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**Evidence for voluminous, bimodal pyroclastic volcanism, during rifting of a
Paleoproterozoic Arc at Snow Lake, Manitoba**

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Abstract

The thrust bounded McLeod Road - Birch Lake sequence (MB sequence) occurs within the Paleoproterozoic Snow Lake arc assemblage (SLA) of the Flin Flon Belt. Stratigraphic correlation of volcanic strata of the MB sequence with strata of the thrust bounded Chisel sequence, indicates that distinctive, submarine, eruption-fed, pyroclastic flow deposits are more extensive and voluminous than previously recognized ($>10 \text{ km}^3$). These voluminous felsic pyroclastic deposits define a distinct magmatic and explosive volcanic event during bimodal volcanism that accompanied rifting of the Snow Lake arc. The felsic pyroclastic deposits define the remnants of a basin, or of nested basins, that formed during arc rifting and subsidence, and their eruption immediately preceded formation of the Chisel sequence volcanogenic massive sulfide (VMS) deposits. Although the Chisel sequence ore interval is recognized in the MB sequence, the lack of VMS-related alteration indicates that VMS hydrothermal activity was restricted to the Chisel portion of the basin. However, the MB sequence is host to the younger Snow Lake gold mine, a 1.4M oz. (43,699kg) gold producer. The overlying MORB-like Birch Lake Basalts, if conformable with the MB sequence, may represent a progression from a rifted-arc to a back-arc setting, however if thrust fault bounded they may represent the initial phases of arc-rifting, prior to the voluminous felsic pyroclastic eruptions. Correlation and integrity of stratigraphy between the thrust bounded MB and the SLA sequences indicates that the bounding thrust faults, which developed during accretionary processes, have less regional significance than previously interpreted.

Key words

Snow Lake Arc assemblage

Flin Flon belt

Explosive submarine felsic volcanism

Rifting

VMS deposits

Introduction

The Snow Lake area is located within the eastern portion of the Flin Flon belt of northern Manitoba (Fig. 1), which lies in the southeastern portion of the Reindeer Zone of the Trans Hudson Orogen. The Paleoproterozoic Flin Flon belt is renowned for its base metal endowment and contains 29 volcanogenic massive sulphide (VMS) deposits (Bailes et al. 2013). The VMS deposits at Snow Lake occur in volcanic rocks of the SLA, which is host to 8 past -producing and 2 producing base metal mines (Fig. 2) (Stern et al. 1995a; Lucas et al. 1996; Bailes and Galley 1999). The SLA assemblage is divisible into three submarine volcanic sequences, which are interpreted to define an evolution from a primitive arc (Anderson sequence) to a mature arc (Chisel sequence) to an evolved arc-rift environment (Snow Creek sequence; Bailes and Galley 1996; Bailes 1997; Bailes and Schledewitz 1998) (Fig. 2).

Strata within a thrust bounded panel, which lies to the north of the SLA is herein named the McLeod Road – Birch Lake (MB) sequence (Fig. 2). It was interpreted as a homoclinal, north-facing sequence of mafic and felsic volcanic and volcanoclastic rocks, with no identified internal stratigraphy (Bailes and Schledewitz 1998; Bailes and Galley 1999), bound to the south by the McLeod Road Thrust, and to the north by the Birch Lake fault (Fig. 3). The MB sequence has no known VMS deposits, but is host to four structurally controlled gold deposits located along stratigraphic contacts at the intersection of a fault and fold hinge in the hanging wall of the McLeod Road Thrust (Fig. 3). The largest gold deposit, the Nor-Acme, of the New Britannia Mine (renamed the Snow Lake Mine by QMX Gold Corporation in 2012), produced 1,404,950 oz. gold (43,699 kg) between 1949–1958 and 1995–2005 (Beaumont Smith and Lavigne 2008) (Fig. 2).

The structural geology of the MB sequence, regional structural history of the Snow Lake area and geochemistry of the SLA volcanic rocks, have been studied by numerous researchers (Harrison 1949, Hogg 1957; Russell 1957; Froese and Moore 1980; Bailes 1980; Bailes and Galley 1996, 1999; Bailes and Schledewitz 1998; Kraus 1998; Kraus and Williams 1999; Ansdell 2005; Connors 1996; and Zwanzig 1999; Beaumont-Smith and Gagné 2008). The setting and geological controls on gold mineralization at the Nor-Acme and associated deposits have been described by Hogg (1957), Galley et al. (1986, 1988, 1991); Fieldhouse (1999), Fulton (1999), Gale (2002), Beaumont-Smith and Lavigne (2008), and Gagné (2009).

A stratigraphy for the MB sequence has not been defined; however, Bailes and Schledewitz (1998), based on geochemical and lithological data, interpreted the MB sequence to be correlative with the Upper Chisel, and Snow Creek sequences of the SLA. They interpreted the MB sequence to comprise discontinuous lenses of mafic and felsic lavas, and volcanoclastic rocks, that lacked an internal stratigraphy, and the potential for VMS deposits was not discussed.

In this paper we: 1) present a new informal stratigraphy for the MB sequence, and provide evidence for previously unreported, voluminous submarine felsic and mafic explosive volcanism, and arguments for concomitant synvolcanic subsidence; 2) present a new lithostratigraphic correlation with strata of the Lower and Upper Chisel and Snow Creek sequences of the SLA and discuss implications for voluminous explosive eruptions that may link the thrust-bounded Chisel and MB sequences; and 3) discuss structural implications of the proposed correlation on accretionary processes.

Regional Geology

The Flin Flon Belt, which is in the internides of the Paleoproterozoic Trans Hudson Orogen represents a broad collision zone that formed during the closure of the Manikewan

Ocean and ultimate formation of Laurentia (Hoffman 1988; Lucas et al. 1996). The Flin Flon Belt is bounded to the north by the Kiseeynew Domain, and south by a Phanerozoic cover sequence. The Pikwitonei Granulite belt and the Superior Craton lie to the east and to the west lies the Rottenstone Domain, Wollaston fold belt and the Hearne Craton. The depositional setting of the Flin Flon Belt has been interpreted as a submarine environment, based on the remnants of ocean floor and island arc assemblages (ca. 1.9 Ga) that differ in geochemistry, metamorphic grade and structural history (Lucas et al. 1996; Syme et al. 1996). From east to west these are: - the SLA, the Amisk Collage, and the Hanson Lake Block (Lucas et al. 1996; Connors et al. 2002; Ansdell 2005). The younger metasedimentary rocks of the Kiseeynew domain (ca. 1.86 – 1.84 Ga) are interleaved with the volcanic assemblages which were intruded by synvolcanic intrusions (ca. 1.89 – 1.88 Ga). The volcanic assemblages and the younger metasedimentary rocks were intruded by later felsic plutons at ca 1.84 - 1.83 (Lucas et al. 1994; Stern et al. 1995a; Bailes and Galley 1996; David et al. 1996; Lucas et al. 1996; Connors 1996; Connors et al. 1999, 2002) (Fig. 1).

The Flin Flon Belt is interpreted to have formed in four stages: 1) formation of submarine arc and ocean floor assemblages at ca. 1.92 – 1.88 Ga, 2) intra-oceanic accretion at ca. 1.88–1.87 Ga, 3) ca. 1.87 – 1.84 Ga formation of submarine and subaerial inter - arc basins and successor arc plutons with deposition of the metasedimentary rocks of the Kiseeynew domain, including the ca. 1.86 – 1.84 Ga Burntwood turbidites (Bailes 1980; Zwanzig 1990; David et al. 1996) and the ca. 1.85 – 1.83 Ga alluvial - fluvial sandstones of the Missi Group, (Ansdell and Connors 1995; Connors et al. 2002), and 4) terminal collision in the Trans Hudson Orogen at ca. 1.84–1.81 Ga (Lewry and Collerson 1990; Stern et al. 1995a; Lucas et al. 1996, Ansdell 2005). VMS deposits are interpreted to have formed during rifting of arc assemblages during stages 1 and 2 (Galley et al. 2007; Pehrsson et al. 2016) and gold deposits are interpreted to be pre (Fieldhouse 1999) – syn (Beaumont – Smith and

Lavigne 2008) or post Stage 4 (Galley et al. 1988; 1991).

In the Amisk Collage, older crust is preserved as thrust-imbricated slices interleaved with juvenile arc and back-arc crust (David et al. 1996; Lucas et al. 1996, Syme et al. 1999). In the SLA there is a higher proportion of Archean crustal slices compared to the Amisk Collage, as demonstrated by ϵNd values that range from -0.4 to +2.4 for mafic volcanic rocks (Stern et al. 1992), and a U-Pb age of 2.65 to 2.82 Ga for inherited zircons in a 1.892 Ga rhyolitic breccia (David et al. 1996; Syme et al. 1999).

Juvenile, submarine arc assemblages (ca. 1.9 Ga) of the SLA are intruded by the Richards Lake and Sneath Lake synvolcanic intrusions 1.89 – 1.88 Ga (David et al. 1996), and younger felsic plutons at ca 1.84 - 1.83 Ga (Connors 1996; David et al. 1996). The SLA is dominated by 1.84–1.81 Ga fold-thrust-style tectonics, and is interpreted to have been thrust over the Amisk Collage along the Morton Lake fault (Syme et al. 1995; Connors 1996, David et al. 1996; Ansdell et al. 1999; Zwanzig 1999; Bailes and Galley 1999). Late during this event at ca. 1.82 – 1.81 Ga (Froese and Moore 1980; David et al. 1996), the SLA underwent peak lower to middle almandine - amphibolite facies conditions with temperatures and pressures in the range 500 – 700 °C and 4-6 kbar, respectively (Zaleski et al. 1991; Menard and Gordon 1995; Kraus and Menard 1997).

