Analysis (From Acme Labs Schedule of Services and Fees 2008) See enclosed CD
Appendix 3 – Excel Spreadsheet containing all Geochemical Data obtained for this Project. See enclosed CD
List of Figures and Tables

Chapter 1 - General Introduction to the Schist Lake and Mandy Mines Project

Figure 1.1: The location of the Trans-Hudson Orogen. 15
Figure 1.2: Simplified regional geological map of the THO in Manitoba and Saskatchewan showing the main lithotectonic subdivisions 16
Figure 1.3: Simplified cross sections illustrating the evolutions of the Reindeer zone in the Trans-Hudson Orogen 17-18
Figure 1.4: Location of the Schist Lake and Mandy mines area 19
Figure 1.5: Stratigraphic column of the main formations in the Flin Flon area 20
Figure 1.6: Schematic diagram of the Mandy orebody 21
Figure 1.7: Schematic diagram of the Schist Lake mine orebody, showing the location of the Schist Lake mine headframe 22

Chapter 2 – The Geology of the Schist Lake and Mandy Mines Area

Figure 2.1: Location of the Schist Lake and Mandy mines area 39
Figure 2.2: Geology of the Schist Lake and Mandy mines area – see map in back pocket
Figure 2.3: Relationship of the Schist Lake and Mandy mines strata to the main Flin Flon camp, showing the major structures within the area 40
Chapter 3 – Geochemical Study of the Schist Lake and Mandy Mines Area

Figure 3.1: Data for all samples define a straight line through the origin 56
Figure 3.2: Modified Winchester and Floyd (1977) plot, by Pearce (1996) 57
Figure 3.3: Clusters emerge when data is plotted against TiO₂ 58
Figure 3.4: Sc-La plot 59
Figure 3.5: Sc-La plot 60
Figure 3.6: Primitive mantle multi-element diagrams 61
Figure 3.7: Primitive mantle multi-element diagrams 62
Figure 3.8: Primitive mantle multi-element diagrams 63
Figure 3.9: North American Shale Composite (NASC) normalised REE plot for argillite lithofacies 64
Table 3.1: Precision data

Table 3.2: Trace element ratios

Chapter 4 – Alteration Geochemistry and Spatial Distribution of Elements and Minerals

Figure 4.1: Cross section of idealised model of alteration zonation for a VMS deposit

Figure 4.2: Alteration box plot

Figure 4.3: Spatial distribution diagram for the CCPI

Figure 4.4: Spatial distribution diagram for the Ishikawa alteration index

Figure 4.5: Spatial distribution diagram for Na2O

Figure 4.6: Spatial distribution diagram for plagioclase

Figure 4.7: Spatial distribution diagram for chlorite

Figure 4.8: Spatial distribution diagram for quartz

Figure 4.9: Spatial distribution diagram for SiO2

Figure 4.10: Spatial distribution diagram for Cu

Figure 4.11: Spatial distribution diagram for Zn

Chapter 5 – Discussion and Conclusions

Figure 5.1: Map of the Schist Lake mine area

Figure 5.2: Stratigraphic and structural relationship of the Flin Flon area to the Schist Lake and Mandy mines area

Figure 5.3: Simplified stratigraphic column illustrating interpreted correlations between undivided strata in the Schist Lake
and Mandy mines area with informally subdivided strata in
the Flin Flon block

Figure 5.4: Primitive mantle normalised multi-element diagram

Figure 5.5: Primitive mantle normalised multi-element diagram

Figure 5.6: Modified Winchester and Floyd (1977) plot, by Pearce (1996)

Figure 5.7: TiO₂ vs. Zr, Nb and Y

Figure 5.8: Primitive mantle normalised multi-element diagram
Chapter 1

General Introduction to the Schist Lake and Mandy Mines Project

1.1 Introduction

The Palaeoproterozoic Flin Flon and Snow Lake belts of the Trans-Hudson Orogen in Manitoba and Saskatchewan contain one of the largest accumulations of Palaeoproterozoic volcanogenic massive sulphide (VMS) deposits on the planet (Galley et al., 2007). The Flin Flon belt and district has been the subject of numerous studies over the years, more recently those conducted by the Manitoba Geological Survey, the Saskatchewan Geological Survey, the Geological Survey of Canada, Mount Royal University, and the Mineral Exploration Research Centre (MERC) at Laurentian University (Stockwell, 1960; Bailes and Syme, 1989; Syme, 1990; Syme and Bailes, 1993; Stern et al., 1993, 1995, 1999; Syme et al., 1999; Ames et al., 2002; Devine et al., 2002; Devine, 2003; DeWolfe and Gibson, 2004, 2005, 2006; MacLachlan, 2006; Simard, 2006; Simard and Creaser, 2007; Kremer and Simard, 2007; Lewis et al., 2007; Cole et al., 2007, 2008; DeWolfe, 2009, 2010, 2011; DeWolfe et al., 2009a and b; Gibson, et al., 2009; Simard and MacLachlan, 2009; Simard et al., 2010; Rayner, 2010).

Despite this past research and the proximity of the Schist Lake and Mandy (VMS) deposits to VMS deposits of the main Flin Flon district, only limited research has been conducted on the Schist Lake and Mandy deposits and their host rocks (Bailes and Syme, 1989; Cole et al, 2007; Cole et al, 2008; DeWolfe, 2009; DeWolfe, 2010). The Schist Lake and Mandy VMS deposits are located approximately 5 km SE of the main Flin Flon District VMS deposits and are hosted by rocks of uncertain stratigraphic affinity,
therefore the focus of this thesis is on strata that host the Schist Lake and Mandy deposits and the alteration associated with these deposits.

This chapter provides a brief overview of Volcanogenic Massive Sulphide (VMS) deposits followed by a discussion of the Flin Flon belt with respect to the larger Trans-Hudson Orogen, as well as a brief discussion of the Flin Flon belt and the geological and stratigraphic setting of the Flin Flon mining district. This is followed by a historical review of the Schist Lake and Mandy mines, and finally the main objectives of this thesis will be stated with an outline of how the thesis is organised.

1.2 Volcanogenic Massive Sulphide Deposits

Volcanogenic Massive Sulphide (VMS) deposits are stratabound accumulations of sulphide minerals that precipitated at or near the ocean floor in association with volcanism (Franklin et al., 2005). They tend to have two parts: a concordant massive sulphide lens and a discordant vein type mineralisation, generally found in the footwall to the deposit, often called the stockwork or stringer zone (Franklin et al., 2005). Volcanogenic massive sulphide deposits on the modern seafloor form in both divergent and convergent geodynamic settings; however, ancient deposits are preserved primarily in rifted arc and back arc basins and have been classified using many criteria (Franklin et al., 2005). Franklin et al., (2005), classify VMS deposits based on the composition and characteristics of lithofacies which comprise the footwall volcanic succession. In the scheme of Franklin et al., (2005) VMS deposits are classified as bimodal mafic, mafic, pelitic mafic, bimodal felsic or siliciclastic felsic deposits.
Using the Franklin et al. (2005) classification, deposits of the Flin Flon district, including the Schist Lake and Mandy deposits, are of the bimodal mafic type, as they are dominated by basalt, but have a felsic component (<25%), the latter often being the immediate host to mineralisation.

1.3 The Trans-Hudson Orogen

The Trans-Hudson Orogen (THO) forms the largest Palaeoproterozoic orogenic belt of Laurentia, and extends from South Dakota, though Saskatchewan, Manitoba and Northern Quebec into Greenland (Fig. 1.1; Hoffman, 1988). In Canada, the THO formed during the collision of the Archaean Superior and Rae-Hearne cratons at ~1.83-1.8Ga (Lewry and Collerson, 1990; Lewry et al, 1994; Corrigan et al., 2005), and consists of a variety of juvenile supracrustal belts, continental margin sedimentary rocks and reactivated rocks of the Archaean Superior and Hearne forelands (Lewry and Collerson, 1990; Lewry et al., 1994; Corrigan et al., 2005). As the THO preserves rocks from a wide range of magmatic and tectonic settings it is host to a variety of mineral deposit types. The most important of these are the VMS deposits of Flin Flon, Snow Lake, Sheridan and Ruttan districts that are hosted by juvenile arc assemblages and the magmatic Ni-Cu-PGE deposits of the Thompson and Lynn Lake districts that are hosted by mafic and ultramafic intrusions emplaced into the rifted Superior Craton margin (Corrigan et al., 2007).

The THO consists of the Cree Lake zone and the Reindeer zone (Fig. 1.2). The Reindeer zone consists of the Glennie, La Ronge, Rottenstone, and Kisseynew Domains and the Wathaman Batholith (Ashton et al., 1987, 1997; Ashton and Leclair, 1991). The Glennie Domain, in Saskatchewan, consists of juvenile volcanic arcs and associated
sedimentary basins that have been thrust stacked and fold repeated, and it overlies the Sask Craton above a basal decollement (Ashton et al., 1987, 1997; Ashton and Leclair, 1991). The Flin Flon Domain, in Manitoba, is interpreted to be an extension of the Glennie Domain, now collectively referred to as the Flin Flon-Glennie Complex (Corrigan et al., 2005). The Flin Flon-Glennie Complex consists of ~1.9-1.87 Ga oceanic arc, ocean-floor, and ocean plateau assemblages (Stern 1995). The La Ronge Domain, in Saskatchewan, and the equivalent Lynn Lake and Leaf Rapid domains, in Manitoba, form a continuous belt consisting of 1.905-1.876 Ga mafic to felsic volcanic rocks and associated sedimentary and plutonic rocks, psammitic to pelitic metasediments (the Milton Island assemblage) and gabbro to granite plutonic rocks.

The Trans-Hudson Orogen (THO) developed during closure of the Manikewan Ocean, which opened circa ~2.16Ga (Corrigan et al., 2005). The sequence of events that formed the THO as described below are from Corrigan et al., (2005). The Milton Island assemblage of the La Ronge Domain, interpreted to be a fore-arc basin or an accretionary prism, and the La Ronge arc formed due to the closure of the Manikewan Ocean between 1.92 and 1.88Ga (Fig. 1.3a), and were accreted to the margin of the Hearne craton at ~1.88-1.865Ga (Fig. 1.3b). The Wathaman Batholith, extending from NE Manitoba to north central Saskatchewan was emplaced between 1.865 and 1.85Ga in a continental arc setting (Fig. 1.3c), probably after the accretion of the La Ronge arc to the Hearne margin. The Flin Flon-Glennie complex was accreted to the Churchill plate along the Duck Lake shear zone between 1.85 and 1.845Ga (Fig. 1.3d). The Kisseynew domain formed on the flank of the Flin Flon-Glennie complex in a back arc basin assemblage that deposited the Burntwood Group between 1.845 and 1.835Ga (Fig. 1.3e). The Burntwood back arc basin
closed shortly after its formation as a result of the Sask craton (Archaean basement rocks).

- Flin Flon-Glennie complex collision at 1.84Ga. The Sask craton and the Flin Flon-Glennie complex collided with the Hearne province between 1.835 and 1.83Ga resulting in the development of several thrust faults (Fig. 1.3f). The final stage in the formation of the Trans-Hudson Orogen was the collision of the Hearne-Sask-Superior cratons between 1.83 and 1.8Ga (Fig. 1.3g).

The Flin Flon belt (Flin Flon-Glennie Complex) is part of the south-western THO (Fig. 1.2) The Flin Flon belt (FFB) can be subdivided into four main tectonostratigraphic assemblages that formed around 1.9 Ga: 1) isotopically juvenile oceanic arc, 2) ocean floor, 3) oceanic plateau-ocean island and 4) isotopically evolved ocean arc (Syme, 1990; Syme and Bailes, 1993; Stern el al., 1995). Juvenile arc assemblages host all 27 VMS deposits in the Flin Flon Belt (Devine, 2003). Volcanic rocks that comprise the Flin Flon assemblage are part of one, circa 1.89 Ga juvenile arc assemblage (Rayner, 2010) within the Flin Flon Belt, and consist of subaqueous mafic and lesser felsic coherent flows and volcaniclastic rocks (Bailes and Syme, 1989). Rocks of the Schist Lake and Mandy Mines area are part of the Flin Flon assemblage (Bailes and Syme, 1989).

1.4 Geological and Stratigraphic Setting of the Flin Flon Mining Camp

Bailes and Syme (1989) divided the Flin Flon area into 10 structural blocks, with each block being separated by a major fault such that stratigraphy between the blocks was not continuous or correlatable. The Schist and Mandy VMS deposits, and those of the main camp (Flin Flon, Callinan and 777 VMS deposits), were interpreted by Bailes and Syme (1989) to occur within a sub-block of the Flin Flon Block, which is separated from the
Hook Lake Block by the Cliff Lake fault (Fig. 1.4) (Bailes and Syme, 1989). Simard (2007) and Kremer and Simard (2007) suggested that volcanic strata that host the Schist Lake and Mandy VMS deposits might be correlated with strata of either the Hook Lake Block or the Flin Flon Block. However, Simard et al. (2009) suggested that strata between the Mandy Road and Cliff Lake faults, which also host the Schist Lake and Mandy deposits, cannot be correlated with certainty to strata of the Flin Flon or Hook Lake Blocks. Recent geochronological work and drilling suggest that the Flin Flon and Hook Lake Blocks (fig 1.4) might not be separate, stratigraphically distinct structural blocks, so it is possible that the blocks may contain parts of the same volcanic succession that were dislocated and repeated by reactivated thrust faults (Gibson et al., 2011); this interpretation will be discussed in later chapters.

To facilitate later discussion, the stratigraphy and deformation history of the Flin Flon and Hook Lake Blocks (Fig 1.4) are briefly described below, and are illustrated in Figure 1.5. The Flin Flon Block is bounded by the West Arm Fault to the west, the Cliff Lake Fault to the east and is unconformably overlain by the Missi Group rocks (Stern et al., 1999; Syme et al., 1999). Strata of the Flin Flon Block within the main Flin Flon VMS district have been subdivided, from oldest to youngest, into the Flin Flon, Hidden, and Louis formations, which are unconformably overlain by sedimentary rocks of the Missi Group on top (Devine, 2003, DeWolfe et al., 2009a; Gibson et al., 2011 Fig. 1.5).

The Flin Flon formation is divided into three members, which from the oldest to youngest, include: the Club, the Blue Lagoon and the Millrock members (Devine et al., 2002; DeWolfe and Gibson, 2006) (Fig. 1.4, 1.5). The Club member is composed of
mafic volcaniclastic rocks with localised aphyric rhyolite flows and associated felsic breccia (Devine et al., 2002; DeWolfe and Gibson, 2006). The Blue Lagoon member consists of aphyric and highly plagioclase porphyritic mafic flows with associated plagioclase crystal rich mafic volcaniclastic rocks (Devine et al., 2002; DeWolfe and Gibson, 2006). The Millrock member is composed of aphyric to sparsely porphyritic mafic flows with associated heterolithologic, mafic volcaniclastic rocks and localised quartz porphyritic rhyolite flows, domes, and associated volcaniclastic rocks. The Callinan-777- Flin Flon VMS deposits are associated with localised rhyolite flows and domes of the Millrock member (Devine et al., 2002; DeWolfe and Gibson, 2006). The Blue Lagoon and Club members and lowermost strata of the Millrock member constitute the footwall succession to the main Flin Flon VMS deposits (Devine, 2003).

The Hidden formation conformably overlies the Flin Flon formation and is composed of the Reservoir, the 1920 and the Stockwell members (DeWolfe and Gibson, 2006; DeWolfe et al., 2009a). The Reservoir member is composed of aphyric flows and synvolcanic sills with localised tuff interbeds, and has negative Nb and Ti anomalies on a primitive mantle normalised multi-element diagrams (DeWolfe and Gibson, 2006; Dewolfe et al., 2009a and b). The 1920 member is an Fe- and Ti-rich andesite cryptoflow, which defines the onset of Hidden formation volcanism. It is located only on the west limb of the Hidden syncline, and has negative Nb and Ti anomalies and a flat HREE pattern on primitive mantle normalised spider diagrams (DeWolfe and Gibson, 2006; DeWolfe et al., 2009a and b). The Stockwell member is composed of plagioclase porphyritic flows with lesser aphyric flows, and is also defined by negative Nb and Ti anomalies on primitive mantle normalised spider diagrams, with a flat HREE pattern and
a slightly enriched LREE pattern (DeWolfe and Gibson, 2006; DeWolfe et al., 2009). The Hidden formation in the Schist Lake – Mandy Mines area is composed of aphyric to sparsely plagioclase porphyritic basalt flows intercalated with minor mafic volcaniclastic rocks (Simard, 2006). The lithofacies changes laterally to heterolithic mafic volcanic breccia across synvolcanic faults (Simard, 2006, DeWolfe, 2009a).

In the Flin Flon area, the Louis formation is subdivided into the Tower and Icehouse members and unsubdivided mafic flows (DeWolfe et al., 2009a). Unsubdivided Louis formation mafic flows consists of plagioclase and pyroxene porphyritic, and lesser aphyric to sparsely porphyritic, basaltic flows and mafic tuff. The Tower member contains local rhyolite flows and felsic breccia of and the Icehouse member is composed of strongly plagioclase and pyroxene porphyritic flows (DeWolfe and Gibson, 2006; DeWolfe et al., 2009b). The Tower member is characterised by negative Nb and Ti anomalies with a slight LREE enrichment and a flat HREE pattern on primitive mantle normalised spider diagrams (DeWolfe et al., 2009b). The Icehouse member is very similar but has no negative Ti anomaly (DeWolfe et al., 2009b).

The Missi Group contains the youngest strata (1.842-1.847Ga) in the Flin Flon area and consists of metamorphosed sandstones and conglomerates that lie unconformably on the Hidden and Louis formations. The Missi Group is interpreted to have been deposited in an alluvial system (Bailes and Syme, 1989).

The Hook Lake Block occurs between the Manistikwan Lake Fault to the east and the Cliff Lake fault to the west. Both faults are north to northwest trending and comprise several splays (Fig. 1.4) (Kremer and Simard, 2007). Kremer and Simard (2007) divided
the Hook Lake Block into a western succession and an eastern succession that are separated by the north-northwest trending Hook Lake fault. The western succession consists of aphyric to sparsely feldspar porphyritic basalt flows, feldspar porphyritic basalt, quartz and feldspar porphyritic rhyolite, plagioclase and pyroxene porphyritic basalt and monolithic to heterolithic mafic to mafic-felsic breccia (Kremer and Simard, 2007). Recent U-Pb zircon geochronology by Rayner et al. (2010) indicates an 1891 +/- 17 Ma for a rhyolite of the western succession, and an age of 1886 +/- 1 and 1888 +/- 1 Ma for the tonalitic and quartz-gabbro phases of the synvolcanic Cliff Lake Pluton, which intrudes the western succession. The western succession of heterolithic breccias and flows are interpreted to represent proximal resedimentation of volcanic rocks into a subsidence structure or basin within the western Hook Lake Block (Kremer and Simard, 2007). Recent mapping has indicated geochemical and lithofacies similarities and differences between strata of the western Hook Lake succession and strata of the Flin Flon Block (Kremer and Simard, 2007). The eastern succession of the Hook Lake Block is ~10 Ma younger than strata of the western succession (Rayner et al., 2010).

1.5 Structural History of the Flin Flon Area

The Flin Flon area is structurally complex and Lafrance et al. (in press) recognized six ductile deformation events, which they referred to as D1 to D6 and will be described below (from Lafrance et al., in press) D1 and D2 events occurred during the intraoceanic arc accretion of the Flin Flon arc to other volcanic terranes prior to the emplacement of 1.872Ga gabbroic dykes (Rayner, 2010). The D1 event produced the Burley Lake syncline, which is expressed as a northwest to north striking fault that juxtaposes the east
younging strata of the Flin Flon and Louis formations, against the west younging strata of the Hidden formation (Fig. 1.4). The D2 event caused the refolding of the Burley Lake syncline and produced the Hidden Lake fold system, which is made up of the Beaver Road anticline, the Hidden Lake syncline and the Mandy Road anticline. The Mandy Road and Beaver Road anticlines have been cut into segments by brittle and ductile faulting (Bailes and Syme, 1989). The D3 event produced east to west directed thrust faults that lead to the deposition of the Missi sediments between 1847 and 1842Ma. The collision of the Flin Flon-Glennie complex with the Sask craton produced several north directed thrust faults (Club Lake, Railway, Catherine) and an east trending fold (Flin Flon Creek syncline), and also truncated the earlier west directed fold/thrust system, in a D4 event. Associated with these structures is a strong lineation, which resulted in the elongation the Flin Flon, Triple 7 and Callinan ore lenses parallel to it. D5 produced the first regional cleavage (S5) and it is observed as a chloritic foliation surrounding deformed volcanic pillows and around clasts in volcaniclastic rocks where it strikes NW to NNW, and dips to the NE. The S5 cleavage is associated with the dextral reactivation of the D3 thrust faults and the final, D6, deformation event formed during the terminal closure of the Manikewan ocean and collision of the Sask craton and the Flin Flon-Glennie complex with the Superior craton between 1.83Ga and 1.79Ga. The D6 event produced a regional NNE striking cleavage, reactivated the east striking D4 thrust faults as dextral shear zones and the D3 thrust faults and D5 dextral shear zones as sinistral shear zones.

1.6 Historical review of the Schist Lake and Mandy VMS mines
The Schist Lake and Mandy mines are located 5km south-east of the town of Flin Flon (Fig. 1.4). Although recent mapping has extended the Flin Flon stratigraphy almost to the Schist Lake and Mandy mines area (Simard, 2006, DeWolfe, 2009a, 2010, 2011), the stratigraphic and structural relationship between the Schist Lake and Mandy deposits to the main Flin Flon-Callinan-Triple 7 VMS deposits remains unclear.

The Mandy mine was the first mine to be put into production in the Flin Flon area. It was discovered by F.C. Jackson and S.S. Reynolds in 1915 (Gale and Eccles, 1992), and was in production from 1916 to 1919 by Hudson Bay Mining and Smelting. The mine was reopened briefly in 1943 and closed permanently in 1944 (Gale and Eccles, 1992). During production 125 000 tonnes of ore was mined, which had an average grade of 8.22% copper and 11.38% zinc (Bailes and Syme, 1989). The orebody had an inner core rich in chalcopyrite, which was surrounded by a zone of sphalerite, which, in turn, was surrounded by a zone rich in pyrite (Gale and Eccles, 1992). The mine was an open pit operation, and during production, only the chalcopyrite-rich inner core was mined. The orebody was 30m long, 4m wide and extended to a depth of 10m (Fig. 1.6) (Gale and Eccles, 1992).

The Schist Lake mine was discovered through exploration by Hudson Bay Exploration and Development and opened in 1954. It was in production intermittently until 1976 when it closed. During production, 1.88 million tonnes of ore with an average grade of 4.21% copper and 7% zinc was mined from an underground operation (Gale and Eccles, 1992). The orebody had a pyrite-sphalerite-chalcopyrite assemblage with minor galena and consisted of two main zones: a north zone and a south zone (Fig. 1.7).
north zone contained three ore lenses, with a maximum size of 60m by 300m, whereas the south zone contained four lenses that range in size from 60-120m in length and occurred at depths ranging from 300-600m (Fig. 1.7). Howkins and Martin (1970) suggested that the four south zone lenses may have been part of one sulphide lens that was segmented by faulting. The ore lenses plunge at 55-65° to the SE, parallel to the plunge of the stretching lineation measured within the mine area.

Modern geological mapping of the area began in the 1940s with mapping by Stockwell (1960). He subdivided rocks on the Schist Lake and Mandy Peninsula into andesite, basalt, dacite and flow breccia, andesite breccia, and quartz porphyry, with quartz porphyry breccia. The general geology of the Schist Lake mine (Cairns et al. 1957) was interpreted to consist of lava flows, with associated pyroclastic breccias, tuff and minor intrusions. The general strike of the rocks is northwest and they dip steeply to the east (Cairns et al., 1957). Cairns et al., (1957) also noted that the lavas are mostly andesitic, but the ore deposits occur in a layer of sericite carbonate schist; derived from fine-grained, grey quartz porphyry. Through level plans and old maps, and from drill core data, it has been established that the orebody occurs within a quartz porphyry unit that is locally a sericite schist (Cotter, 1969).

More recent mapping by Bailes and Syme (1989), refined the mine stratigraphy and placed the VMS deposits within a heterolithic mafic-felsic volcanic breccia. They noted that breccias within the deposits footwall had been hydrothermally altered in the ore zone. The rocks are strongly foliated and have chlorite, quartz, and pyrite alteration (Bailes and Syme, 1989).
1.7 Objectives of thesis

While the Schist Lake and Mandy VMS deposits have produced in the past and have been tentatively correlated with the VMS deposits in the main Flin Flon camp, there is a poor understanding of their stratigraphic location and associated alteration. The objectives are:

- To characterise and describe the host rocks of the Schist Lake and Mandy volcanogenic massive sulphide deposits and their associated hydrothermal alteration zones.

- To compare the host rocks and the volcanic environment of these VMS deposits to those of the main Flin Flon camp.

- To determine if the Schist Lake and Mandy VMS deposits are time stratigraphic equivalents to VMS deposits in the main Flin Flon camp, or to the rocks of the Hook Lake Block.