Terminology

The term volcanoclastic is a descriptive term that refers to rocks composed primarily of volcanic components including lithic and vitric fragments and crystals and may encompass primary autoclastic, pyroclastic, and sedimentary deposits as originally defined by Fisher (1961). In interpreting volcanoclastic rocks, the term “primary” refers to a deposit that formed directly from an explosive eruption or is an in situ deposit produced through fragmentation (i.e. quench fragmentation - hyaloclastite) (Fisher, 1961; Gibson et al. 1999). Syneruptive, as defined by McPhie and Allen (2003) includes

deposits where primary clasts were transported and deposited following initial fragmentation (pyroclastic or autoclastic) and deposition; essentially primary deposits that were resedimented. However, it is often difficult to differentiate primary volcanoclastic deposits from syneruptive deposits, especially in ancient volcanic successions where the rocks have undergone significant alteration, metamorphism and deformation (Cas et al. 1990; Cas and Wright 1991; Kano et al. 1996; Gibson et al. 1999; Kano 2003; McPhie and Allen 2003; Allen and McPhie 2000, 2009; White 2000; White et al. 2003; Jutzeler et al. 2014). Recognizing these difficulties, the granulometric terminology proposed by Fisher (1961), based on the size and percentage of fragments and crystals, is used herein in a non-genetic sense to classify volcanoclastic deposits as proposed by Gibson et al. (1999), Busby et al. (2003) and White and Houghton (2006). In this terminology tuff represents a particle size of <2mm, lapilli 2-64mm, and blocks and bombs >64mm.

The term “unit” is used herein as an informal, mappable stratigraphic unit comprised of one or more depositional units that share distinct internal structures, textures or compositions that distinguishes them from bounding units. Lithofacies is an informal stratigraphic unit that has characteristic lithologic features (i.e. rock type).

Stratigraphy and Lithofacies of the McLeod Road – Birch Lake sequence

The MB sequence (Rubingh 2011, Rubingh et al. 2012a, b) which has been metamorphosed to amphibolite facies, contains 5 distinct lithostratigraphic units (Figs. 3, 4), with typical features of the units illustrated in (Figs. 5a – e). It is intruded by four mafic and two felsic intrusions, which are not described herein. The units are repeated by two bedding-parallel thrust faults, which subdivide the MB sequence into 3 structural panels (Rubingh et al. 2012a, b, Rubingh et al. 2013). The location of the lower thrust fault (Fig. 3) is inferred

by the juxtaposition of unit 1 above younger unit 3. The upper thrust fault, called the Bounter Fault (Fig. 3) is associated with gold occurrences (Hogg 1957). It repeats units 1, 2 and 3. The latter is locally marked by a single, aphyric felsic sill.

Unit 1: Heterolithic felsic volcanoclastic lithofacies

Lithology and Distribution

Unit 1 is repeated in all structural panels (Fig. 3) its maximum thickness is 450 m and its strike length is continuous for 3.5 km. The unit weathers to an orange/grey colour and is pale pink to pale yellow on fresh surface. It consists of heterolithic, plagioclase-porphyritic and lesser quartz-porphyritic felsic volcanoclastic rocks with distinctive, dark wispy fragments (Fig. 5a). The 4 volcanoclastic lithofacies are grouped as a single unit because they share the distinctive dark wispy fragments (Fig. 5a). The 4 volcanoclastic lithofacies are further subdivided into 13 depositional units based on bedforms and components (i.e. fragments, tuff, crystals), as described below, and as shown in Figure 4.

Lithofacies 1.1: Heterolithic volcanoclastic lithofacies with dominantly dark wispy fragments

Lithofacies 1.1 ranges from 110 to 410 meters in thickness along a strike length of 3.5 kilometers (Fig. 3). Round epidotized alteration patches are a common feature throughout this lithofacies. Its lower contact is sharp and in contact with a felsic intrusion. It comprises 6 depositional units (1a-1f) (Fig. 4), which have thicknesses of 25 to 45 meters.

Depositional units are defined by normal grading of mafic lithic and dark wispy fragments, and by an increase in fine tuff (ash sized component), which occurs towards the top of some beds (1c and 1d, Fig. 4). The components, in variable amounts, comprising each of the depositional units are; i) tuff (< 2mm), ii) intact and broken plagioclase crystals (1 to 2 mm), iii) dark wispy fragments, iv) mafic lithic fragments, and v) plagioclase-porphyritic felsic fragments.

In the massive, block-rich base of depositional units, matrix tuff constitutes from 25 to 45% and it increases to greater than 60% in the upper portion of the depositional units, with units 1c and 1d (Fig. 4) having upper portions composed only of tuff over 2 meter intervals. The crystal content ranges from 5–12% feldspar and averages 8%. Dark wispy fragments (Fig. 5a) range in abundance from 10 – 45%, and consist entirely of biotite. The wispy fragments are markedly elongate (up to 15 cm min size), have length to width ratios of 15 to 1, and have irregular curved margins; in some only a relict ghost wispy dark outline remains. The wispy fragments are reversely graded in the upper, finer-grained portion of depositional units 1a, 1b, and 1d (Fig. 4).

Mafic lithic fragments consist of biotite and hornblende. They vary in size from 5 cm to 30 cm and in abundance from 0 - 20%. They do not show the same degree of elongation common to the dark wispy fragments, and have a blocky, angular appearance (Fig. 5a).

Plagioclase-porphyritic felsic fragments in depositional unit 1f (Fig. 4) range in size from 3 to 7cm, are typically densely packed and framework supported (Fig. 4). The fragments are ellipsoid in shape, but do not exhibit the same degree of elongation as the dark wispy fragments.

Lithofacies 1.2: Heterolithic volcanoclastic lithofacies with dominantly quartz and feldspar – porphyritic rhyolite breccias

Lithofacies 1.2 comprises 3 depositional units (h-j) (Fig. 4), ranges in thickness from 20 to 150 meters, and is continuous along strike for 3.0 kilometers. This lithofacies is dominated by a monomictic, coarse, framework supported, angular to subangular monolithic quartz and feldspar-porphyritic rhyolite breccia that is crudely bedded; the matrix tuff component ranges from 20 - 40 % in abundance. Fragments range from 20 – 60 cm in size and contain 8–15% quartz and 8–15% plagioclase feldspar crystals that are

up to 10mm in size (Fig. 5b). Some beds contain dark wispy fragments, as described for lithofacies 1.1; however, the abundance of the dark wispy fragments is less than 15% and they are not observed in the densely packed fragment supported beds. The lower contact of this lithofacies was not observed.

Lithofacies 1.3: Heterolithic volcanoclastic lithofacies

Lithofacies 1.3 is 25 m thick, and comprises two depositional units (1k-l; Fig.4).

Depositional unit 1k is massive, contains plagioclase- and quartz-porphyritic felsic fragments (25 – 40%), and plagioclase crystals (5-8%). Depositional unit 1l (Fig. 4), has plagioclase- and quartz-porphyritic fragments (50-60%), is framework supported, and contains plagioclase crystals (5-8%). The matrix tuff comprises up to 45% of both depositional units. The lower contact of lithofacies 1.3 is sharp and defined by a 30 cm thick bed of fine (<1/16mm) tuff.

Lithofacies 1.4: Monolithic quartz and feldspar-porphyritic volcanoclastic lithofacies

Lithofacies 1.4 is a single depositional unit that is framework supported, and contains 60-65% subangular quartz- and feldspar-porphyritic fragments in a fine tuff matrix (25%) containing plagioclase and quartz crystals (10-15 %). The lower contact of lithofacies 1.4 is not exposed.

Unit 2: Felsic lavas and volcanoclastic lithofacies

Lithology and distribution

This unit is repeated in 2 structural panels within the MB sequence (Fig. 3). It is continuous along strike for 3.7 kilometers and changes in thickness from 80 to 110 m. It comprises two, lithofacies: a lesser felsic volcanoclastic lithofacies (lithofacies 2.1), which defines depositional unit 2a and a plagioclase-porphyritic (1–5%) coherent felsic lithofacies (lithofacies 2.2), which defines 3 depositional units (2b – 2d) (Fig. 4). The unit weathers to a dark orange to grey color and is salmon pink to orange on fresh surfaces. The felsic groundmass contains 50-60 % quartz, 15 % feldspar, 3-5 % garnet, 5-8% biotite, 3-8% white

mica.

Lithofacies 2.1: Felsic volcanoclastic lithofacies

The felsic lapillistone to lapilli tuffs contain quartz and feldspar-porphyritic felsic fragments that are similar to unit 1, lithofacies 1.4 and range in size from 2 to 5 cm. The lithofacies is crudely bedded, beds are matrix supported, and the matrix contains 10% feldspar crystals.

The lower contacts with lithofacies 1.4 are not observed. At one locality, densely packed, jigsaw fit angular fragments and a fine, well bedded tuff (10cm thick), occur near the contact.

Lithofacies 2.2: Plagioclase-porphyritic rhyolitic lava

The coherent lithofacies contains lobe-like forms of massive rhyolite defined by a massive interior and margins that display a lobe-parallel “flow foliation” outlined by the alignment of biotite. The flow foliation imparts a banded appearance with bands 0.5-1.5 cm wide. The lobe margins grade into a breccia containing fragments identical to coherent rhyolite. The gradation is marked by in situ or jigsaw fit fragments that grade inwards into a massive coherent lobe and outwards into clast rotated breccia in contact with the lobes (Fig. 5c).