1.8 Organisation of thesis

This thesis is organised into five chapters. The first chapter provides a general introduction to the thesis topic, including a brief summary of volcanogenic massive sulphide deposits, the regional geology of the Flin Flon area, a summary of the main lithofacies and structure of the Flin Flon area, a historical review of the Schist Lake and Mandy deposits, which includes a brief description of rock types, structure and the orebodies. The second chapter focuses on the field work done in the Schist Lake and Mandy mines area and includes descriptions of lithofacies and structure. The third chapter
focuses on the geochemistry of the informal stratigraphic units and lithofacies in the Schist Lake and Mandy mines area. The fourth chapter examines the alteration associated with the Schist Lake and Mandy VMS deposits and the spatial distribution of alteration with respect to the known deposits. Lastly, the fifth chapter provides a summary and discussion of the objectives.
Figure 1.1 The location of the Trans-Hudson Orogen. From Ross and Villeneuve (2003).
Figure 12. Simplified regional geological map of the TIKO in Manitoba and Saskatchewan showing the main tectonic subdivisions. FRB, Fox River Belt; SBZ, Superior Boundary Zone; DMZ = Domain. Modified after Coniglio et al. (2016, 2007).
Figure 1.3. Simplified cross sections illustrating the evolution of the Reindeer zone in the Trans Hudson Orogen. LWG, Lower Wollaston Group; MIA, Milton Island Assemblage; PIA, Park Island Assemblage; SBZ, Superior Boundary Zone; UWG, Upper Wollaston Group; Cplx, Complex. From Corrigan et al. (2005).
Figure 1.4. Location of the Schist Lake and Mandy mines area. Red box shows map area. Modified from Simard et al. (2010).
Figure 1.5. Stratigraphic column of the main formations in the Flin Flon area. Modified from Simard (2006) and DeWolfe and Gibson (2006).
Figure 1.6. Schematic diagram of the Mandy orebody (from Hanson, 1920). Please note that no scale, coordinates or location data are available for this diagram.
Figure 1.7. Schematic diagram of the Schist Lake mine orebody, showing the location of the Schist Lake mine headframe (from Hudson Bay Exploration and Development archive data). Numbers 1-4 represent the ore lenses in the south zone and numbers 5-7 represent the ore lenses in the north zone.
Chapter 2

The Geology of the Schist Lake and Mandy Mines Area

2.1 Introduction

The Schist Lake and Mandy mines area (Schist-Mandy area) is located 5 km southeast of the town of Flin Flon, on the western shore of Schist Lake (Fig. 2.1). During the summers of 2007 and 2008, part of the area was mapped at a scale of 1:1000, including detailed descriptions of the lithofacies and the alteration facies. A systematic sampling grid was employed to facilitate systematic sampling for geochemical analysis as part of the alteration study. In 2008 five drill holes were re-logged: SCH-7 (977 m), SCH-10 (1065 m), SCH-3 (1403 m), SCH-9 (494 m) and SCH-15 (584 m) (see Appendix 1). Core logging was done in order to trace the strata in three dimensions and to help resolve structural and stratigraphic problems.

The purpose of this chapter is to define and describe the stratigraphy and structure of the Schist-Mandy area.

2.2 Schist Lake and Mandy Mine Area

Strata of the Schist-Mandy area are generally well exposed along the east and west shores of the Schist Lake peninsula with fewer outcrops located in the forested areas of the peninsula (Fig. 2.2). On the Schist Lake and Mandy Mine Peninsula, the volcanic strata strike north-south, have dips between 70° and 80° to the east and young to the west (Fig 2.1). The stratigraphy is dissected by several north-north west striking faults, most notably the Ross Lake and Mandy Road faults (Fig. 2.1). The Mandy Road Fault is the
most pronounced and important structure mapped and the stratigraphic relationship of strata east of this shear zone to strata west of the shear zone was uncertain during mapping. Similarly, Simard et al. (2010) referred to the strata between the Mandy Road Fault and the Cliff Lake Fault as “undivided strata”, as the relationship of these strata to that within the adjacent Flin Flon Lake Block (west) and the Hook Lake Block (east) is uncertain (Fig. 2.3). Strata hosting the Schist Lake and Mandy VMS deposits occur east of the Mandy Road Fault and they have undergone significant deformation and are strongly foliated (Fig 2.4).

The Schist Lake and Mandy area has undergone deformation that has made some primary volcanic features difficult to determine. Two foliations are recognised with one trending at 340-360° and the other at 310-330°. The former foliation is axial planar to the Mandy Road anticline, as defined by Simard (2006, 2007) and DeWolfe (2009). The volcanic strata are metamorphosed to lower greenschist facies and contain a mineral assemblage dominated by chlorite, actinolite, and albite, with localised epidote patches.

**2.3 Schist Lake and Mandy Mines Area Stratigraphy**

Strata of the Schist Lake and Mandy mines area are herein divided into four informal stratigraphic units with several sub-units, or lithofacies. From east to west, these are: 1) a Lower Mafic volcaniclastic unit, which includes a pillowed mafic flow lithofacies, a mafic volcaniclastic lithofacies, a felsic volcaniclastic lithofacies and an argillite lithofacies; 2) a Middle Mafic volcaniclastic unit, which contains a mafic volcaniclastic lithofacies; a quartz crystal mafic volcaniclastic lithofacies and a felsic intrusive rock; 3) a Bedded Tuff unit; and 4) an Upper Mafic volcaniclastic unit
composed of a mafic volcaniclastic lithofacies and a feldspar porphyritic mafic volcaniclastic lithofacies (Figs. 2.2, 2.5). The Mandy Road fault, as recognised in this study and by Bailes and Syme (1989), separates the Lower and Middle mafic volcaniclastic units, and the Schist-Mandy orebodies occur immediately east of the Mandy Road fault within the mafic volcaniclastic lithofacies of the Lower Mafic volcaniclastic unit.

2.3.1 The Lower Mafic Volcaniclastic Unit

The Lower Mafic volcaniclastic unit outcrops along the entire east side of Schist Lake and the Mandy mines area, extending west to the Mandy Road fault (Fig. 2.2). The mafic volcaniclastic lithofacies occurs throughout the map area, whereas the pillowed lithofacies is restricted to the north and the felsic volcaniclastic lithofacies is restricted to the Schist Lake mine area (Fig. 2.2). The argillite lithofacies does not outcrop, but is recognised in drill core. All outcropping lithofacies strike north-south and dip steeply to the east.

For ease of description the mafic volcaniclastic lithofacies is divided into three areas based on their geographical location with respect to the other lithofacies; they will be referred to as areas A, B and C, where A is the most northerly, as shown on Figure 2.2. Area A is located outside of the mine area and contains up to 8 mafic clast types: 1) scoria; 2) brown rimmed aphyric; 3) plagioclase pyroxene porphyritic, 4) aphyric amygdaloidal; 5) feldspar porphyritic; 6) aphyric hematised; 7) aphyric aphanitic; and 8) epidote altered. The volcaniclastic rocks are bedded with beds ranging in thickness from 20cm to 1m; and some beds are normally graded (Fig. 2.6). Within each bed the clast
sizes are moderately- to well-sorted, and where graded, clast size decreases from the base to the top of the bed indicating a west facing direction. The scoria clasts average 3cm in size, are subrounded to rounded, and are a dark brown/grey colour containing 20% amygdules averaging 2mm in size, some of which are quartz filled, whereas others have no filling. The brown-rimmed basalt clasts are partially rimmed, and are aphanitic, aphyric, angular to subangular in form, grey in colour, and most likely represent the chilled margins of pillows. The plagioclase-pyroxene porphyritic basalt clasts average 3cm in size and contain 15% phenocrysts of plagioclase and pyroxene that range from 2-4mm in size. The aphyric amygdaloidal basalt clasts average 5cm in size and contain up to 30% quartz filled amygdales that are 5-7mm in size. The feldspar porphyritic clasts average 6cm in size and contain 5% feldspar phenocrysts 5-6mm in size. The hematised basalt clasts are aphyric, average 5cm in size and have a distinct purple colour; some of these clasts contain up to 5% feldspar phenocrysts, 3-4mm in size. The aphyric aphanitic basalt clasts are dark grey in colour, average 6cm in size and are subrounded. The epidote altered basalt clasts average 4cm in size and are subangular. The matrix of the mafic volcanioclastic lithofacies is a plagioclase pyroxene bearing crystal tuff containing up to 10-15% plagioclase phenocrysts (1-2mm in size) and up to 5% pyroxene phenocrysts (1mm in size); however, the phenocryst content of the matrix is somewhat variable (Fig. 2.7a). As area A lies outside of the mine area, and is relatively unaltered by the VMS hydrothermal system, the lithofacies are relatively unaltered and the variety of clasts types is easily observed. The mafic volcanioclastic lithofacies of area B is located around the Mandy mine and is separated from area C by a felsic volcanioclastic lithofacies, which
is located between the Schist Lake and Mandy mines (Fig. 2.2). The mafic volcaniclastic lithofacies in areas B and C contain the same clast types and will be described together.

The mafic volcaniclastic lithofacies in areas B (Fig. 2.7b) and C are characterised by mafic clasts in a mafic matrix and range from being clast to matrix supported: Clasts range in size from 4mm to 4cm and average 1-2cm in size, and include aphanitic aphyric mafic, plagioclase porphyritic mafic, quartz porphyritic felsic, and finely laminated mafic tuff clasts. The aphanitic aphyric mafic clasts are dark grey in colour, tend to be subrounded and account for up to 90% of the clasts. The plagioclase porphyritic mafic clasts constitute 5% of clasts, are subrounded, and are dark grey in colour with 5-10% plagioclase phenocrysts that average 1mm in size. The remaining 5% of clasts include quartz porphyritic felsic clasts and tuff clasts. The quartz porphyritic felsic clasts tend to be subangular, pale grey in colour, average 2cm in size, and contain 5-10% quartz phenocrysts up to 4mm in size. The tuff clasts are angular to subangular, dark to medium grey in colour, and have laminations on a millimetre to centimetre scale. The volcaniclastic matrix is mafic in composition and very fine-grained, although it locally contains up to 2% plagioclase crystals that are 3-4mm in size. The upper contact of this lithofacies is bounded by the Mandy Road fault, identified as fault breccia in drill core, and the lower contact, as observed in drill core (SCH-10), has a sharp, regular contact with an underlying, more coherent felsic lithofacies. The contact with the pillowed lithofacies is not exposed at surface; however, the contact with the felsic volcaniclastic lithofacies is sharp.
The felsic volcaniclastic lithofacies is distinguished by pale grey to white felsic clasts in a mafic matrix. This lithofacies is poorly sorted with respect to clast size, and is typically clast supported, with clasts ranging in size from 6mm to 6cm and averaging 3cm in size. Aphanitic, aphyric felsic clasts constitute 70% of clasts and they tend to be subangular to subrounded. The remaining 30% of clasts are quartz porphyritic felsic clasts and aphanitic aphyric mafic clasts. The quartz porphyritic felsic clasts tend to be subangular, pale grey in colour, average 2cm in size, and contain 5-10% quartz phenocrysts that range from 2-4mm in size. The aphanitic aphyric mafic clasts are dark grey in colour and tend to be subrounded. The matrix is generally fine-grained and mafic in composition, but is locally intensely sericite altered, especially along foliation planes (Fig. 2.7c). The lower contact of the felsic volcaniclastic lithofacies is not exposed at surface or in drill core, but its contacts with the mafic volcaniclastic lithofacies are sharp and irregular.

The pillowed mafic flow lithofacies is basaltic in composition and consists of pillows that are 20-50cm in size and average 35cm. The pillows are aphanitic and aphyric, but contain 10% amygdules that average 4mm in size. Pillows are reddish brown on the weathered surface and are dark grey green on fresh surfaces. The pillows have been variably flattened during deformation and their irregular morphology precludes their use as a facing indicator. Inter-pillow material is also difficult to recognise given the degree of alteration. The pillowed lithofacies outcrops just north of the Mandy mine shaft and its contacts are not exposed at surface or in the drill core examined.
The argillite lithofacies is characterised by coarse (>0.5mm)- and fine-grained (<0.5mm) laminae; it was only observed in drill core (SCH-3). The coarse material is composed of 2-3mm, sand-sized grains, whereas the fine material is composed of grains less than 0.5mm in size (fine-grained mud). The laminations range from a few millimetres in thickness up to beds 7cm thick. The coarse sandy layers are brown in colour and in some cases exhibit normal grading, load casts and cross bedding, which indicate a facing direction to the west. In contrast, the mud layers are very dark grey in colour with no other visible features (Fig. 2.7d). The argillite lithofacies occurs within the mafic volcaniclastic lithofacies and its upper and lower contacts with this unit are sharp.

Cotter (1969) described a sheared quartz porphyry unit and localised sericite schist as host rocks to Schist Lake ore bodies. These felsic units were not recognized in surface outcrops or in the drill core examined.

2.3.2 The Middle Mafic Volcaniclastic Unit

The Middle Mafic volcaniclastic unit is composed of a mafic volcaniclastic lithofacies, a mafic volcaniclastic lithofacies containing quartz porphyritic felsic clasts and is intruded by a felsic intrusion. These lithofacies strike north-south, dip steeply to the west, and occur immediately west of the Mandy Road fault.

The mafic volcaniclastic lithofacies is characterised by mafic clasts in a mafic matrix. It is poorly sorted and can be either matrix or clast supported with clasts ranging in size from 2mm to 4cm and averaging 1.5cm. Mafic clast types include aphanitic, aphyric, feldspar porphyritic, scoria and tuff clasts. The aphanitic aphyric mafic clasts are dark grey in colour and tend to be subrounded. They constitute about 80% of the clasts.
within this lithofacies. The plagioclase porphyritic mafic clasts constitute up to 10% of clasts; they are subangular to subrounded, and dark grey in colour with 5-10% ~1mm plagioclase phenocrysts. Approximately 5% of clasts are tuff clasts whose internal bedding is at various angles to bedding within the unit. It is this variation in bedding that distinguishes tuff clasts from tuff interbeds; the latter of which are 3-4cm thick and their bedding is parallel to the bedding in the rest of the lithofacies. The tuff clasts are angular to subangular, dark to medium grey in colour, have thin laminations on a millimetre to centimetre scale, and consist of very fine-grained mafic material. The volcaniclastic matrix is mafic in composition and very fine-grained, although locally it contains 1-2% plagioclase phenocrysts that are 1-2mm in size (Fig 2.7c). The upper contact of the lithofacies is gradational, over roughly 20cm, with a mafic volcaniclastic lithofacies containing sparse quartz porphyritic felsic clasts. The lower contact is bounded by the Mandy Road fault, which occurs as fault breccia in drill core. The fault breccia is roughly 75cm thick and consists of highly chloritised and angular fragments, although the alteration is too intense to distinguish the fragment types.

The felsic intrusion contains 5-10% quartz phenocrysts that range from 2-6mm in size. The intrusion is pale grey in colour on weathered surfaces and is a slightly darker grey on fresh surfaces. Contacts with the surrounding lithofacies are sharp and regular, indicating an intrusive contact.

The mafic volcaniclastic lithofacies containing quartz porphyritic felsic clasts is identical to that of the mafic volcaniclastic lithofacies, the only difference being the occurrence (<5%) of angular to subangular quartz porphyritic felsic clasts. They are pale
grey in colour, average 4cm in size and are composed of 5-10% quartz phenocrysts that average 4mm in size. The mafic volcaniclastic lithofacies with quartz porphyritic clasts occurs west of the mafic volcaniclastic lithofacies and the contact is gradational over 20cm.

2.3.3 The Bedded Tuff Unit

The Bedded Tuff unit (Fig. 2.7f) is a 100m thick unit of variably thick, well bedded to laminated, plane bedded tuff that is well exposed at surface and in drill core. The Bedded Tuff unit extends almost the entire length of the Schist peninsula (Fig. 2.2); contacts with the middle mafic volcaniclastic unit and the upper mafic volcaniclastic unit are sharp and bedding in the tuff is conformable to the contact. The absence of shearing, which is typical of faults exposed at surface that are manifest as metre- to metres-wide shear zones (DeWolfe, 2009; Lewis et al., 2006, 2007; Lafrance et al., in press), suggests that the contacts are not faulted, and could be conformable. Very fine-grained beds are composed of grains <1mm in size in 1-2cm thick beds that are pale grey in colour. Coarser beds are composed of grains that are 3-4mm in size and are darker in colour than the fine-grained beds. Some beds of tuff are crystal rich, containing up to 25% feldspar phenocrysts that are 0.5-6 mm in size, and are pink to grey in colour. In drill core the beds often display normal grading that consistently indicates a west-facing direction.

2.3.4 The Upper Mafic Volcaniclastic Unit

The Upper Mafic volcaniclastic unit is composed of a feldspar porphyritic mafic lithofacies (the furthest to the east) that is conformably overlain by a mafic volcaniclastic lithofacies. The lithofacies strike north-south and dip steeply to the west.
The feldspar porphyritic mafic volcaniclastic lithofacies is defined by the presence of feldspar phenocrysts within the clasts and feldspar crystals in the matrix. This lithofacies is moderately sorted, is either clast supported or matrix supported, and clasts range in size from 1-6cm, averaging 4cm. Feldspar porphyritic mafic clasts make up approximately 75% of clasts. They are subangular to subrounded, dark grey in colour and contain up to 20% feldspar phenocrysts, ranging from 2-4mm in size. Aphanitic aphyric mafic clasts constitute 20% of this lithofacies; they are subrounded and dark grey in colour. Mafic scoria, aphyric and aphanitic mafic clasts constitute the remaining 5% of clasts. They are subrounded and the scoria clasts contain up to 20% amygdales (2-4mm in size), some of which are filled with quartz. The matrix of this lithofacies is mafic in composition and contains approximately 30% plagioclase crystals, 1-12mm in size, that average 3-4mm in size (Fig. 2.8a), with the remaining 70% being fine-grained and aphanitic.

The feldspar porphyritic mafic volcaniclastic lithofacies occurs to the west of the Bedded Tuff unit and is localised in extent. Its upper contact is sharp and conformable where it is in contact with the pillow lavas; however, where it is in contact with the mafic volcaniclastic lithofacies the contact is gradational over 20cm and is defined by an decrease in feldspar phenocrysts and feldspar porphyritic mafic clasts. The contact with the Bedded Tuff unit is observed in drill core to be sharp and conformable; it is not sheared.

The mafic volcaniclastic lithofacies is very similar to that described for the middle mafic volcaniclastic lithofacies. It is composed of 90% aphanitic aphyric mafic clasts, 5%
feldspar porphyritic mafic clasts, and 5% mafic scoria and tuff clasts. The matrix is a fine-grained mafic tuff containing up to 2% feldspar crystals that range from 1-4mm in size. The mafic volcaniclastic lithofacies occurs in the western portion of the map area and is conformably overlain by pillow lavas to the west (Fig. 2.2). The lower contact of the upper mafic volcaniclastic lithofacies with the tuff unit is a sharp, distinct, non-sheared, intact contact.

2.3.5 Other

The far west portion of the map area is underlain by pillow lavas, which have been interpreted as part of the Hidden formation by Bailes and Syme (1989) and Simard (2006, 2007). The pillowed flows are mostly aphyric and aphanitic containing up to 5-10% quartz-filled amygdales. Consistent facing directions indicate tops are to the west. Epidote-quartz alteration patches are present within the interiors of the pillows. The pillows are reddish brown in colour when weathered and a dark grey colour on fresh surfaces. Pillows range up to 2m in size, but average 60-70cm. The rims tend to be 1cm thick on average, and some of the inter-pillow material is tuffaceous.

2.4 Structural Observations

Two foliations occur throughout the map area and are defined by the alignment of chlorite and sericite, and by the flattening of clasts. The main foliation strikes 340-360° and dips 70-85° to the east. It is overprinted by a second foliation that strikes 310-330° and dips 60-70° to the east (Fig. 2.4). A stretching lineation, defined by the elongation of clasts, with a ratio of 1:3, in the volcaniclastic rocks trends 110-140° and plunges 55-65°.
The Mandy Road fault transects the centre of the peninsula and its location is shown in Figure. 2.2. The Mandy Road fault, as exposed at surface, is a 5m wide shear zone defined by a pronounced foliation and lineation, and is expressed in drill core by a small, approximately 30cm wide, segment of fault breccia. Both lineation and foliations are more intensely developed within the Mandy Road fault zone, clast elongation increases to a ratio of 1:6 and the second foliation shows an anticlockwise change in orientation as it passes into the plane of the main foliation. This geometry and increase in fabric development within the shear zone suggest that the second foliation is a mylonitic S-fabric that was displaced along the main foliation which acted as a C-fabric during sinistral, east-side up shear parallel to lineation. The mapped location and orientation of the Mandy Road fault on the Schist Lake and Mandy peninsula is the same as that shown on the geological map of Bailes and Syme (1989), and in this study, it is interpreted to separate the Lower Mafic volcaniclastic unit from the Middle Mafic volcaniclastic unit (Figs. 2.2 and 2.5). However, on the geological map of Simard et al., 2010, the Mandy Road fault is divided, west of the Schist Lake and Mandy peninsula, into an east and a west fault, both of which are interpreted to lie west of the Mandy Road fault as recognised in this study and as defined by Bailes and Syme (1989). The East Mandy Road fault occurs between the Middle Mafic volcaniclastic unit and the Bedded Tuff unit, as shown on the map of Simard et al. (2010; Fig. 2.10), whereas the West Mandy Road fault occurs at the contact between the Bedded Tuff and the Upper Mafic volcaniclastic units. The upper mafic volcaniclastic unit is correlated with the Hidden formation (Simard et al., 2010). However, the East and West Mandy Road faults do not outcrop in the Schist Lake and Mandy mines area, and they were not recognised in the drill holes logged that
penetrated this stratigraphic succession (SCH3 and SCH15, Appendix 1). The west Mandy Road fault is exposed in outcrop to the north of the Mandy mine and outside of this study area (Simard et al., 2010; DeWolfe, 2010) where its location corresponds approximately with the north extent of the Mandy Road fault as interpreted by Bailes and Syme (1989) (Fig. 2.10). The West and East Mandy Road faults (Simard et al. 2010), and the Mandy Road fault as defined herein and by Bailes and Syme (1989), join to become a single fault north of this exposure, the Channing Fault (fig 2.1). Movement along the “combined Mandy Road fault” is difficult to assess. Based on an apparent horizontal dextral offset of the Missi Group, post Missi movement is at least approximately 200 metres of horizontal movement (Simard et al., 2010), and minor offset of volcanic lithofacies infer minimal movement along the West Mandy Road fault (approximately 3 m; DeWolfe, 2010). The location of the Mandy Road fault (Figure 2.10) and the movement along this fault (or fault splays) is significant in this study for the following reason: the Mandy Road fault as mapped herein and the East and West splays of this structure as mapped by Simard et al. (2010) are interpreted to separate informally subdivided volcanic strata of the Flin Flon Block to the west, from the undivided volcanic strata that are host to the Schist Lake and Mandy VMS deposits to the east, i.e., stratigraphic correlation is not possible across the West and East splays of the Mandy Road fault (Simard et al., 2010). Part of the focus of this study is to determine if strata on either side and between the Mandy Road faults can be correlated. The implications of the Mandy Road fault on stratigraphic correlations will be discussed in Chapter 5.

2.5 Alteration Facies and Mineralisation
The Schist Lake and Mandy mines area exhibit four different types of alteration facies: 1) iron staining; 2) chlorite; 3) sericite; and 4) quartz veining.

1) Weathering of sulphides is a common occurrence in the rocks of the Schist Lake mine area, particularly east of the Mandy Road fault, where it imparts a bright orange red (weaker alteration) to deep purple colour that is more intense in the mafic volcaniclastic rocks (Fig. 2.8c). The stained zones are linear in their morphology and are parallel to the main foliation with a tendency to follow shear zones or fractures. The fractures and shear zones are most likely associated with the Mandy Road fault, so the alteration is likely to be secondary, and later than the pervasive alteration associated with hydrothermal alteration zones. Along the fractures, the host rock is more intensely altered to a deep purple colour that diffuses outwards to red and then orange. These iron stained zones are found throughout the area and also occur as spots scattered within the rock. The stained zones have diffuse boundaries with their host rocks.

2) Two types of chlorite alteration are recognised. The first occurs within vein stockworks (Fig. 2.8d) and the second occurs as small discrete veins. Where the chlorite occurs with a vein stockwork it is dark green to black in colour. This alteration type is particularly prominent on the western shore of Schist Lake where it occurs within a 5-25m wide zone containing vertically dipping chlorite veins that are orientated ~315°. The stockwork veins cover a 20m² area where the veins gradationally decrease in size and disappear except for a couple of isolated patches (Fig 2.9). Isolated patches of chlorite stockwork
veins occur throughout the strata of the mine area. The second type of chlorite alteration is found as discrete chlorite veins that have resistant silicified envelopes. This type of alteration is found proximal to the main chlorite alteration zone, but the veins do not show a distinct orientation. Both types of chlorite alteration are surrounded by areas of iron staining.

3) Sericite alteration occurs throughout most of the lithofacies east of the Mandy Road fault, where it imparts a whitish appearance to the rock (Fig. 2.8b) and, when scraped, has a chalky nature. It occurs along foliation planes and is most prominent in the felsic volcanioclastic lithofacies of the lower mafic volcaniclastic unit. The contact between sericitised and non-sericitised rocks is gradational.

4) Quartz veins are present in most parts of the peninsula, particularly east of the Mandy Road fault, where they range in width from 1cm to 3m. Commonly the quartz veins are <10cm wide, randomly oriented, and cross cut their host rocks in a network pattern. Localised quartz veins, 1-3m in width are associated with areas of intense iron staining, along with other, smaller, quartz veins ranging in size from 10-20cm. These veins trend north-east, but have a limited strike length.

Mineralisation in the Schist Lake and Mandy mines area is minimal at surface, and is largely restricted to outcrops and drill core east of the Mandy Road fault, where it is associated with the deposits. Malachite occurs within the plane of the main 340° foliation, along with chalcopyrite and azurite. Small patches of disseminated pyrite are common on outcrops and in drill core, where it occurs as
patches that contain pyrite cubes up to 2cm in size. Minor chalcopyrite is also found in drill core, where it is generally associated with pyrite.
Figure 2.1. Location of the Schist Lake and Mandy mines area. Red box shows map area. Modified from Simard et al. (2010). Purple area represents the town of Flin Flon.
Figure 2.3. Relationship of the Schist Lake and Mandy mines strata to the main Flin Flon camp, showing the major structures within the area.
Figure 2.4. Early and late foliations of the Schist Lake and Mandy mines area. The early foliation strikes 340-360° and dips 70-85° to the east. The late foliation strikes 310-330° and dips 60-70° to the east.
Figure 2.5. Stratigraphic column through the Schist Lake and Mandy mines map area. A, B and C refer to the section lines on the map in figure 2.2. Colour legend can be found in figure 2.2.
Figure 2.6. Graded bedding from outside of the mine area, yellow chalk indicates the outlines of the clasts.
Figure 2.7. a) Representative area of the package A lower mafic volcaniclastic unit; 
b) Representative area of the package B lower mafic volcaniclastic unit; 
c) Representative area of the felsic volcaniclastic lithofacies of the lower mafic 
volcaniclastic unit; 
d) Representative area of the argillite lithofacies of the lower mafic volcaniclastic unit; 
e) Representative area of the middle mafic volcaniclastic unit; 
f) Representative area of the tuff unit.
Figure 2.8. a) Representative area of the feldspar porphyritic mafic volcaniclastic lithofacies of the upper mafic volcaniclastic unit; b) Representative area of sericite alteration; c) Representative area of iron staining; d) Chlorite stockwork veins.
Figure 2.9. Alteration map of the Schist Lake mine area. See figure 2.2 for location of alteration study.
Figure 2.10. Three schematic diagrams showing a) the placement of the Mandy Road fault as proposed by Bailes and Syme (1989). The rocks to the west of the Mandy Road fault are predominantly basaltic to basaltic andesite flows and breccias of the Hidden formation, to the west of the Mandy Road fault the rocks are heterolithic breccias; b) the placement of the Mandy Road fault as proposed by this thesis, see Figure 2.2 for map legend; and c) the placement of the East and West Mandy Road fault as proposed by Simard et. al., 2010. Units to the west of the the West Mandy Road fault comprise of the Hidden formation, whereas the rocks to the east are undivided volcanic strata.
Chapter 3