Unit 3: Mafic volcanic and volcanoclastic lithofacies

Lithology and distribution

Unit 3 is continuous along strike for 3.5 kilometers (Fig. 3) and ranges in thickness from 40 to 250 meters. It weathers to a dark green to grey green / black colour and is green/ grey on fresh surface. The dominant lithofacies include: well-bedded, heterolithic, lapilli tuff, lapillistone to tuff breccia and lesser plagioclase-porphyritic pillowed lavas. Fragments are lapilli and block size, and fragment types include aphyric to plagioclase-porphyritic mafic, aphyric to plagioclase-porphyritic felsic, scoriaceous mafic, and plagioclase- and pyroxene-porphyritic mafic fragments. The matrix contains 50 –55% hornblende, 35 –40% plagioclase feldspar, 10 – 15% quartz, 5 – 8 % chlorite, 3 – 5% biotite, and 1% white mica. The unit is subdivided into seven lithofacies, which are, in turn divisible into 17 depositional units

defined by changes in lithofacies (Fig. 4).

Lithofacies 3.1: Mafic tuff lithofacies

Lithofacies 3.1 comprises depositional unit 3a (Fig. 4), ranges in thickness from 0 – 30 meters, and extends along strike for 1 kilometer. It consists of mafic tuff to lapilli tuff containing plagioclase and up to 5% hornblende crystals, the latter are all after pyroxene (1 – 3mm in size). The lower contact with unit 2 is not observed.

Lithofacies 3.2: Heterolithic volcanoclastic lithofacies with scoriaceous fragments

Lithofacies 2 comprises 4 depositional units (3b – e; Fig. 4), ranges in thickness from 5–80 m, has a 3 kilometers strike length, and consists of well bedded, heterolithic lapillistone and tuff breccia, with lesser scoriaceous mafic fragments. It is intruded by basaltic sills. The rocks are framework- to matrix- supported, contain subangular to subrounded fragments of rhyolite (aphyric to feldspar-porphyritic) and subrounded mafic scoriaceous fragments (0.5 – 25 cm in size) in a finer, mafic tuff matrix containing <5% plagioclase crystals. Fragment elongation is approximately 6:1. Lapillistone beds are massive and moderately well bedded, 8 to 50 cm in thickness, as defined by changes in clast size and a decrease in the proportion of fragments to matrix towards the top of beds. Normal grading is common and indicates a consistent younging direction to the north. The lower contact with lithofacies 3.1 mafic tuffs is sharp.

Lithofacies 3.3: Plagioclase-porphyritic pillowed lithofacies

Lithofacies 3.3 is characterized by plagioclase-porphyritic pillow lava of depositional units 3f and 3k (Fig. 4). The pillow lavas range in thickness from 3–56 m over a strike length of 3 kilometers, and consist of densely packed pillows (Fig. 5d) with narrow thin aphanitic selvages. The pillows contain plagioclase (10%) and amphibole after pyroxene (10%) phenocrysts, and up to 25 % amygdules, which range in size from 0.3 to 1.5 cm and are located in the center and top of the pillows. The lower contact was not observed.

Lithofacies 3.4: Well-bedded, crystal-rich mafic volcanoclastic lithofacies

Lithofacies 3.4 consists of mafic, plagioclase and amphibole after pyroxene crystal-rich (35 – 50 %; 1-3mm), well-bedded, crystal and crystal lapilli tuff and comprises depositional units 3g-i (Fig. 4). It ranges in thickness from 5 to 24 meters over a strike length of 3 kilometers. Beds are 0.3 to 1.5 meters thick. Normal grading is common, and thin beds of fine felsic tuff separate individual crystal-rich lapilli tuff beds; cross bedding within crystal rich beds was observed. The lower contact is not exposed.

Lithofacies 3.5: Monolithic scoriaceous bomb lithofacies

Lithofacies 3.5 is a framework- to matrix-supported, monolithic, scoriaceous breccia that comprises depositional unit 3j (Fig. 4). It has a strike length of 1 kilometer and a thickness of 4 to 10 meters. The breccia is monolithic and contains mafic, scoriaceous bombs (5% abundance) and scoriaceous clasts (40-45% abundance) within an amphibole after pyroxene –feldspar crystal rich (35 –40%) tuff matrix. The scoriaceous bombs (Figs. 6 a, b) are elliptical in shape and some display asymmetric tails. They contain 10-15% quartz and feldspar-filled amygdules, of which the coarser amygdules are distributed towards the center of the bombs and finer amygdules are localized towards the rims. The bombs which have intact chilled margins, indicate depression into the underlying beds, and the beds are locally reverse graded. Beds of tuff, 15 cm thick, with sharp contacts occur intermittently throughout this lithofacies. The lower contact is sharp and defined by a tuff bed, which is 15 cm thick.

Lithofacies 3.6: Dominantly felsic heterolithic volcanoclastic lithofacies

Lithofacies 3.6 is continuous along strike for 3 kilometers, ranges in thickness from 6–27 meters, and comprises depositional units 3l – n (Fig. 4). The lapillistone and tuff breccia are framework to matrix supported, and contain subangular to subrounded fragments of plagioclase-porphyritic rhyolite, mafic scoria and rare basaltic fragments in a pyroxene –

feldspar crystal-rich (35–45 %) matrix. Rhyolite fragments (2–40 cm) dominate and some subangular fragments exhibit jigsaw fit fractures. The rhyolite fragments contain 5% quartz-filled amygdules and 10% plagioclase phenocrysts. Mafic fragments (aphyric basalt and mafic scoria) comprise 3–5% of the fragment population; the fragments have a strong lineation, which is more pronounced than the foliation in the rock. Round epidote alteration patches up to 5 cm in diameter occur locally throughout the unit. Mafic bombs up to 30 cm in size constitute 5% of the breccia. These mafic bombs are similar to those observed and illustrated in the Threehouse basalts of the SLA, as subsequently described and compared to Unit 3 of the MB sequence. The bed thickness ranges from 0.5 to 2 meters, where grading of beds is defined by variations in clast size; and the beds are normally graded. The lower contact is sharp.

Lithofacies 3.7: Dominantly mafic heterolithic volcanoclastic lithofacies

Lithofacies 3.7 has a strike length of 3 kilometers, ranges in thickness from 8 to 25 meters, and comprises depositional units 3o – q (Fig. 4). It consists of lapillistone with subrounded fragments of; i) fine-grained basalt, ii) plagioclase-porphyritic basalt, iii) aphyric basalt, iv) scoriaceous basalt, v) plagioclase-porphyritic rhyolite, and vi) aphyric rhyolite; 15% of the fragments (2–10 cm in size) are felsic. The fragments occur within a pyroxene–feldspar crystal rich (35–40%) tuff matrix. Graded beds, defined by variations in fragment size, range in thickness from 1 to 2 meters. The lower contact is gradational, as defined by a decrease in the percentage of felsic rhyolite fragments and an increase in the percentage of mafic fragments.

Unit 4: Felsic lava lithofacies

Lithology and distribution

Unit 4 is a massive, aphyric, aphanitic coherent rhyolite (Figs. 4, 5e). The rhyolite ranges from 110 to 155 meters in thickness over a 4 kilometers strike length (Fig. 3). It weathers a

dark grey to orange, and is salmon pink to light grey/white on fresh surfaces. The groundmass contains 60-70 % quartz, 5-10% feldspar, 10 % garnet, 5-8% biotite and 3-8% white mica. This rhyolite has a well-developed, spaced disjunctive cleavage defined by biotite, and a mineral stretching lineation defined by quartz, feldspar and garnet (Fig. 5e). A characteristic feature of the rhyolite is well-developed lobes that have a banded appearance along their margins reflecting different biotite content (Fig. 5f). The lobes are mantled by breccia containing fragments that are identical to coherent rhyolite. The rhyolite displays columnar jointing and contains rare quartz-filled amygdules (2 to 5 mm). The lower contact of the coherent rhyolite unit with mafic volcanoclastic rocks of unit 3, lithofacies 3.7, is sharp and highly strained.

Unit 5: Mafic volcanoclastic and lava lithofacies

Lithology and distribution

Unit 5 comprises mafic volcanoclastic and lava lithofacies, which comprise depositional units 5a and 5b, respectively (Fig. 4). It ranges from 45 to 90 meters in thickness over a 4 kilometer strike length). Unit 5 weathers to a dark black / brown to dark green and dark green on fresh surfaces. The groundmass comprises 55-60% hornblende, 20-25% feldspar, 5-7% biotite, 5% quartz, 5% chlorite, and 3 - 5% white mica.

Lithofacies 5.1: Mafic volcanoclastic lithofacies

The distinguishing characteristic of this unit are coarse relict pyroxene crystals, replaced by amphibole, ranging in size from 0.5 to 1 cm (Fig. 5g). The unit consist of lapillistone and tuff breccia, which are distinct from mafic volcanoclastic rocks of unit 1 by their crystal-rich matrix of pyroxene and plagioclase and monolithic fragments of similar mineralogy and composition. The lower contact with the underlying coherent rhyolitic lavas (unit 5) is sharp and highly strained.

Lithofacies 5.2: Mafic lava Lithofacies

Pyroxene-plagioclase–porphyritic mafic lava (Fig. 5h) conformably overlies the crystal-rich, mafic pyroxene-plagioclase volcanoclastic lithofacies. The pillowed and massive lavas contain large (5 -10mm) pyroxene phenocrysts, replaced by amphibole. The pillows have thin selvages.

Geochemistry of the McLeod Road Birch Lake sequence

Samples collected are representative of all the stratigraphic units established during mapping. Forty-nine representative samples were selected for petrography, from which a subset of samples were submitted for geochemical and isotope analysis. Samples selected for geochemical analysis were carefully chosen to be i) free from significant alteration and ii) as homogeneous as possible. Samples submitted did not contain cracks, veins or voids. Where volcanoclastic rocks contained felsic and mafic clasts, areas within the units dominated by one of the clasts types were sampled.

Analytical techniques

Sample preparation was completed at the Ontario Geoscience Laboratories (Geoscience Laboratory), Sudbury, Ontario. The samples were crushed using mild steel, and pulverized using an agate ball mill, to reduce contamination by Cr, Fe and Al, although minor Si may be added to the sample. A closed beaker multi acid digest method, was used to achieve total dissolution. Major elements were determined by wavelength dispersive X ray fluorescence (XRF) spectrometry, on fused disks, with a borate flux, at the Geoscience Laboratory, and one sample batch was analyzed at Activation Laboratories. Analysis of minor and trace elements for all samples was performed using Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) at the Geoscience Laboratory. The analytical procedures and quality assurance and quality control (QA/QC) used at the Geoscience Laboratory, are discussed in Burnham (2008).

Quality assurance and quality control

Accuracy was measured using international standards SY-4, BHVO-2, GSD-11, AGV-2 and NCS DC73304 (GBW 07106) at the Geoscience and Activation Laboratories, respectively. The majority of major, and trace elements analyzed from either laboratory are accurate to +/- 10%. The exceptions are Li, Rb, Ta, Nb, which are accurate within the range of >10% - <20%, and MgO, P₂O₅, and Sb which are accurate within the range of 20% to 23%. Na₂O is accurate to <48%.

Precision was measured by comparing duplicate analysis of a submitted sample that was powdered and then the powder re analyzed. The relative precision is better than 10%, for all major and minor elements, except for Sn, Mo, Cd, and V, which are precise within the range of 10 % to 20%, BaO, Bi and P₂O₅, which are precise within the range 20% to 48% and Cr₂O₃ which has a precision of <84%. LOI has a precision of <5%, however one analysis has a precision of 37.2%.

Isotope geochemistry

Neodymium isotopic geochemistry was completed at the Pacific Centre for Isotopic and Geochemical Research (PCIGR), Department of Earth, Ocean and Atmospheric Sciences, the University of British Columbia, Vancouver, B.C. Samples were analyzed using a Nu1700 and a Nu Plasma MC-ICP-MS according to procedures outlined in Weiss et al. (2006). The reference materials G-3, JB-3, and Kil93, yielded ¹⁴³Nd/¹⁴⁴Nd ratios of 0.512244 (± 0.000006), 0.513069 (± 0.000006), and 0.512977(± 0.000006) respectively at 2 sigma deviation. The precision and the accuracy of Nd isotopic analyses were established relative to the JNdi-1 standard (Tanaka et al. 2000), and the Rennes standard, which have true values of ¹⁴³Nd/¹⁴⁴Nd = 0.512116 and an average value of ¹⁴³Nd/¹⁴⁴Nd of 0.512117 (n=15) +/- 0.000011 and ¹⁴³Nd/¹⁴⁴Nd 0.512051 (n=15) +/- 0.000020 (2SD). Neodymium isotopic compositions are normalized to ¹⁴⁶Nd/¹⁴⁴Nd = 0.7219, and initial epsilon (ε) Nd values are reported relative to a chondritic uniform reservoir (CHUR) with

present-day values of $^{147}\text{Sm}/^{144}\text{Nd} = 0.1967$ (Jacobsen and Wasserburg 1980) and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512638$ (Goldstein et al. 1984). Initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios and ϵNd values were calculated at 1890 Ma, which is the assumed age of all reported samples in the Snow Lake area (Stern et al. 1992).

Lead isotopic geochemistry was also performed at the PCIGR. Pb isotopes were measured using a multiple collector inductively-coupled plasma mass spectrometer (MC-ICP-MS). Each isotope ratio of Pb (208, 207, 206 and 204) is measured with Tl (205 and 203), to monitor and correct for instrumental mass bias, following the procedures outlined in Weiss et al. (2006). Sample precision was achieved using the SRM981 standard (Todt et al. 1996), which has accepted Pb isotopic ratios of $^{206}\text{Pb}/^{204}\text{Pb} = 16.9356$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4891$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7005$. Analyses at the PCIGR measured Pb isotopic ratios relative to the standard. Average ratios for SRM981 are $^{206}\text{Pb}/^{204}\text{Pb} = 16.9430 \pm 0.0007$, $^{207}\text{Pb}/^{204}\text{Pb} = 15.4999 \pm 0.0007$, and $^{208}\text{Pb}/^{204}\text{Pb} = 36.7260 \pm 0.0018$ (all corrected to 2 standard deviations).

Results

The geochemical data were normalized to 100% volatile free, and several geochemical filters were applied to select a least altered subset. Alteration was identified by loss on ignition values greater than 4.5wt. %, depletion in Na_2O values to less than 1 wt. %, $\text{Al}_2\text{O}_3 / \text{Na}_2\text{O}$ ratios greater than 10 (Spitz and Darling 1978), the Chlorite Carbonate Pyrite Index, <15 or $>85\%$ (Large et al. 2001) and a Hashimoto index <20 or $>65\%$ (Ishikawa et al. 1976). Rare earth element (REE) mobility was evaluated using Ce, where Ce/Ce^* (Ce sample / Ce interpolated) values that deviate from 1 are anomalous, and those within the range 0.9-1.1 are acceptable (Polat and Hoffman, 2003). Of the 39 samples analyzed, 14 did not meet the geochemical screens for alteration, and 5 were removed as they contained

mixed clast types, leaving 20 samples for geochemical evaluation. On some of the geochemical plots, altered samples are included where only a few least altered representatives are available; these are displayed by light grey symbols. The trace element geochemistry for units 1 to 5 are: contained in Tables 1 and 2, displayed in Figures 7, 8 and 9 and are described below. Their $\epsilon\text{Nd}_{(1.9\text{Ga})}$ and Pb isotopic data are contained in Table 3.

Unit 1: Heterolithic felsic volcanoclastic lithofacies

Unit 1 plots as rhyodacite – dacite on a Winchester and Floyd (1977)'s diagram; all samples have similar ratios of Zr /TiO₂ (Fig. 7a), but differ in their Nb/Y ratio. The four volcanoclastic lithofacies are divided into those containing black wispy fragments and those that do not (Figs. 8a and 9a). The trace element profiles for the wispy fragment lithofacies define a consistent trend on primitive mantle (Fig. 8a) and chondrite normalized plots (Fig. 9a) whereas profiles for the volcanoclastic lithofacies, without wispy fragments, show more variability. For example, one sample is relatively enriched in LREE, whereas another sample has a flatter REE profile (Fig. 9a); this variability may reflect differences in fragment types and or matrix. The wispy fragment volcanoclastic lithofacies provides a consistent geochemical dataset that is used for comparison with other units. Wispy fragment volcanoclastic lithofacies are enriched in LREE and their profile is identical to that of the Powderhouse Dacite unit (Fig. 9a) with Nb/La_{mn} = 0.40– 0.58 (mn, primitive mantle normalized) and negative Nb (Nb/Th_{mn} = 0.21 –0.29) and Ti anomalies (Table 2; Fig. 8a). Chondrite normalized geochemical plots (Fig. 9a) display a slight negative Eu anomaly and flat consistent HREE patterns, which are similar to felsic units 2 and 4 (Figs. 9b and 9c). However, the wispy fragment volcanoclastic lithofacies have a steeper negative La /Yb (LREE) trend than other coherent rhyolitic lavas of the MB sequence (La /Yb_{ch} = 2.66 – 3.44; Table 2; Fig. 9a).

Unit 2: Felsic lavas and volcanoclastic lithofacies

Felsic volcanic and volcanoclastic rocks of unit 2 plot as rhyodacite – dacite on Fig. 7a.

The felsic lavas of unit 2 have consistent trace element profiles compared to the volcanoclastics lithofacies (Fig. 8b, 9b). Felsic lavas and volcanoclastic lithofacies show a decrease in the LREE abundance, relative to unit 1, with slight negative Eu anomalies and flat HREE patterns (Fig. 9b). The Zr/Y and Nb/Y values are similar to those of unit 4 (Fig. 8c), and are lower than those of unit 1. On a primitive mantle normalized plot, the felsic lavas display negative Nb (Nb/Th mn = 0.28 – 0.30; Nb/La mn = 0.27 – 0.45; Nb/Th mn = 0.28 – 0.30) and negative Ti anomalies (Table 2; Fig. 8b). On a chondrite normalized diagram, the felsic lavas display a moderately steep LREE trend; (La /Yb ch = 2.69– 3.11; Table 2; Fig. 9b).

Unit 4: Felsic lava lithofacies

Felsic lavas plot in a tight cluster within the rhyodacite/dacite field of Figure 7a and exhibit consistent trace element profiles (Fig. 8c, 9c). On primitive mantle normalized plots, felsic lavas display negative Nb (Nb/Th mn = 0.29 – 0.30; Nb/La mn = 0.35 – 0.36; Nb/Th mn = 0.29 – 0.30) and negative Ti anomalies (Table 2; Fig. 8c). On chondrite normalized plots (Fig. 9c) the felsic lavas are most similar to felsic lavas of unit 2 (Fig. 9b) as they display a slight negative Eu anomaly, and a flat HREE pattern, which are comparable to felsic units 1 and 2. On the chondrite normalized plot, the felsic lavas display a moderate slope of the LREE (La /Yb ch = 2.42 – 2.73; Table 2; Fig. 9c), which is consistent with that displayed for units 2 and 1.