Geochemical Study of the Schist Lake and Mandy Mines Area

3.1 Introduction and Objectives

A geochemical study of strata that host the Schist Lake and Mandy VMS deposits was undertaken to: 1) determine if the mapped lithofacies are compositionally distinct; 2) to determine the composition of the different lithofacies; 3) to define contacts and units that are otherwise difficult to determine when altered; and 4) to determine the alteration types (Chapter 4). Ultimately, the geochemical study also will provide another means to compare strata that host the Schist Lake and Mandy deposits to strata that host the Flin Flon, Callinan and 777 deposits in the main Flin Flon camp. This study was undertaken in two stages. The first stage, conducted during the summer of 2007, was to establish a sampling grid over altered rocks in the Schist Lake mine area, where samples were taken at 10m intervals in areas of high exposure (detailed alteration study will be discussed in Chapter 4). The second stage was sampling the drill core and surrounding outcrops from the Schist Lake and Mandy mines area in the summer of 2008 to establish a chemostratigraphy and the magmatic affinity of the mapped units. The purpose of this chapter is to describe the results of the latter geochemical study. In order to determine the composition of different lithofacies and the alteration types in the Schist Mine area, a total of 79 samples were collected in 2007 using a 10m sampling grid in areas of alteration with high outcrop exposure. Of these 79 samples, 30 were from the mafic volcaniclastic facies, 32 were from the felsic volcaniclastic facies and the remaining 17 samples were from the bedded tuff facies. In 2008, a further 13 samples were collected...
from the Mandy Mine and surrounding area, as well as 199 samples from drill holes
SCH-3, SCH-7, SCH-9, SCH-10 and SCH-15

3.2 Sampling and Analytical Techniques

Samples were analysed at Acme Laboratories Ltd. in Vancouver for major, trace and rare earth elements. Major elements were analysed by inductively coupled plasma-emission spectrometry (ICP-ES) following a lithium metaborate/tetraborate fusion and dilute nitric acid digestion. In addition, total trace, rare earth and refractory elements were determined by ICP-mass spectrometry (ICP-MS) following a lithium metaborate/tetraborate fusion and nitric acid digestion of a 0.1g sample. A separate 0.5g split digested in Aqua Regia was analysed by ICP-MS for precious and base metals. A table of detection limits can be found in Appendix 2. The data was statistically analysed for precision to assess the quality of the data using the procedure of Jenner (1996). Table 3.1 shows the calculated precision of each element based on multiple analyses of standards and will be referred to in this chapter as a quality control measure of the data.

3.3 Methodology

Stratigraphic units defined through mapping are defined geochemically herein. However, as strata of the Schist Lake and Mandy mines area are predominantly composed of volcaniclastic lithofacies, and because the samples include more than one clast type and variable amounts of matrix, the compositions may not define a primary composition for the unit or lithofacies. Given this intrinsic variability in the composition of each volcaniclastic lithofacies, each analysis, at best, can only represent an approximate or hybrid composition. Thus, only significant differences in composition can be regarded as
being significant and important in distinguishing and characterising each map unit or lithofacies. This limitation must be considered in the analysis of the geochemical data that follows. However, having stated this limitation it is important to note that the majority of the volcaniclastic lithofacies contain only mafic fragments, separated on the basis of texture, phenocryst mineralogy, and vesicularity and, therefore, may share a common magmatic source but different fractionation history. Additionally, the matrix is also predominantly mafic.

Given the degree of alteration, deformation and metamorphism that has affected the rocks, many of the major elements that are commonly used to identify and define lithology (e.g. SiO₂, Na₂O, K₂O) are assumed to have been mobile. Thus, only immobile elements are used to determine the lithogeochemical attributes of each map unit and lithofacies. To establish which elements or oxides were immobile during alteration and metamorphism binary plots were constructed of element/oxide pairs for each lithofacies and map units to determine element immobility according to the methodology of MacLean and Barrett (1993). Using this technique, data for element pairs that define linear arrays that plot through the origin on binary diagrams and have constant inter-element ratios are considered to be immobile; this is the case for the following trace elements. The high field strength elements (HFSE) and rare earth elements (REE) are commonly assumed immobile during hydrothermal alteration and although there is some scatter in the data, binary plots of Zr, Nb, (excellent precision, Table 3.1), Sm, Tb, Ho (very good precision, Table 3.1), Hf, and Nd (good precision, Table 3.1), define straight lines through the origin indicating that these incompatible elements were immobile during alteration (Fig. 3.1). Some of the scatter may be due to primary lithological variation
given that the samples are volcanioclastic rocks, and the precision of the elements are
deemed excellent to good (Table 3.1).

3.4 Results

All samples from the Schist Lake and Mandy mines area have basaltic to basaltic-
andesite affinities when plotted on the Winchester and Floyd (1977) classification
diagram (Fig. 3.2). However, each sample represents a hybrid or approximate
composition because the volcanioclastic rocks contain a mixture of different mafic clast
types with some units containing up to 15% clasts of a more intermediate to felsic
composition. The latter may account for some of the samples plotting in the
andesite/basalt field of Figure 3.2. The samples also define linear arrays when plotted on
binary immobile element plots (Fig. 3.1). This suggests that they have similar inter-
element ratios with respect to Zr, Y and Nb and that these elements cannot be used to
differentiate the different units/lithofacies (Fig. 3.1). In order to determine if the
lithofacies within the lower mafic volcanioclastic unit define compositionally distinct
populations, the samples were plotted on binary diagrams of immobile elements versus
TiO₂ (Fig. 3.3), a compatible, but commonly immobile element (MacLean and Barrett,
1993). The Middle Mafic volcanioclastic unit, Bedded Tuff unit and Upper Mafic
volcanioclastic unit are very similar (Figure 3.3). However, the majority of the samples
from the lower mafic volcanioclastic lithofacies of the Lower Mafic volcanioclastic unit
define a cluster that differs by having slightly lower TiO₂ values and lower immobile
element values than other samples of this lithofacies, and from data of all other
lithofacies. Within each unit it is possible to break out some of the lithofacies, although
there is significant overlap between populations and lithofacies. In sedimentary rocks, a higher Sc content is often indicative of a higher mafic component and a higher La is often indicative of a higher felsic component (Bhatia and Crook, 1986), thus samples with higher La content may reflect a higher proportion of felsic clasts. In Sc-La space of Figures 3.4 and 3.5 the samples from the Lower Mafic volcaniclastic unit’s mafic volcaniclastic lithofacies have a similar range in Sc content but lower La content than other samples of this and other lithofacies. Samples from the argillite lithofacies of the lower mafic volcaniclastic unit tend to plot in groups with higher proportions of immobile, incompatible, elements and have higher La values, when compared to data of the other lithofacies (Figs. 3.3, 3.4 and 3.5). The Middle Mafic volcaniclastic unit and the Upper Mafic volcaniclastic unit show a very similar pattern to the lower mafic volcaniclastic unit. The lower La, Zr, Y and Nb content of most of the mafic volcaniclastic lithofacies samples of the Lower, Middle and Upper mafic volcaniclastic units relative to the spread of La, Zr, Y and Nb values associated with the felsic volcaniclastic lithofacies of the Lower Mafic volcaniclastic unit supports a more felsic composition for the latter. However, none of the aforementioned diagrams effectively discriminate the different lithofacies of the units.

Samples of each lithofacies from each unit were plotted on primitive mantle normalised spider diagrams to test for internal consistency within each lithofacies and to examine and compare their overall geochemical patterns. Trace element ratios for all units and lithofacies are presented in Table 3.2. The REE patterns for the lithofacies of the Lower, Middle and Upper Mafic volcaniclastic and Bedded tuff units (Figs. 3.6, 3.7, 3.8) are similar and relatively internally consistent. Samples from most lithofacies have
relatively flat HREE but with variable amounts of LREE enrichment, with samples of the felsic lithofacies having the highest LREE enrichment of all lithofacies in the Lower Mafic volcaniclastic unit (La/Sm ratio for the mafic lithofacies is 0.69-1.88 and for the felsic lithofacies is 0.92-2.47; Table 3.2). Samples from all lithofacies show a negative Nb anomaly relative to Th and La, with some samples of each lithofacies showing negative Eu, Ti and V anomalies. The negative Eu anomaly could be caused by the fractionation of plagioclase feldspars and therefore reflect a primary magmatic composition related to the source area or Eu removal during alteration (Meyer and Hemley, in Barnes, 1967; Hajash and Chandler, 1981). The negative Nb anomaly may indicate an arc signature (Pearce and Cann, 1973). Samples of the argillite lithofacies of the Lower Mafic volcaniclastic unit show a marked depletion in the LREE when plotted on a North American Shale Composite (NASC) normalised spider diagram, a pattern that is inconsistent with their derivation from a continental or an evolved arc source (Fig. 3.9). However, on primitive mantle normalised spider diagrams the argillite lithofacies (Fig. 3.6) has a pattern that is similar to lithofacies from most of the volcaniclastic units and also displays a similar negative Nb (relative to Th and La), Eu, and Ti anomalies but is missing the V anomaly that characterises some samples (the La/Sm ratio for the argillite lithofacies is 1.67-2.38. Table 3.2). This similarity in REE patterns suggests that the argillite could be derived from a volcanic source similar to that of the volcaniclastic lithofacies.

3.5 Discussion
The four informal units of the Schist Lake and Mandy mines area are similar in their geochemical composition, and several interpretations can be drawn from the data:

1. The negative Nb anomaly relative to Th and La for all lithofacies of each unit is consistent with an arc derivation and/or geodynamic setting (e.g. Sun and McDonough, 1989) as initially proposed by Stern et al. (1995, 1999), Syme (1990), Syme and Bailes (1993).

2. The Upper Mafic volcaniclastic unit has been included within the Hidden formation, and this is consistent with its geochemistry (Simard et al., 2010). The possible stratigraphic position of the Middle and Lower volcaniclastic units will be discussed in Chapter 5 of this thesis.

3. The overlap of trace element (La, Sc, TiO₂, Nb, Zr) and REE data for mafic and felsic volcaniclastic lithofacies and mafic lithofacies with felsic clasts indicates that the felsic component observed in core logging is not readily recognised geochemically.

4. The felsic intrusive rock found within the Middle Mafic volcaniclastic unit is geochemically distinct from other lithofacies and is characterised by low Sc values (Fig. 3.4) and low La/Lu ratios (Table 3.2.).

5. Based on subtle differences in geochemistry, it appears that the mafic volcaniclastic lithofacies of the Lower Mafic volcaniclastic unit differs from the mafic volcaniclastic lithofacies of the Middle and Upper volcaniclastic units in having a cluster of samples from the mafic
lithofacies with lower average TiO₂, Zr, Nb (Fig. 3.3 and 3.4) and a flatter REE profile (Fig. 3.7 and 3.8). However, the Lower and Middle Mafic Volcaniclastic units overlap in Sc content and show very little difference. This could be because Sc tends to be rare in hydrothermally altered suites of rocks (Taylor, 1964), so those lithofacies closer to more intense alteration by hydrothermal fluids may have lower Sc than those that are more distal. However, with respect to TiO₂, Zr, Nb and Sc (Fig. 3.3 and 3.4) the felsic volcaniclastic and argillite lithofacies of the Lower Mafic volcaniclastic unit are similar to volcaniclastic lithofacies within the Middle and Upper Mafic volcaniclastic units, with the exception of the middle felsic intrusive lithofacies.
Figure 3.1. Data for all samples define a straight line through the origin when plotted using immobile elements: a) Y vs Zr; b) Nb vs Zr; c) Nb vs Y. See Figure 3.2 for symbol key.
Figure 3.2. Modified Winchester and Floyd (1977) plot, by Pearce (1996). Classification diagram for the lower, middle, upper mafic volcaniclastic units and the tuff unit.
Figure 3.3. Clusters emerge when data is plotted against TiO₂: a) TiO₂ vs Zr; b) TiO₂ vs Y; c) TiO₂ vs Nb. See Figure 3.2 for symbol key.
Figure 3.4. Sc-La plot; a) Lower mafic volcaniclastic unit; b) Middle mafic volcaniclastic unit.
Figure 3.5. Sc-La plot; a) Tuff unit; b) Upper mafic volcaniclastic unit.
Figure 3.6. Primitive mantle (PM) normalised multi-element diagrams for a) the mafic volcaniclastic lithofacies; b) the felsic volcaniclastic lithofacies; and c) the argillite lithofacies. Primitive Mantle values from Sun and McDonough (1989).
Figure 3.7. Primitive mantle normalised spider diagrams for a) the mafic volcaniclastic lithofacies; b) the mafic volcaniclastic lithofacies with quartz porphyritic clasts; c) felsic intrusive rock. Primitive mantle values from Sun and McDonough, 1989.
Figure 3.8. Primitive mantle normalised multi-element diagram for:
a) Tuff unit; b) Upper mafic volcaniclastic unit. Primitive mantle values from Sun and McDonough (1989).
Figure 3.9. North American Shale Composite (NASC) normalised REE plot for argillite lithofacies. NASC values from Gromet (1984).
<table>
<thead>
<tr>
<th>Excellent Precision (0-3%)</th>
<th>Very Good Precision (3-7%)</th>
<th>Good Precision (7-10%)</th>
<th>Poor Precision (&gt;10%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂, Al₂O₃, Fe₂O₃, MgO, CaO, Na₂O, K₂O, TiO₂, MnO, Ba, Sc, Nb, Sn, Ta, Th, Zr, Gd, Yb, Cu, Zn, Sb</td>
<td>P₂O₅, Co, Ga, Rb, Sr, V, Y, Sm, Tb, Dy, Ho, Er, Mo, Pb</td>
<td>Cr₂O₃, Ni, Hf, U, W, La, Ce, Pr, Nd, Eu, As</td>
<td>Cs, Tm, Lu, Cd</td>
</tr>
</tbody>
</table>