Mafic lavas and volcanoclastic lithofacies (units 3 and 5)

Altered mafic lavas and least altered and altered volcanoclastic lithofacies of unit 3 plot in the subalkaline basalt field of Fig. 7a, but exhibit a wide range of Zr/TiO₂ and Nb/Y ratios. The two least altered volcanoclastic samples plot as andesite/basalts. Altered and least

altered mafic lavas of Unit 5 fall within the subalkaline basalt field of Fig. 7a; they have similar Zr/TiO₂ but different Nb/Y ratios. Basaltic lavas for unit 3 and 5 plot in the low Ti/Island Arc Tholeiite and Boninite field on Shervais (1982)'s diagram (Fig. 7b). Basaltic volcanoclastic rocks of unit 3 display a negative Nb anomaly (Nb/Th mn = 0.42–0.43; Nb/La mn = 0.43 – 0.47) on primitive mantle normalized plots; and all samples display negative Ti anomalies (Table 2; Fig. 8d). Chondrite normalized patterns show a variable LREE enrichment (La /Yb ch = 2.43 – 2.62; Table 2; Fig. 9d). A basaltic lava from unit 5 displays a similar profile to unit 3 mafic volcanoclastic lithofacies, with negative Nb, Zr, and Ti anomalies on primitive mantle normalized plots (Table 2; Fig. 8e). However, Chondrite normalized patterns for the unit 5 basaltic lavas have a flat profile, compared to the slight LREE enrichment (La /Yb ch = 1.38; Table 2; Fig. 9e) of unit 3 volcanoclastic rocks.

Discussion

Felsic, mafic and heterolithic volcanoclastic lithofacies comprise more than 60% of the 1.0 kilometers thick MB sequence. Rhyolitic lavas and basalt lithofacies and their associated breccias comprise less than 40% of the sequence. We will first address the origin and mechanism of emplacement for lithofacies that define depositional units of the MB sequence, followed by a discussion of their geochemistry, a reconstruction of volcanic events, and will end with a comparison to strata that comprise the VMS-hosting Chisel Sequence. A primitive to more evolved marine arc setting for the SLA and MB has been proposed (Stern et al. 1995a, 1995b; Bailes and Galley 1996, 1999; David et al. 1996; Lucas et al. 1996; Bailes and Schledewitz 1998; Syme et al. 1996, 1999). Evidence that the MB sequence was emplaced into a subaqueous environment include: pillows in mafic lava, hyaloclastite, mass flow deposits, and planar cross bedding. None of these features have water depth implications, and cross bedding may indicate in situ reworking by bottom

currents and is not evidence for shallow water. The 1 kilometer thickness of the MB sequence requires a water depth in excess of 1.2 kilometers to account for the lack of storm wave base bed forms ($>200\text{m}$) (Cas and Wright, 1991; Kano et al. 1996; Hudak et al. 2003; Kessel and Busby 2003; Cas et al. 2003; Busby 2005; Allen and McPhie 2009); however, water depth could have been much shallower if subsidence accompanied emplacement of the units.

Felsic Volcaniclastic Lithofacies

The most voluminous and widespread felsic volcaniclastic lithofacies is represented by the wispy fragment depositional units 1a to 1f, and 1i of unit 1 (Fig. 4). These are characterized by their dark wispy fragments and crystal-rich nature, and they are interpreted to be a product of explosive submarine eruptions. Interpreting a pyroclastic origin for deposits in ancient successions is difficult at best, as alteration, deformation and metamorphism can destroy or modify the delicate textures (e.g. Y-shaped shards, pumice), which are required to unequivocally identify explosive fragmentation and, along with other criteria, primary deposits. This is particularly true for volcaniclastic deposits of the MB sequence, which have been deformed and metamorphosed to amphibolite facies, where arguments in support of an explosive origin must be based on larger textures and structures that can “survive” deformation and metamorphism, and are consistent with documented primary submarine volcaniclastic rocks.

Explosive fragmentation results in the formation of i) ash, ii) pumice/scoria, iii) lithic (rock) fragments, and iv) the liberation of crystals; the occurrence, and relative proportion of each is dependent, in part, on the explosivity of the eruption, magma composition, crystal content, and magmatic versus hydrovolcanic explosive fragmentation processes (Fiske, 1963). Felsic volcaniclastic lithofacies of unit 1 preserve components consistent with explosive fragmentation, these include lithic, crystal, and wispy fragments.

The distinctive, dark wispy fragments, which characterize the felsic volcaniclastic

lithofacies display a pronounced elongation – flattening, which defines a bedding parallel foliation. The flattening is, in part, a product of deformation. However, the differential flattening of wispy fragments, as compared to adjacent lithic or scoriaceous fragments indicates that their flattening was, in part, pre-deformation. This is consistent with a pre-deformational phyllosilicate mineralogy, which would preferentially develop in glassy and vitric juvenile fragments, making them more susceptible to synvolcanic alteration, hydration, and flattening during submarine burial and compaction (e.g. Allen and Cas 1990; Gifkins and Allen 2001; McPhie and Allen 2003; Gifkins et al. 2005; Bull and McPhie 2007). The wispy nature of the fragments, and their characteristic delicate tails are consistent with altered and deformed pumice (Gifkins and Allen 2001; Kessel and Busby 2003; Gifkins et al. 2005; Bull and McPhie 2007).

Crystals, principally feldspar and less commonly quartz occur within the dark wispy fragments (10 %), but are more concentrated within the tuff matrix where they comprise from 15 to 30 % of depositional units. The occurrence of feldspar and quartz crystals, in both wispy fragments and tuff matrix is consistent with a common magma source for both, and their greater concentration within the matrix, is consistent with crystal liberation during explosive fragmentation and concentration during transport and deposition.

Tuff comprises 30-70% of the Unit 1 volcanoclastic lithofacies and consists of a fine, <2mm in size, compositionally and mineralogically homogeneous assemblage of quartz and feldspar crystals with <1% mafic minerals and <30% feldspar, +/- quartz. Tuff is interpreted to represent original volcanic ash which, along with contained crystals, were produced by explosive fragmentation. Collectively, the association of wispy – pumice – fragments, lithic fragments, crystals, and matrix tuff is typical of pyroclastic deposits (Fiske and Matsuda 1964; Fisher and Schminke 1984; Kano et al. 1996; Gibson, et al. 1999). The compositional

uniformity of Unit 1 felsic volcanoclastic rocks (Figs. 8a and 9a) indicates a single magmatic source, consistent with a primary pyroclastic origin for the deposits.

The internal organization of components and bedforms within the unit 1 depositional units mirrors those that were first described by Fiske (1963), Fiske and Matsuda (1964), Bond (1973), Yamada (1973), Niem (1977), Morton and Nebel (1984) and later by others (e.g., Kano 1996; Gibson et al. 1999) for primary pyroclastic deposits produced by submarine, eruption-fed and water-supported pyroclastic flows (Figs. 10a and b, respectively). Both are characterized by a massive lithic –and crystal- rich base, which grades upwards into finer crystal and wispy – pumice- fragments, and ultimately into a predominantly finer ash-sized uppermost section that may display plane parallel beds. The flattened shape of the wispy fragments is consistent with hot deposition and welding, but can equally be attributed to an earlier primary compaction and subsequent tectonic deformation. Evidence of welding would have been destroyed by metamorphism and deformation.

The 13 depositional units of Unit 1 are interpreted to represent the successive emplacement of eruption-fed, submarine pyroclastic flows. The term submarine pyroclastic flow is used herein as the subaqueous equivalent of subaerial pyroclastic flows, where the former refers to water (gas) supported eruption-fed density currents, regardless of emplacement temperature (Fiske and Matsuda 1964; Kano 1996; Gibson et al. 1999, Hudak et al. 2003, Busby et al. 2003; White and Houghton 2006), and the latter refers to hot, gas supported eruption-fed density currents (Cas and Wright 1987; Stix 1991; McPhie et al. 1993).

Unit 1 represents a significant pyroclastic event(s). The deposits have a thickness of up to 400 meters, are continuous for 3.5 kilometers along strike, and have an estimated volume of approximately 5 cubic kilometers based on an estimated depth extent that is half of the strike extent (1.75 kilometers) and structural repetition within two fault panels. This

volume is smaller than some subaqueous pyroclastic flows deposits. For example, the volume of pyroclastic flow deposits associated with subaerial calderas ranges from 10's – 1000's of cubic kilometers, and the volume of submarine pyroclastic flow deposits associated with the collapse of the Archean Sturgeon Lake Caldera Complex, is estimated to range from 7 to 24 cubic kilometers (Hudak et al. 2003). The Mount Read pyroclastic deposits are more than 800 meters thick and extend 14 kilometers strike length (McPhie and Allen 2003). The large volumes associated with pyroclastic flow deposits are often interpreted to be the product of caldera forming eruptions (Scott et al. 2003; Wright et al. 2003). The estimated 5 km³ volume for unit 1 pyroclastic flows suggests that synvolcanic subsidence was likely, but of unknown depth, size or shape.

Explosive, subaqueous magmatic pyroclastic eruptions are interpreted to be restricted to water depths less than 2000 meters due to the limiting effects of hydrostatic pressure on the critical pressure of water (Kokelaar 1986; Cas 1991; Gibson et al. 1999). This is supported by documented deeper water felsic pyroclastic fragmentation at around 1000 meters on the modern seafloor such as the Healy caldera, southern Kermadec arc, New Zealand (Wright and Gamble 1999; and Wright et al. 2003) and the Brothers caldera located to the northeast (Embley et al. 2012). There is evidence for pumice at depths > 2100 meters in extensional rift settings, such as the Woodlark and Manus Basins, of Papua New Guinea (Binns 2003). Studies of ancient deposits such as those of the Archean Sturgeon Lake Caldera by Hudak et al. (2003) and of the Bald Mountain caldera in northern Maine (Kessel and Busby 2003) indicate that pyroclastic eruptions can occur in deeper water settings (> 1.5 kilometers). Therefore, the wispy fragment depositional units of unit 1 (Fig. 4), suggest a maximum vent water depth of 2 km and a minimum water depth that was below storm wave base (>200 meters).

Monolithic tuff breccias of lithofacies 2, 3 and 4 of unit 1 (Fig. 4) have a higher

crystal content and contain only sparse dark wispy fragments. They are not interpreted as resedimented, due to their lack of internal structure and thick monomictic clast supported beds; they are interpreted as primary dome collapse breccia deposits.

The higher crystal content of lithofacies 2, relative to lithofacies 1, is perhaps a result of derivation from a different magma (McPhie and Allen 2003). The sparse wispy fragments may indicate: i) that dome collapse occurred during pyroclastic eruptions, ii) that the wispy fragments were incorporated during transport from underlying pyroclastic flow, or iii) they were derived from pumiceous parts of a dome.

Mafic Volcaniclastic Lithofacies

Features that indicate a primary pyroclastic fragmentation for units 3 and 5 include i) mafic scoriaceous and fluidal bombs (e.g. depositional unit 3j, Figure 4, Figure 6a and b) characterized by amygdule-rich interiors, thin non-amgydaloidal crusts and equant bomb-like, to fluidal shapes, all typical of submarine fire fountain pyroclasts, which can form at water depths of >3000 meters (Gill et al. 1990; Cas et al. 2003), and ii) mafic bombs (depositional units 3l - n, Figure 4) that indent underlying beds, indicating pyroclastic fragmentation and ballistic emplacement in a shallower water environment (White et al. 2000).

Mafic volcaniclastic lithofacies of the MB sequence are divided into 2 types: 1) monomictic and 2) heterolithic. Monomictic volcaniclastic lithofacies, are interpreted as primary or syneruptive pyroclastic deposits, owing to their homogeneity (one provenance) and the bedded to massive depositional units (e.g. depositional units 3a, and 3g-j, Figure 4). Heterolithic volcaniclastic deposits that contain mafic and felsic components indicate a dual provenance, which suggests re-sedimentation of unconsolidated deposits during active volcanism, consistent with syneruptive deposits (depositional units 3b – e and 3l – 3q, Figure 4).

Felsic and Mafic Lava Lithofacies

Felsic lava lithofacies of units 2 and 4 (Fig. 4) are interpreted as subaqueous rhyolitic lavas or domes. The difference between the coherent rhyolites is in their plagioclase crystal content. Characteristic features observed in the rhyolitic lavas include columnar joints and hyaloclastite, which occur at the margins of the lavas and indicate slow, steady cooling and quenching by seawater, respectively. Lobes, defined by amygdules and flow banding are typical features. Breccias at the margins of the lava lobes (Fig. 5c) which are of the same composition as the felsic lavas, and which transition into massive rhyolitic lavas through an in-situ breccia, are interpreted to be autobreccias. The rhyolitic lavas or domes are interpreted to have been erupted from intrabasinal vents.

The dominantly feldspar-porphyritic, pillowed basaltic lavas of depositional units 3f, 3k, (Fig. 4) indicate a submarine environment, and are evidence for intrabasinal effusive vents, which deposited pillowed basaltic lavas in-between heterolithic mass flow deposition. Pyroxene-porphyritic pillowed lavas of unit 5 (Fig. 5h) were emplaced following mass flow deposition. The overlying Birch Lake basalts consist of massive to pillowed aphyric lavas. The pillowed lavas have thin selvages, minimal hyaloclastite and quartz-rimmed gas cavities up to 12 cm in diameter, whereas the more massive lavas have a gabbroic textured interior (Bailes and Schledewitz 1998).

The mafic and heterolithic volcanoclastic and rhyolitic and basaltic lava lithofacies were deposited in a below storm wave base, intrabasinal setting. There is no evidence of shallow water features, within or in the bounding lithofacies. The association of voluminous pyroclastic lithofacies (Unit1), rhyolitic lavas and domes, and basaltic lavas, and the compositional similarity of the felsic and mafic volcanoclastic rocks to their associated rhyolitic and basaltic lava lithofacies is consistent with a proximal volcanic environment and their derivation from submarine pyroclastic and effusive eruptions.

Tectonic Setting

Coherent felsic lavas and volcanoclastic lithofacies of Units 1 to 3 are all rhyodacite to dacite in composition (Fig. 7 a). Their ratios of La/Yb_{ch} (2.66-6.12) and Zr/Y (3.89-7.25), Yb (1.54 – 3.64 ppm) and Y (14.06-31.46) contents, flat HREE patterns, negative Eu anomalies, and weak LREE enrichment are typical of FIII-IV felsic volcanic rocks, as defined by Hart et al. (2004; Figs. 8 and 9; Tables 1 and 2); their depletion in high-field strength elements and the REE are consistent with FIV felsic volcanic rocks. Hart et al. (2004), interpreted FIII-IV felsic volcanic rocks to be a product of partial melting of hydrated mafic volcanic rocks at a shallow crustal level in a high-heat flow, rift environment. The negative Nb anomalies of the felsic volcanic rocks are consistent with rifting of a suprasubduction zone arc setting.

The mafic volcanic and volcanoclastic lithofacies (Fig. 7 a) have a tholeiitic affinity, and an island arc geochemical signature (Fig. 7 b). The mafic lavas and volcanoclastic lithofacies of units 3 and 5 have higher contents of Th relative to Nb (Fig. 8 d-e), negative Nb and Zr anomalies, and low overall HREE contents on primitive-normalized plots (Fig. 8 d-e), features that are consistent with subduction-related magmas formed within an oceanic arc settings (Gill 1981; Pearce 1983). The Birch Lake basalts (Fig. 8f) have a MORB-like geochemical signature, with no depletion of Nb relative to Th (Bailes and Schledewitz 1998).

Initial ϵNd values for coherent and primary mafic volcanoclastic lithofacies range from +2.0 to +3.8 (Table 3) which implies juvenile magmas within minimal contamination or contamination by a crust of similar age (Stern et al. 1992; Bailes and Galley 1999). The low ϵNd value of +0.7 obtained for the felsic sill within unit 1 (depositional unit, 1g, Fig. 4) may indicate contamination from an Archean crust with strongly negative ϵNd values, as suggested for the Stroud Breccia of the SLA by Stern (1992). The Pb reference isochron (Fig. 11a) for the basaltic lavas and volcanoclastic rocks lies between upper crust and model N-MORB isochrons (data from Kramers and Tolstikhin 1997), consistent with an end-

member depleted mantle source and contamination by slab-derived fluids (and/or melts) or through sediment subduction (Stern et al. 1992). Recent work by Babechuk and Kamber (2011) and Kamber (2015) suggested alternatively that the depleted mantle curve of Kramers and Tolstikhin (1997) (Fig. 11a) may not be suitable for comparison with Paleoproterozoic rocks. The higher $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ values observed for the Flin Flon Arc assemblage and ocean floor rocks, may be an actual feature of the average depleted mantle in the Paleoproterozoic, arising from re-fertilisation of the depleted mantle after mixing with less depleted (lower) mantle (Babechuk and Kamber 2011).

The data plotted on a Th/Yb vs. Nb/Yb diagram together with other basaltic lavas and volcanoclastic rocks (Fig. 11 b) define a linear array that falls within the volcanic arc field and suggests crustal input via subduction processes or contamination by crust of similar age, to account for initial positive ϵ_{Nd} values.

The geochemical signature, and Nd and Pb isotope data for the MB mafic volcanic rocks are consistent with a submarine, volcanic arc setting, as proposed for the SLA by Stern (1992); Bailes and Schledewitz (1998); Bailes and Galley, (1999). However, the bimodal nature of the volcanic rocks and associated subvolcanic intrusions (Bailes and Galley 1999), the FIII-IV geochemistry of the felsic volcanic rocks (Hart et al. 2004), and the presence of VMS deposits have been interpreted to indicate a rifted arc environment for the SLA by Bailes and Galley (1999), Galley et al. (2007), Bailes et al (2016) and Pehrsson et al. (2016).

The Birch Lake Basalts, which are inferred to lie structurally and stratigraphically above unit 5 of the MB sequence have a distinctive MORB signature indicating a change, or progression to, a back-arc tectonic setting.

Inferred Volcanic and Subsidence Events of the MB sequence

Thick successions of volcanoclastic rocks accumulate in topographic basins (Cas and

Wright 1987). The MB sequence is interpreted to have been emplaced in a submarine basin that was undergoing subsidence during concomitant rifting and volcanism. The restricted strike length of depositional units 1f – 1m and 3k, as illustrated in Figure 12, may result from subsidence; however, these depositional units are dome collapse breccias and flows respectively, and may have had a limited strike length. The limited extent of units such as the thinly bedded tuffs of unit 3a (Fig. 12), which would be expected to have had a more extensive distribution, may indicate lateral restriction due to subsidence. Thus, although the evidence for localized synvolcanic faulting and subsidence within a larger basin is not unequivocal, the large volume of Unit 1 deposits (5 cubic kilometers), their interpreted rapid emplacement by eruption-fed submarine pyroclastic flows, and location within a rifted arc tectonic environment are consistent with large scale subsidence, which is most clearly evident by the basin they occupy.