Table 3.1. Precision data based on the method of Jenner, 1996. Elements in bold were shown to be immobile during hydrothermal alteration (Figure 3.1)
<table>
<thead>
<tr>
<th>Lithofacies and unit</th>
<th>La/Sm ratio</th>
<th>Median</th>
<th>Average</th>
<th>La/Lu ratio</th>
<th>Median</th>
<th>Average</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower mafic volcaniclastic lithofacies</td>
<td>0.69-1.88</td>
<td>1.21</td>
<td>1.24</td>
<td>0.58-2.15</td>
<td>1.12</td>
<td>1.14</td>
</tr>
<tr>
<td>Lower felsic volcaniclastic lithofacies</td>
<td>0.92-2.47</td>
<td>1.55</td>
<td>1.56</td>
<td>0.69-4.72</td>
<td>1.59</td>
<td>1.82</td>
</tr>
<tr>
<td>Lower argillite lithofacies</td>
<td>1.67-2.38</td>
<td>1.99</td>
<td>2.00</td>
<td>2.29-4.72</td>
<td>2.71</td>
<td>2.95</td>
</tr>
<tr>
<td>Middle mafic volcaniclastic lithofacies</td>
<td>1.12-2.82</td>
<td>2.12</td>
<td>2.02</td>
<td>0.90-6.46</td>
<td>3.12</td>
<td>3.30</td>
</tr>
<tr>
<td>Middle mafic volcaniclastic lithofacies with quartz porphyritic clasts</td>
<td>1.14-2.61</td>
<td>2.10</td>
<td>2.09</td>
<td>1.10-5.51</td>
<td>3.23</td>
<td>3.25</td>
</tr>
<tr>
<td>Felsic intrusive rock</td>
<td>0.91-1.16</td>
<td>1.15</td>
<td>1.07</td>
<td>0.79-1.06</td>
<td>1.06</td>
<td>0.97</td>
</tr>
<tr>
<td>Tuff unit</td>
<td>0.67-2.66</td>
<td>1.71</td>
<td>1.75</td>
<td>0.84-4.44</td>
<td>2.62</td>
<td>2.68</td>
</tr>
<tr>
<td>Upper mafic volcaniclastic lithofacies</td>
<td>1.62-2.48</td>
<td>1.98</td>
<td>1.99</td>
<td>2.23-4.90</td>
<td>3.16</td>
<td>3.20</td>
</tr>
<tr>
<td>Upper feldspar porphyritic mafic volcaniclastic lithofacies</td>
<td>1.80-2.03</td>
<td>1.89</td>
<td>1.91</td>
<td>2.21-2.94</td>
<td>2.83</td>
<td>2.83</td>
</tr>
<tr>
<td>Upper mafic volcaniclastic lithofacies with quartz porphyritic clasts</td>
<td>1.83-2.17</td>
<td>1.98</td>
<td>1.99</td>
<td>2.23-3.92</td>
<td>3.29</td>
<td>3.19</td>
</tr>
</tbody>
</table>

Table 3.2. Trace element ratios for each lithofacies in each unit of the Schist Lake and Mandy mine area. Note: primitive mantle normalised ratios using values of Sun and McDonough (1989).
Chapter 4

Alteration Geochemistry and Spatial Distribution of Elements and Minerals

4.1 Introduction

The purpose of this chapter is to describe compositional variations and the limits of alteration in the Schist Lake and Mandy mines area as indicated by lithogeochemical and mineralogical data obtained from rock samples collected during mapping and core logging. Before results of the alteration study are presented, a brief overview of alteration associated with volcanogenic massive sulphide deposits is given.

4.2 Alteration associated with Volcanogenic Massive Sulphide Deposits

Areas of hydrothermally altered rock occur proximal to VMS deposits and act as a guide for mineral exploration because they are much larger than the deposit itself (Giffkins et al., 2005). Different alteration assemblages occur proximal versus distal to VMS mineralisation. Regional semi-conformable alteration forms distal to VMS deposits, and in bimodal mafic successions like Flin Flon, is characterised by spilitisation, silicification, epidote-quartz and carbonate alteration (Franklin et al., 2005). At Schist-Mandy, spilitisation and epidote-quartz alteration are recognised. Spilitisation is a texturally non-destructive alteration and is characterised by an albite, chlorite (actinolite), quartz-epidote assemblage that is compositionally marked by Na₂O-enrichment and CaO-depletion (Franklin et al., 2005). Epidote-quartz alteration is characterised by an epidote-quartz +/-actinolite assemblage that forms irregular pale-green patches characterised by an addition of CaO and depletion in FeO, MgO (Gibson, 1989; Galley, 1993; Franklin et al., 2005).
Discordant alteration zones in the immediate footwall and locally the hanging wall to bimodal mafic VMS deposits are compositionally and mineralogically zoned (Franklin et al., 2005). In an idealised bimodal mafic discordant alteration zone there are 3 zones: 1) a siliceous core zone with a quartz-chlorite (sericite) assemblage that sometimes contains talc; 2) an inner zone of chlorite alteration where Fe-chlorite in the interior grades out into an outer zone of Mg-chlorite (Fig. 4.1). At the Schist Lake mine area the chlorite zone is very dark green/grey in colour and contains localized stringers of pyrrhotite and chalcopyrite; and 3) an outer sericite zone characterised by a sericite + chlorite + quartz + pyrite assemblage. This sericite zone tends to be laterally extensive, depending on the lithofacies, and the intensity of alteration will decrease towards the edge of the zone (Franklin et al., 2005). In some deposits a weakly altered outer zone of albite has been observed; however, it is possible that this is related to diagenetic alteration and not hydrothermal alteration (Franklin et al., 2005). Locally, small zones of carbonate alteration occur between the siliceous zone and the chlorite zone, adjacent to the massive sulphide. The carbonate zones have an assemblage of chlorite + carbonate + pyrite, and are not laterally extensive. Compositional changes with alteration zone typically include: K$_2$O-enrichment and Na$_2$O- and CaO-depletion within the sericite zone, FeO- and MgO-enrichment and SiO$_2$-depletion in the chlorite zones, and SiO$_2$- and/or MgO-enrichment in the silicified or talc altered core zone (Franklin et al., 2005). With respect to base metals, copper is enriched in the chlorite zone and zinc is enriched in the sericite zone (Franklin et al., 2005).
4.3 Methodology and Alteration Indices

Alteration is defined as being a change in the chemical or mineralogical composition and/or texture of a rock, usually produced by hydrothermal solutions or weathering, and element mobility describes the chemical changes which take place in a rock after its formation (Lapidus and Winstanley, 1990). The alteration box plot in Figure 4.2 shows the mobility of selected elements during alteration, using the chlorite-carbonate-pyrite and Ishikawa indices, within VMS hydrothermal systems.

The geochemical data used to create the element, oxide and alteration index maps in this chapter have been described in the previous chapter and the elements and oxides used to examine discordant alteration are based on compositional changes outlined above. In addition, a suite of samples was selected from the systematic sampling grid on the Schist Lake Mine Peninsula to be analysed by X-ray diffraction (XRD) with quantitative mineralogical abundance determinations measured using the Rietveld method. Of particular importance to defining alteration are the abundance of chlorite, sericite and quartz. Details of the XRD technique and the Rietveld method can be found in Albinati and Willis (1982). Mass balance calculations were not used to define alteration at the Schist Lake and Mandy deposits because a single precursor was difficult to determine due to the volcaniclastic nature of the rocks. In addition to the compositional and mineralogical data, select alteration indices were plotted and the relevance of each index is described below. Data were plotted on plan maps of the Schist Lake and Mandy mines.
area, created using ArcGIS software, in order to examine the spatial location of the data with respect to the two VMS deposits.

Alteration indices that were calculated and plotted include the chlorite-carbonate-pyrite (CCPI), the Ishikawa, sericite and chlorite indices. The chlorite-carbonate-pyrite index is calculated using the following equation:

\[
CCPI = 100\frac{(MgO + FeO)}{(MgO + FeO + Na_2O + K_2O)}
\]

The CCPI is used to measure the increase in MgO and FeO associated with Mg-Fe chlorite, which commonly replaces albite, K-feldspar or sericite in volcanic rocks, leading to the loss of Na_2O and K_2O (Large et al 2001). The CCPI is also affected by Fe-Mg carbonate alteration and by the enrichment of pyrite, magnetite and haematite. The CCPI is regarded as a proximal alteration index because Fe-Mg chlorite, Fe-Mg carbonate and pyrite typically develop in the inner alteration zones of VMS deposits (Large et al 2001).

The Ishikawa alteration index is calculated using the following equation:

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

The Ishikawa alteration index was first determined by Ishikawa et al. (1976) to quantify the intensity of sericite and chlorite alteration that occurs in footwall volcanic rocks proximal to Kuroko-type VMS deposits. The index measures the breakdown of sodic plagioclase and volcanic glass and their replacement by sericite and chlorite. The Ishikawa alteration index has been found useful by providing estimates of the intensity of alteration close to a VMS deposit, increasing to a maximum in the vent zone below the deposit (Ishikawa et al., 1976).
The sericite and chlorite indices are after Saeki and Date (1980) and were developed to measure compositional changes associated with sericite and chlorite alteration in VMS systems. The sericite and chlorite indices are calculated using the following equations:

Sericite index = $\frac{K_2O}{(K_2O + Na_2O)}$

Chlorite index = $\frac{(MgO + Fe_2O_3)}{MgO + Fe_2O_3 + 2CaO + 2Na_2O}$

4.4 Results: The Spatial Distribution of Selected Elements, Oxides, Alteration Indices and Mineralogy

An alteration box plot that is based on the CCPI and the Ishikawa alteration index is shown in Figure 4.2. On the box plot some samples from strata hosting the Schist Lake and Mandy VMS deposits fall in the least altered field for basalt and andesite, but there are also a significant number of samples that plot towards the chlorite-pyrite corner in the alteration field indicating they have undergone chlorite alteration. Upon examining the spatial distribution of samples it is apparent that the highest values for CCPI are located on the east side of the Mandy Road fault and within the footwall to the north zone of the Schist Lake deposit, with lesser-altered samples to the west and south of the Mandy Road fault (Fig. 4.3). The area of intense CCPI alteration that defines the discordant alteration zone for the north zone orebody also reflects the greater number of samples that were collected in this area due to the abundance of outcrop, although systematic sampling indicates there is a real increase in intensity of alteration related to the north zone orebody. The CCPI also highlights what is believed to be part of the alteration pipe for the south zone orebody. The CCPI indicates two further areas of alteration, the first area
is located to the north of the north zone orebody and the second area is located on the west side of the Mandy Road fault. The Ishikawa alteration index mirrors the distribution of CCPI index, where samples with values of between 80 and 100 indicate significant alteration within the north zone footwall of the Schist Lake deposit (Fig. 4.4).

Unaltered mafic volcanic rocks typically have Na$_2$O values of 2-5wt\% (Meyer and Hemley, in Barnes, 1967; Hajash and Chandler, 1981; Riverin and Hodgson, 1980), those with less than 2 wt\% Na$_2$O have likely had Na removal during alteration, which is commonly referred to as feldspar destructive alteration (Meyer and Hemley, in Barnes, 1967; Hajash and Chandler, 1981; Riverin and Hodgson, 1980). In Figure 4.5, the spatial distribution of lower Na$_2$O values indicates that the footwall area to the north zone orebody has been significantly altered, as well as the footwall to the south zone orebody. Low Na$_2$O values (Fig. 4.5) on either side of the Mandy Road fault correlate with CCPI and Ishikawa anomalies in Figures 4.3 and 4.4, which shows the two areas of previously unknown alteration. A decrease in the abundance of plagioclase (defined by XRD analysis), as illustrated in Figure 4.6, correlates with the loss of Na$_2$O, which is consistent with feldspar destruction in the footwall to the north zone orebody.

Chlorite formation involves the addition of iron and magnesium to the rocks and is typically associated with a loss of Na$_2$O and CaO (+/-K$_2$O) (Meyer and Hemley, in Barnes, 1967; Hajash and Chandler, 1981; Riverin and Hodgson, 1980. Figure 4.7 shows the data for chlorite, determined through XRD analysis. Samples with a high concentration of chlorite are found over most of the peninsula, but particularly in the footwall to the north zone orebody, coincident with the areas of Na$_2$O and plagioclase
loss (Fig. 4.5). The chlorite abundance in Fig. 4.7 also identifies the same anomalous areas to the north of the map area and the footwall to the south zone orebody.