The change to MORB-like basaltic lavas of the Birch Lake Sequence marks the onset of back-arc type volcanism, which may represent a progression from the rifted arc environment interpreted for the MB sequence. However, the abrupt contact between the MB and Birch Lake sequences is not exposed and, although interpreted to be conformable (Bailes and Schledewitz 1998), it could be structural.

Stratigraphic Correlation with the SLA and Implications

The thrust bound MB and SLA sequences are separated by intervening clastic metasedimentary rocks of the Burntwood group, and collectively they constitute a west verging thrust fault panel (Fig 2). The stratigraphy established for the MB sequence (Fig. 4 a) allows, for the first time, a lithostratigraphic correlation with volcanic units of the Lower and Upper Chisel sequence of the SLA (Figs. 2; 4 a, b). Bailes and Schledewitz (1998) proposed a correlation between the MB sequence and SLA based on the geochemical attributes of the units.

Stratigraphic correlation between strata of the MB and SLA is based on lithologic and, compositional similarities and mirrored cyclicity in explosive and effusive events as follows: 1) Voluminous felsic pyroclastic volcanism: Unit 1 with the Powderhouse Dacite, 2) Effusive felsic volcanism: Unit 2 and Unit 4 with the Chisel / Photo rhyolite, 3) Mafic pyroclastic volcanism: Unit 3 with the Threehouse and 4) Voluminous MORB-like effusive volcanism: Birch Lake Basalt with the Snow Creek Basalts, as illustrated in Fig. 4.

Unit 1 of the MB sequence and the Powderhouse Dacite of the SLA, share consistent physical characteristics such as the tuff-rich nature, crystal type and content, and occurrence of distinctive dark wispy “pumice” fragments and mafic lithic fragments; Fig. 13 a - d). On chondrite normalized plots the REE profile (Fig. 9a) of the Powderhouse Dacite is similar to that of Unit 1; both have negative Nb and Ti anomalies and a distinct slightly steeper LREE trend (Fig. 9a), compared to felsic units 2 and 4 (Fig. 9 b, c).

Unit 2 and 4 rhyolitic lavas are flow banded and have lobes and associated breccias (Fig. 5c), which are similar to those described for the Photo Lake / Ghost / Chisel and un-subdivided rhyolite of the SLA (Bailes 1996; Bailes and Schledewitz 1998). Their primitive mantle and chondrite normalized trace element profiles are also similar (Figs. 8b, 9b), with both characterized by negative Nb, Ti (Fig. 8b) and weak negative Eu anomalies and similar LREE enrichment (Fig. 9b) (Bailes and Galley 1996; Bailes 1997; Bailes and Galley 1999). However, rhyolites of the MB sequence do not have a negative Zr anomaly (Fig. 8b) and have a higher REE abundance. There is no comparable unit in the Chisel sequence to unit 4; however, it may be correlative with the undivided felsic lavas of the Chisel sequence, which lie at the same interpreted stratigraphic position (Fig. 4).

Mafic volcanoclastic rocks of unit 3 and the Threehouse unit of the Chisel sequence (Fig. 4) are plagioclase and pyroxene crystal-rich (Fig. 13e, f), well bedded, and contain scoriaceous and amoeboid fragments and associated bomb sags (Fig. 13g, h). Their REE profiles on primitive mantle and chondrite normalized plots (Fig. 9d) are similar and both display negative Nb and Ti anomalies, although unit 3 has a minimal Zr anomaly and higher REE abundances. Unit 5 porphyritic basalts are similar to Threehouse basalts, in that they both display negative Nb, Zr, and Ti, anomalies, on mantle normalized plots (Fig. 8e; Bailes and Schledewitz 1998), implying an arc influence, and therefore unit 5 is considered to be analogous to the Chisel sequence.

The Birch Lake basalts are identical to basalts of the Snow Creek sequence of the SLA in their morphology and in their distinct MORB-like signature expressed as a relatively flat profile on primitive mantle normalized plots without negative Nb or Ti anomalies (Fig. 8f). Their position at the stratigraphic top of the MB and SLA sequences may indicate a change or progression to a back-arc basin or ocean floor geodynamic setting. However, the lower contacts of the Birch Lake and Snow Creek basalts are not exposed and may be structural. If so, the Birch Lake and Snow Creek Basalts are fault bounded and may have been thrust over the MB and SLA sequences.

The litho- and chemo-stratigraphic correlation between the MB and SLA sequences has implications for the interpretations presented herein. First, the pyroclastic deposits of Unit 1 and the Powderhouse Dacite, when combined, define the remnants of an originally much larger and more extensive pyroclastic deposit. Using the same methodology used to estimate a volume for Unit 1 pyroclastic deposits, the Powderhouse Dacite (units J16 and J11 of Bailes and Galley 2007) with a total strike length of 11.9 km and a total average thickness of 2.31 km, has an estimated volume of 6.2 km^3 , and when combined with Unit 1, a total estimated volume of $>10 \text{ km}^3$.

Second, this unique magmatic and pyroclastic event, characterized by voluminous pyroclastic deposits, occurred immediately prior to VMS formation in the Chisel Sequence. The proposed stratigraphic correlation places the Chisel VMS hosting ore interval (Engelbert, et al. 2014) within the MB sequence (Figs. 4 and 12). However, no significant VMS-related hydrothermal alteration or VMS mineralization has been found in the MB sequence, at least in surface exposures.

Third, the entire MB sequence is subaqueous, and is interpreted to have been erupted and deposited within a deeper water (below storm wave base) basin or subsidence structure within a larger rift environment. However, an interpreted shallower water, to intertidal environment for parts of the uppermost unit of the Upper Chisel sequence (the Threehouse; Bailes and Galley (1996) suggests that variable water depths occurred with a single common basin, or between nested basins within a larger rifted-arc setting. The VMS hydrothermal system was apparently confined to the Chisel basin.

Thrust faults identified within the Snow Lake area and Flin Flon Belt are of three orders of magnitude: 1) thrusts which duplicate stratigraphy of the MB sequence, 2) thrusts which have juxtaposed the volcanic rocks and younger metasedimentary rocks of the Burntwood and Missi groups, McLeod Road Thrust, Birch Lake Fault, Snow Lake Fault (Fig. 2), and 3) regional scale faults, such as the Morton Lake Fault Zone (Fig. 3) (Syme et al. 1995; Lucas et al. 1996; Bailes and Schledewitz 1998), which separates the Snow Lake area from the central Flin Flon Belt and which bound different geodynamic environments and juxtapose different exotic terranes. The correlation of stratigraphy and the reconstruction of a common volcanic edifice between thrust panels separated by the Snow Lake and McLeod Road Thrust Faults indicates that these thrust faults do not have regional-scale dislocation as the integrity of the volcanic stratigraphy is still in place. However, the Snow Lake Fault had been interpreted to have regional offset as it is

interpreted to extend across the Flin Flon Belt as the Loonhead Lake Ductile fault (David et al. 1996; Connors 1996; Kraus and Williams 1998; Kraus and Williams 1999; Zwanzig 1999).

Conclusions

1. Voluminous felsic pyroclastic volcanism represents a unique magmatic and volcanic event during MB sequence volcanism, which may have been accompanied by localized subsidence within a larger submarine, rifted-arc setting. Felsic, mafic and heterolithic volcanoclastic, rhyolitic and basaltic lava lithofacies were deposited in a below storm wave base setting, as there is no evidence of shallow water features.
2. The compositional similarity of the bimodal felsic and mafic volcanoclastic rocks with equivalent lava lithofacies, is consistent with a proximal intrabasinal volcanic rift environment and derivation from submarine pyroclastic and effusive eruptions.
3. The MORB-like Birch Lake Basalts, if conformable with the MB sequence, may represent a progression from a rifted-arc to a back-arc setting. However, if the Birch Lake Basalts are thrust bounded, they may have been thrust over the MB sequence, in which case they could represent the initial phases of arc-rifting prior to voluminous pyroclastic eruption associated with Unit 1.
4. A new informal stratigraphy for the MB sequence and a stratigraphic correlation with strata of the Chisel sequence, indicates that Unit 1 pyroclastic deposits are more extensive, and of larger volume than previously recognized.
5. The hydrothermal environment of the MB sequence is different from the Chisel sequence. Stratigraphic correlation between the two sequences recognized the VMS interval in the MB sequence; however, it lacks the hydrothermal alteration assemblages that are typical of the Chisel Sequence VMS deposits.

6. During accretion some faults are major and juxtaposed different exotic terranes, whereas others resulted in duplexed stratigraphy and the interleaving of younger metasedimentary rocks with older volcanic rocks. In particular, correlation of individual volcanic complexes of the Chisel versus the MB sequence across structures such as the McLeod Road Thrust and Snow Lake Fault, implies that movement on these faults was not regional as previously interpreted.

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Figure captions

Figure 1: Regional geology of the Flin Flon – Snow Lake belt, of Manitoba (modified after Syme et al. 1999). Abbreviations: BL, Birch Lake; BLC, Batty Lake complex; FI, Fourmile Island; HGD, Herblet Lake gneiss dome; LHF, Loonhead Lake fault; ML, Morton Lake Fault; PGD, Pulver gneiss dome; SB, Sandy Bay; SHC, Sherridon- Hutchinson Lake complex; W, Schist-Wekusko assemblage. Field study area is highlighted by the yellow box.

Figure 2: Geology of the Snow Lake arc assemblage and the McLeod Road-Birch Lake sequence, showing the location of the Snow Lake gold mine and volcanogenic massive sulphide (VMS) deposits. Modified after Bailes and Galley (2007).

Figure 3: Geology of the McLeod Road - Birch Lake thrust panel, showing the locations of gold deposits (1:7000 scale; modified after Rubingh et al. 2012).