Figures 4.8 and 4.9 illustrate the spatial abundance of quartz (determined through XRD analysis) and SiO₂, respectively. As expected, and as has been previously described, both SiO₂ and quartz increase in the two footwall alteration zones, and also in the two anomalous areas to the north. The data also suggest that the areas of least altered rocks occur on the east and west sides of the Mandy road fault in the southern portion of the map area.

Figures 4.10 and 4.11 illustrate the spatial variations in the abundance of Cu and Zn, respectively. Most of the samples on the peninsula have less than 200ppm copper; however, the area defining the alteration zone for the north zone of the Schist Lake deposit contains values of over 500ppm, and up to 1800ppm Cu. However, the other two altered areas identified to the north have low copper values (fig. 4.10). Figure 4.11 shows relatively high zinc values in the north zone and scattered high values over the entire peninsula, but does not define the north zone footwall alteration zone as well as the copper.

4.5 Discussion

The north zone of the Schist Lake orebody projects to surface adjacent to, and east, of the Mandy Road fault and the results presented herein, coupled with field and petrologic evidence, illustrate that this represents the discordant, footwall alteration zone to the north zone of the Schist Lake orebody. This area is characterised by high alteration index values, anomalous Cu values, low Na₂O and plagioclase contents, and high quartz
and SiO₂ contents (Figs. 4.3-4.11). Similar characteristics, although not associated with known mineralisation, are found in other areas in the Schist Lake and Mandy mines area, most notably in the northern part of the map area, and to the east and west of the Mandy Road fault. The south zone of the Schist Lake orebody projects to surface south of the peninsula, and its footwall alteration zone on the south eastern tip of the peninsula is shown by the anomalous Zn, Cu, chlorite, Na₂O, and by high percentages of alteration as shown by the CCPI and Ishikawa alteration indices.

Some indices, such as chlorite and Zn, did not highlight any anomalous areas outside of the mine areas (Figs. 4.7 and 4.11), which suggest that the whole peninsula is pervasively altered by a weak background chlorite alteration. From the archived data it is known that the Schist Lake orebody had a chalcopyrite core surrounded by areas of higher sphalerite and pyrite content, therefore, the anomalous Cu values within the footwall rocks to the north zone mirrors the copper rich core to the north zone orebody.
Figure 4.1. Cross section of idealised model of alteration zonation for a VMS deposit (modified after Lydon, 1984, 1988; Gemmell and Large, 1992).
- Lower mafic volcaniclastic lithofacies
- Lower felsic volcaniclastic lithofacies
- Argillite lithofacies
- Middle mafic volcaniclastic lithofacies
- Felsic intrusive rock
- Middle mafic volcaniclastic lithofacies with quartz porphyritic clasts
- Bedded tuff unit
- Upper mafic volcaniclastic lithofacies with quartz porphyritic clasts
- Upper mafic volcaniclastic lithofacies
- Upper feldspar porphyritic mafic volcaniclastic lithofacies

Figure 4.2. Alteration box plot (Large et al., 2001).
Figure 4.3. Spatial distribution diagram for the chlorite-carbonate-pyrite index (CCPI). Refer to Figure 2.2 for the map legend.
Figure 4.4. Spatial distribution diagram for the Ishikawa alteration index. Refer to Figure 2.2 for the map legend.
Figure 4.5. Spatial distribution diagram for Na2O. Refer to Figure 2.2 for map legend.
Figure 4.6. Spatial distribution diagram for plagioclase. Refer to Figure 2.2 for the map legend.
Figure 4.7. Spatial distribution diagram for chlorite. Refer to Figure 2.2 for the map legend.
Figure 4.8. Spatial distribution diagram for quartz. Refer to Figure 2.2 for the map legend.
Figure 4.9. Spatial distribution diagram for SiO2. Refer to Figure 2.2 for the map legend.
Figure 4.10. Spatial distribution diagram for copper. Refer to Figure 2.2 for the map legend.
Figure 4.11. Spatial distribution diagram for zinc. Refer to Figure 2.2 for the map legend.
Chapter 5
Discussion and Conclusions

5.1 Discussion

Despite past production and considerable exploration interest in the Schist and Mandy VMS deposits, there remain some fundamental uncertainties regarding their host rocks, deposit style, alteration and their time stratigraphic relationship to the VMS deposits of the main Flin Flon district. The objectives of this thesis were firstly to characterise and describe the host rocks of the Schist Lake and Mandy VMS deposits and their associated hydrothermal alteration zones, in order to better understand the stratigraphy and setting of the deposits. The second objective is to compare the host rocks and the volcanic environment of these deposits to those of the main Flin Flon district and the Western Hook Lake succession, in order to determine if the Schist-Mandy VMS deposits occur at the same stratigraphic interval as the Callinan-777-Flin Flon deposits or if their host strata are the stratigraphic equivalent of strata in the Western Hook Lake succession. If the latter correlation is correct the VMS potential of strata within the Western Hook Lake succession would increase. In the discussion that follows, the geological setting and alteration of the Schist Lake and Mandy VMS deposits are discussed first, followed by a discussion of the time and stratigraphic position of the Schist Lake and Mandy deposits and their host strata relative to strata in the Flin Flon and Hook Lake Blocks.

From previous mapping and historical data, both the Schist Lake and Mandy VMS deposits are hosted predominantly within mafic volcaniclastic rocks and consist of several
mineralogically zoned sulphide lenses (Gale and Eccles, 1992) that plunge parallel to the regional stretching lineation (55-65° southeast) in the area. Cotter (1969) stated that the Schist Lake and Mandy orebodies occur within a quartz porphyry unit with localised sericite schist; however, this association of mineralization with felsic volcanics could not be verified during this study as there are currently no drill holes that penetrate the deposit and it is not possible to visit the underground exposures. Assuming the previous observations of Cotter (1969) are correct, the Schist Lake and Mandy VMS deposits are hosted in a rhyolitic unit within a thick succession of mafic volcaniclastic rocks referred to herein as the Lower Mafic Volcaniclastic unit. The deposits also occur within a shear zone recognised by Bailes and Syme (1989; see Chapter 2) and this study, as the Mandy Road fault, which was interpreted by Howkins and Martin (1970) to be responsible for the segmentation and “stretching” of the Schist Lake massive sulphide lenses.

Alteration associated with the Schist Lake and Mandy deposits is similar to that of massive sulphide deposits in the main Flin Flon district and is typical of bimodal mafic-type VMS deposits (e.g., Franklin et al., 1981, 2005). Based on surface sampling, alteration at the Schist orebody is characterised by sericite, pyrite and lesser chlorite. The alteration is characterised by high CCPI; which is most likely from footwall pyrite mineralisation as the chlorite from the XRD data does not reflect high amounts of chlorite alteration; and Ishikawa alteration indices, anomalous Cu and Zn contents, low Na₂O, and high quartz and SiO₂ contents (Figures 4.3 to 4.11). Alteration in the north zone of the Schist Lake orebody is much stronger than in the south zone of the deposit and there is a general decrease in alteration intensity towards the south, which is illustrated by spatial variations in the CCPI and Ishikawa alteration indices (Figs. 4.3, 4.4). In contrast, the
Mandy orebody does not have an intense chlorite alteration zone surrounding it at surface; however, strata in the vicinity of the deposit contain patches of carbonate and local pervasive sericite alteration. The alteration zone associated with the Schist Lake deposit was transposed into the prominent 340-360° foliation during deformation and sinistral, east side up movement along the Mandy Road fault, and does not have a distinct pipe-like morphology typical of undeformed bimodal mafic VMS deposits (Franklin et al., 1981, 2005). Two separate alteration zones are defined in Figures 4.3 to 4.11. These occur midway between the Schist Lake and Mandy VMS deposits and on either side of the Mandy Road fault. These alteration zones have not been tested and, given their similarity to alteration patterns associated with the Schist Lake VMS deposit, may represent prospective exploration targets (Fig. 5.1).

While the Schist Lake and Mandy VMS deposits have features common to the Flin Flon, Callinan and 777 VMS deposits, and to bimodal mafic VMS deposits in general, their time and stratigraphic relationship to strata hosting VMS deposits in the main Flin Flon district of the Flin Flon Block to the west, or to the strata of the Hook Lake Block to the east, is uncertain, which justified their placement within undivided strata of Figure 5.2 and on the geological map of Simard et al. (2010). In order to assess potential stratigraphic correlations of the undivided strata hosting the Schist Lake and Mandy VMS deposits it is first necessary to examine the time, stratigraphic and structural relationship between the Flin Flon and Hook Lake Blocks.

Historically, the Cliff Lake Fault has been interpreted to separate strata of the Flin Flon Block from strata the Hook Lake Block, (Bailes and Syme 1989). Bailes and Syme
(1989) and Kremer and Simard (2007) described a surface exposure of the Cliff Lake fault located immediately east of Highway 10 and just south of the Flin Flon intersection. Here, Missi Group rocks located west of the fault and Hook Block volcanic rocks located east of the fault are "strongly foliated, mylonitised and hematised" and define a 15m wide shear zone that trends north-northwest and dips 65° to the east (Bailes and Syme, 1989; Kremer and Simard, 2007). Stauffer and Mukheijee (1971) interpreted the fault to have a minimum net slip of 1500m and to be a significant structure, as the Missi Group rocks are not found on the eastern side of the fault. Kremer and Simard (2007) also noted a similar dextral movement for the Cliff Lake fault and subsequent sinistral reactivation. Even though Bailes and Syme (1989) interpreted the Cliff Lake fault as a block bounding fault, they noted physical and compositional similarities of rocks within the Hook Lake and Flin Flon Blocks. Common features recognized by Bailes and Syme (1989) included: 1) large-scale intercalation of porphyritic and aphyric basalt flows; 2) pillow fragment breccia (including amoeboid breccia); 3) scoria-rich mafic tuff with similar bedforms; 4) similar geochemical characteristics; and 5) north-northwest trending folds. In addition, they also pointed out that glomeroporphyritic basalt flows in the Burley Lake area of the Flin Flon Block are "virtually identical" to basalt flows south of Hook Lake, and that these shared features suggest that volcanic rocks in both blocks were "parts of the same general volcanic sequence". Recent work by Kremer and Simard (2007) also noted that heterolithic basaltic volcaniclastic units and felsic volcanic rocks in their Western Hook Lake succession are similar to those of the VMS hosting Millrock member of the Flin Flon formation. However, it was the two U-Pb zircon ages (ID-TIMS) of 1903 +7/-5 Ma and 1903 +15/-12 Ma for Millrock member mine rhyolites in the Flin Flon Block, and a
single, but substantially younger age of 1886 +/- 1 Ma (U-Pb zircon) for the synvolcanic Cliff Lake tonalite of the Hook Lake Block that suggested that although the volcanic strata in the two blocks are similar, they are not time and therefore not stratigraphic equivalent (Stern et al., 1999). As strata hosting the Schist and Mandy deposits occur west of the Cliff Lake Fault, the VMS deposits were assumed by many workers to be part of the Flin Flon Block and perhaps the time and/or stratigraphic equivalent of the Flin Flon-Callinan and -777 VMS deposits (Kelly Gilmore, personal communication, 2008).

Recent work completed as part of the Flin Flon TGI3 program, including this study, has questioned some of the previous interpretations regarding the time and stratigraphic relationship between the Flin Flon and the Hook Lake Blocks described above. U-Pb zircon dating (ID-TIMS) by Rayner et al. (2010) has provided numerous and important new ages for volcanic strata and intrusions of the Flin Flon District. Rhyolite breccia and coherent rhyolite from the Millrock member at Millrock Hill and from the Flin Flon South Main shaft area yielded ages of 1888 +/- 2Ma and 1887 +/- 2Ma with several other interpreted stratigraphically equivalent rhyolites in the area yielding a similar 1888 Ma age (Rayner et al., 2010). The 1888 Ma age is a substantially younger age for the Flin Flon rhyolites (1903 Ma) than reported by Stern et al (1999) and although the reason for this older U-Pb age remains undetermined, it may represent an inherited zircon age as these apparently “older rhyolites” have pronounced negative εNd values (-3.7) as compared to other rhyolites in the Flin Flon Block (+3.6 to +5; Gibson personal communication, 2011). The 1888 Ma age for the Flin Flon formation rhyolites is similar to new U-Pb zircon ages obtained for a rhyolitic unit (1891 +/- 17Ma) and the quartz gabbro phase of the synvolcanic Cliff Lake pluton (1888 +/- 1Ma) within the Western
Hook Lake Block (Rayner et al., 2010). Although the U-Pb zircon age of a Western Hook Lake Block rhyolite is imprecise, the precise 1888 +/- 1 Ma (quartz-gabbro phase) and 1886 +/- 1 Ma (cognate xenolith) Ma ages for the synvolcanic Cliff Lake Pluton indicates that volcanic strata of the Western Hook Lake Block may be time-equivalent to volcanic strata of the Flin Flon Block. In addition, recent drilling by HudBay Minerals and the results of the TGI 3 seismic survey indicate that the dip of the Cliff Lake fault shallows with depth and that the Cliff Lake fault is a thrust fault, which, like many thrust faults within the Flin Flon Block (e.g., Flin Flon Lake and Railway faults), placed older volcanic strata on top of the younger Missi Group sedimentary rocks (Gibson et al., 2011, Lafrance et al., in press). The physical, and compositional similarities, and similar ages of volcanic strata of the Western Hook Lake succession and strata of the Flin Flon Block are consistent with an interpretation that the strata in both blocks are coeval, and, as originally proposed by Bailes and Syme (1989), may be part of the “same general volcanic sequence.” Furthermore, the Cliff Lake fault, although exhibiting significant movement, does not separate assemblages of different ages. However, lithostratigraphic correlations between the lithofacies in the Western Hook Lake succession and lithofacies within informal lithostratigraphic units in the Flin Flon Block, at this time, remain uncertain (Kremer and Simard, 2007; Simard and Creaser, 2007).

Thus, in consideration of the arguments presented above, it is reasonable to interpret the undivided strata, which host the Schist Lake and Mandy VMS deposits, to be part of the same “volcanic sequence” that comprises the Flin Flon and Western Hook Lake Blocks. However, the question remains as to whether the Schist and Mandy VMS
deposits are the time or lithostratigraphic equivalent of the Flin Flon, Callinan and 777 deposits?

If only volcanic strata west of the West Mandy Road fault of Simard et al (2010) are considered, previous interpretations by Bailes and Syme (1989), Simard and Creaser (2007), and the recent TGI 3 geological map (Simard et al., 2010), place the west-facing Upper Mafic Volcaniclastic unit, as defined and described herein, within the base of the Hidden formation, and along the east limb of the D2 Hidden Lake syncline. This interpretation is consistent with the geochemical data for the Upper Mafic Volcaniclastic unit and Hidden formation presented in Figure 5.4. This lithostratigraphic correlation between the Upper Mafic volcaniclastic unit and Hidden formation is significant as the latter constitutes the immediate hanging wall to VMS deposits within the Millrock member of the Flin Flon formation (Fig. 5.2).

That leaves the problem of determining what is the stratigraphic relationship between the Bedded Tuff and Middle and Lower mafic volcaniclastic units to the Upper Mafic Volcaniclastic unit, and therefore, to strata of the Flin Flon formation. The West and East splays of the Mandy Road fault, as shown by Simard et al. (2010), were interpreted to separate the Bedded Tuff unit from the Upper and Middle Mafic Volcaniclastic units. However, as discussed in Chapter 2 these faults are: 1) not observed at surface in the map area (exposed to the north) and, more importantly, were not recognised during re-logging of drill core from drill holes that penetrated these units and their contacts. In this regard it is important to note that all faults associated with significant or insignificant movement in the Flin Flon block are defined by metre-
metres-wide shear zones (Lafrance et al., accepted) and structures such as these would have been readily recognizable in drill core; and 2) offset along the West and East Mandy Road faults, based on the limited horizontal offset of the Missi Group sedimentary strata to the north, appears to be minimal (Chapter 2). Given these observations, a reasonable interpretation is that the contacts between the Upper Mafic Volcaniclastic, Bedded Tuff and Middle Mafic Volcaniclastic units are conformable, but are locally defined by faults with apparently limited movement. If correct, this interpretation suggests that the Bedded Tuff unit may correlate with the bedded tuff lithofacies at the top of the Millrock member and that the Middle Mafic Volcaniclastic unit may correlate with the mafic flow and volcaniclastic lithofacies within the Millrock member (Fig. 5.3). In stratigraphic correlations it is important to recognise that the lithofacies and even the composition of the lithofacies may differ between correlated units. For example, the basal units of the Hidden formation at Flin Flon are coherent mafic flows and sills, whereas immediately west of the Schist Lake and Mandy area, mafic volcaniclastic lithofacies (Upper Mafic volcaniclastic unit) comprise a significant portion of the basal units of the Hidden formation (Bailes and Syme, 1989, Simard and Creaser, 2007; Simard et al., 2010). For comparison, the trace element composition of the Bedded Tuff, Lower, Middle and Upper Mafic Volcaniclastic units are plotted along with average compositions of bedded tuff, mafic flows and volcaniclastic lithofacies from the Millrock member in Figures 5.4 to 5.8: there are no significant compositional differences between the two areas. However, previous researchers have noted that there is very little difference in the composition of volcanic lithofacies that comprise all of the rocks within the Flin Flon and Hook Lake Blocks. Thus, geochemical arguments to support lithostratigraphic correlations cannot be
used as conclusive evidence because of the lack of distinct characteristics between the Schist-Mandy lithofacies and those of the main Flin Flon district (Bailes and Syme, 1989, Simard and Creaser, 2007; Simard et al., 2010).

The Lower Mafic Volcaniclastic unit, which hosts the Schist Lake and Mandy VMS deposits, and the Middle Mafic Volcaniclastic unit are separated by the Mandy Road fault (Chapter 2). Although it is a significant shear zone at surface and in drill core, it is interpreted to merge to the north with the East and West Mandy Road faults and collectively they have not been demonstrated to significantly offset volcanic lithofacies (Bailes and Syme, 1989; Chapter 2). The lack of a significant demonstrable offset, plus the similarity between the mafic volcaniclastic lithofacies within each unit and their similar composition as indicated on binary and primitive mantle normalized diagrams (Figs. 5.6.-5.8) suggests they may represent the same unit repeated by faulting. This is only one interpretation, and without conclusive evidence of the amount of movement associated with the Mandy Fault, it must be regarded as tentative. However, assuming this interpretation is correct, it would place the Schist Lake and Mandy VMS deposits within mafic volcaniclastic lithofacies that are potentially the stratigraphic equivalent of those of the Millrock member that host the Flin Flon, Callinan and 777 VMS deposits.

5.2 Conclusions

1. The Schist Lake and Mandy VMS deposits are hosted by a quartz porphyry rhyolitic unit and localised sericite schist within a succession dominated by mafic volcaniclastic lithofacies of the Lower Mafic Volcaniclastic unit. The deposits are segmented by the Mandy Road fault, which also caused the “stretching and segmentation” of the sulphide
lenses. Alteration is typical of bimodal mafic VMS deposits, although surrounding the Schist Lake mine the alteration zone has been transposed to a near parallel to bedding attitude during deformation. The Schist Lake orebody is clearly recognised at surface using alteration indices, geochemistry, and modal mineralogy obtained from surface samples. Using these same alteration indices, elements and modal mineralogy two new areas with exploration potential, north of the Schist Lake deposit, were identified.

2. There are very little physical or compositional differences between the host rocks of the Schist Lake and Mandy VMS deposits to those of the Flin Flon camp and Western Hook Lake block, suggesting they may belong to the same volcanic succession.

3. The Mandy Road fault(s) may have had minimal offset and may not be major faults within the area. If this tentative interpretation is correct then stratigraphy across the faults, although locally repeated, is interpreted to be largely intact.

4. The Upper Mafic Volcaniclastic unit has been interpreted as the stratigraphic equivalent to the Hidden formation in the main Flin Flon district. Using the Hidden formation as a stratigraphic datum, and assuming minimal offset along the Mandy Road faults, the Bedded Tuff unit and Middle and Lower Mafic Volcaniclastic units could be interpreted as the stratigraphic equivalent of similar lithofacies within the Millrock member of the Flin Flon Formation.

5. The Schist Lake and Mandy VMS deposits may be hosted in volcanic strata that are the stratigraphic equivalent of strata hosting the Flin Flon, Callinan and 777 VMS deposits.
Figure 5.1. Map of the Schist Lake mine area. Circles represent prospective targets derived from the spatial distribution diagrams for the alteration minerals. See Figure 2.2 for the map legend.
Figure 5.2. Stratigraphic and structural relationship of the Flin Flon area to the Schist Lake and Mandy Mines area. Red box indicates area of focus. Simard et al. (2010).
MVU = mafic volcaniclastic unit

Figure 5.3. Simplified stratigraphic column illustrating interpreted correlations between undivided strata in the Schist lake and Mandy mines area with informally subdivided strata in the Flin Flon block. Figure modified from Bailes and Syme (1989).
Figure 5.4. Primitive mantle normalised multi-element diagram for the upper mafic volcaniclastic unit compared to the Hidden formation, reservoir member, from volcanic flows and volcaniclastic rocks (average of 35 samples). Shaded area shows the range of data. The data shows a very similar pattern for the Hidden formation samples, the only difference being a slightly lower abundance of La, Ce, Pr, Nd and SM. Primitive mantle values from Sun and McDonough (1989).
Figure 5.5. Primitive mantle normalised multi-element diagram for the Tuff unit compared with the bedded tuff of the Millrock member (average of 9 samples). Pink shading indicates range of bedded tuff data. Primitive mantle values from Sun and McDonough (1989).
Figure 5.6. Modified Winchester and Floyd (1977) classification diagram, by Pearce (1996), illustrating the lower and middle mafic volcaniclastic units and the Hidden formation, Reservoir member and Millrock member. Circles around the data for the Hidden formation, reservoir member, the Millrock member and the bedded tuff at the top of the Millrock member indicate ranges of data. Although the data do not overlap with the analysis provided by this project, most data lie within the basalt field and border on the andesite/basalt field.
Figure 5.7. TiO₂ vs: a) Zr; b) Nb; c) Y. Shaded areas represent the range in data. All data lie within the ranges provided by the data for the Hidden formation, Millrock member and the bedded tuff from the Millrock member. See Figure 5.6 for symbol key.
Figure 5.8. Primitive Mantle normalised mult-element diagrams for the lower and middle mafic volcaniclastic units compared with the Millrock member (average of 50 samples). Shaded area represents range in data for the Millrock member, where it can be seen that all data lie within the range for the Millrock member of the Flin Flon formation. See figure 5.6 for the symbol key. PM values from Sun and McDonough (1989).
References


Bhatia, M.R. and Crook, K.A.W. 1986: Trace element characteristics of greywackes and
tectonic setting discrimination of sedimentary basins. Contributions to Mineralogy
and Petrology, v. 92, p181-193.

1957: Schist Lake Mine; in Structural Geology of Canadian Ore Deposits, G.
258–262.

Cole, E.M., Gibson, H.L. and Lafrance, B. 2007: Preliminary description of the
lithofacies and structure of the Schist Lake mine area, Flin Flon, Manitoba (part of
NTS 63K12) in Report of Activities 2007, Manitoba Science, Technology,

Lake mine area, Flin Flon, Manitoba (part of NTS 63K12); in Report of Activities

Paleoproterozoic arc-continent to continent-continent collisional zone, Trans-
Hudson Orogen, from geological and seismic reflection studies. Canadian Journal

Corrigan, D., Galley, A.G. and Pehrsson, S. 2007: Tectonic evolution and metallogeny of
the southwestern Trans-Hudson Orogen; in Mineral Deposits of Canada: A
Synthesis of Major Deposit-Types, District Metallogeny, The Evolution of
Geological Provinces, and Exploration Methods, W.D. Goodfellow (ed.),
Geological Association of Canada, Mineral Deposits Division, Special
Publication 5, p. 881–902.

Cotter, D. 1969: Proposals for future exploration at Schist Lake Mine; Hudson Bay
Exploration and Development Co. Ltd., internal report.

1990. U–Pb sphene/zircon geochronological investigations. In Summary of
-4, pp. 54–57.

Devine, C.A., Gibson, H.L., Bailes, A.H., MacLachlan, K., Gilmore, K. and Galley, A.G.
2002: Stratigraphy of volcanogenic massive sulphide-hosting volcanic and
volcaniclastic rocks of the Flin Flon formation, Flin Flon (NTS 63K12 and 13),

Devine, C.A. 2003: Origin and emplacement of volcanogenic massive sulfide-hosting,
Paleoproterozoic volcaniclastic and effusive rocks within the Flin Flon subsidence
structure, Manitoba and Saskatchewan, Canada. Laurentian University,

DeWolfe, Y.M. and Gibson, H.L. 2004: Physical description of the 1920 member,
Hidden formation, Flin Flon, Manitoba (NTS 63K16SW). In Report of Activities


DeWolfe, Y.M. 2010. Description of the megabreccias and other evidence for subsidence and vent proximity in the Schist Lake-Mandy mines area, Flin Flon, west-central


Hanson, G. 1920: Some Canadian occurrences of pyritic deposits in metamorphic rocks. Journal unknown.


Saeki, Y. and Date, J. 1980: Computer application to the alteration data of the footwall dacite lava at the Ezuri kuroko deposits, Akita Prefecture. Mining Geology, v. 30, p241-250.


Simard, R-L. and MacLachlan, K. 2009: Highlights of the new 1:10 000 scale geology map of the Flin Flon area, Manitoba and Saskatchewan Manitoba Science, Technology, Energy and Mines, Manitoba Geological Survey (part of NTS 63K12, 13).


Appendix 1

Drill Core Logs for the Schist Lake and Mandy Mines Area
Lithofacies key

- Felsic intrusion
- Mafic intrusion
- Diorite
- Felsic coherent
- Felsic volcaniclastic
- Argillite
- Mafic volcaniclastic with quartz eye clasts
- Mafic tuff
- Feldspar porphyritic mafic volcaniclastic
- Mafic volcaniclastic
- Mafic coherent
- Pillowed flow
The following appendices can be found in separate documents provided with this thesis:

Appendix 2: Detection Limits for Geochemical Whole Rock Major & Trace Element Analyses

(From Acme Labs Schedule of Services and Fees 2008)

Appendix 3: Excel spreadsheet containing all geochemical data obtained for this project.