Figure 4: Idealized stratigraphic column illustrating lithostratigraphic units of the McLeod Road - Birch Lake sequence. The five lithostratigraphic units are denoted with their depositional units, which are outlined by red solid lines. Individual lithofacies for each unit are denoted by (L). The vertical scale is in meters. There are breaks in the scale bar at 135, 168, 205 and 576 meters. The Chisel sequence stratigraphic column lies to the right and proposed correlations with the MB sequence are denoted by black dashed lines. Location of VMS deposits are shown in red (modified after Bailes and Galley 2007).

Figure 5: Typical features for lithostratigraphic units of the McLeod Road - Birch Lake sequence. (a) Unit 1, depositional units 1 (a-e): Felsic lapilli tuff with dark wispy fragments

(wf) and mafic lithic fragments (ml), outlined in yellow. (b) Unit 1, depositional units 1 (k-l): crystal rich (quartz and feldspar crystals are labelled), with no dark wispy fragments. (c) Unit 2: Rhyolitic lava and associated breccias. Note the lobate shape of the rhyolitic lava highlighted in yellow. (d) Unit 3: Plagioclase-porphyritic pillowed basalt. (e) Unit 4: Aphyric, rhyolitic lava with a well-developed spaced cleavage defined by biotite and recrystallized quartz, feldspar and garnet. (f) Unit 4: Aphyric rhyolitic lava lobes with margins defined by biotite. (g) Unit 5: Coarse pyroxene and plagioclase-porphyritic volcanoclastic rocks. (h) Unit 5: Pillowed lava of the coarse pyroxene and plagioclase-porphyritic lithofacies. (a-h) Scale is denoted by a pen or 8.5 cm white scale card.

Figure 6: Characteristic features of scoriaceous bombs of the MB sequence (a)

Scoriaceous bomb showing asymmetrical shape with a distinct tail, highlighted in yellow, which indents into the underlying beds. The interior of the bomb is quartz amygdaloidal (10-15%) and is mantled by an intact chilled margin. (b) Equant elliptical bomb displaying an intact chilled margin. There are smaller amygdules around the margin of the bomb and larger ones predominantly in the center. (a-b) Scale is denoted by an 8.5cm white scale card.

Figure 7: (a) Discrimination diagram to classify the felsic units 1, 2 and 4 and mafic units, 3 and 5 (from Winchester and Floyd 1977). (b) V vs Ti tectonomagmatic discrimination diagram for mafic units 3 and 5 (from Shervais 1982). Altered samples, where shown, are denoted in pale grey on all diagrams.

Figure 8: Primitive mantle-normalized trace element plots (normalized to values from Sun and McDonough 1989) for all units of the MB sequence. (a) Unit 1 is subdivided to show wispy fragment volcanoclastic rocks and volcanoclastic rocks. (b) Unit 2 felsic lava and

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Figure 9: Chondrite normalized trace element plots (normalized to chondrite values from Sun and McDonough 1989) for the MB sequence. (a) Unit 1 is subdivided to differentiate wispy fragment volcaniclastic rocks and volcaniclastic rocks. (b) Unit 2 felsic lava and volcaniclastic lithofacies. (c) Unit 4 felsic lava and volcaniclastic lithofacies. (d) Unit 3 volcaniclastic lithofacies. (e) Unit 5 mafic lava lithofacies. Data for mafic and felsic units of the Snow Lake Arc assemblage, are from Bailes and Schledewitz (1998) and the Powderhouse dacite analysis are from Bailes' (written comm. 2014) North Chisel Dacite unit, which is now included within the Powderhouse of Friesen et al. (2015) and are included for comparison where applicable.

Figure 10: (a) Submarine pyroclastic flow depositional unit modified after Fiske (1963), Fiske and Matsuda (1964), Bond (1973), Yamada (1973), Niem (1977) and Morton and Nebel (1984). (b) The 6 depositional units (1a – f) from unit 1 illustrated in Fig.4a.

Figure 11: Diagrams for coherent mafic and felsic lavas of the MB sequence that illustrate crustal input: (a) Common Pb diagram (utilising data from Kramers and Tolstikhin (1997), to plot N-MORB and upper crust isochrones). (b) Th/Yb vs Nb/Yb diagram from Pearce (2008) N-MORB, E (enriched)-MORB, and OIB (ocean-island basalt)

Figure 12: Schematic cross section to illustrate the sequence of eruptive events for the McLeod Road – Birch Lake sequence and the volcanic environment. Labels for the depositional units correspond to units illustrated in the stratigraphic section in Fig. 4.

Figure 13: Comparison of features for units in the Chisel sequence and McLeod Road - Birch Lake (MB) sequences. (a) Unit 1 pyroclastic flow deposits of the MB sequence with dark wispy fragments highlighted in yellow. (b) Powderhouse Dacite (Lalor shaft location) showing flattened dark wispy fragments highlighted in yellow. (c) Unit 1 pyroclastic flow deposits of the MB sequence, with mafic lithic fragments and dark wispy fragments both highlighted in yellow. (d) Powderhouse Dacite (Lalor shaft location) showing a high percentage of flattened dark wispy fragments. One clast highlighted in yellow. (e) Unit 3: Crystal rich mafic volcanoclastic rocks of the MB sequence. (f) Threehouse mafic volcanoclastic rocks of the Chisel sequence. (g) Unit 3: Well bedded, mafic MB sequence volcanoclastic rocks with bomb sags and draping over the top of the bomb. (h) Chisel sequence Threehouse mafic volcanoclastic rocks with bomb sags. (a-h) Scale is denoted by a white 8.5cm scale card.

Table 1: Ranges in composition for stratigraphic units 1 to 5 for the McLeod Road Birch Lake sequence

	Unit 1 wispy fragments	Unit 1 QFP breccia	Coherent lavas unit 2	Volcaniclastic rocks unit 2	Volcaniclastic rocks unit 3	Coherent lavas unit 4	Volcaniclastic rocks unit 4	Volcanic lavas unit 5
Major oxides (wt.%)								
SiO ₂	71.54 - 74.52	75.36 - 80.53	74.76 - 79.86	72.85 - 74.54	54.30 - 55.11	77.78 - 77.92	74.48 - 76.06	47.81
TiO ₂	0.23 - 0.28	0.21 - 0.28	0.18 - 0.25	0.25 - 0.26	0.48 - 0.49	0.20 - 0.22	0.23 - 0.24	0.46
Al ₂ O ₃	11.90 - 13.10	9.97 - 12.57	10.47 - 12.14	12.40 - 14.20	14.98 - 15.66	9.85 - 9.96	10.94 - 11.39	14.27
Fe ₂ O ₃	3.91 - 4.84	2.72 - 4.09	3.14 - 3.84	2.16 - 5.70	11.47 - 12.99	3.86 - 4.82	5.29 - 5.62	13.18
MnO	0.06 - 0.10	0.04 - 0.06	0.04 - 0.08	0.04 - 0.09	0.18 - 0.19	0.09 - 0.10	0.08 - 0.12	0.23
MgO	0.65 - 1.11	0.58 - 0.72	0.29 - 0.63	0.49 - 1.10	4.34 - 4.76	0.49 - 0.66	0.65 - 0.78	9.75
CaO	2.08 - 2.61	1.00 - 1.77	1.45 - 3.33	1.46 - 4.11	8.42 - 9.33	1.77 - 3.74	0.64 - 1.44	9.35
Na ₂ O	3.48 - 4.22	2.03 - 4.04	2.57 - 4.54	2.39 - 4.32	2.73 - 3.41	1.35 - 2.12	2.56 - 4.39	3.59
K ₂ O	1.57 - 3.35	2.10 - 3.46	1.44 - 1.75	1.98 - 2.06	0.42 - 0.47	1.95 - 2.03	2.19 - 2.40	0.51
P ₂ O ₅	0.06 - 0.07	0.05 - 0.07	0.04 - 0.07	0.05 - 0.08	0.07 - 0.08	0.03 - 0.03	0.03 - 0.04	0.08
LOI	0.25 - 1.00	0.50 - 1.95	0.47 - 1.32	0.55 - 0.60	0.37 - 1.31	1.88 - 4.02	0.63 - 1.27	3.68
Trace elements (ppm)								
Li	7.80 - 12.40	11.60 - 17.60	7.90 - 13.80	13.60 - 17.30	9.00 - 12.50	15.90 - 26.60	9.80 - 21.20	27.70
Be	0.71 - 0.77	0.65 - 0.97	0.73 - 0.85	0.76 - 0.87	0.47 - 0.51	0.65 - 0.85	0.75 - 1.03	0.35
Bi	0.15 - 0.15	0.15 - 0.15	0.15 - 0.15	0.15 - 0.15	0.15 - 0.15	0.15 - 0.15	0.15 - 0.15	0.15
Cr	32.00 - 47.00	24.00 - 72.00	23.00 - 37.00	28.00 - 41.00	63.00 - 99.00	34.00 - 37.00	25.00 - 31.00	214.00
Ni	1.60 - 5.10	1.60 - 14.50	1.60 - 3.60	3.10 - 3.90	17.40 - 18.40	1.60 - 1.80	1.60 - 1.60	44.40
Sc	11.80 - 16.70	8.10 - 11.70	11.60 - 19.90	11.90 - 16.00	40.50 - 46.80	11.10 - 12.70	14.30 - 15.20	50.90
Ti	1258.00 - 1551.00	1180.00 - 1463.00	1018.00 - 1464.00	1427.00 - 1528.00	2487.00 - 2604.00	1045.00 - 1096.00	1274.00 - 1322.00	2274.00
V	24.10 - 45.20	20.00 - 36.10	3.30 - 23.80	15.60 - 22.00	264.60 - 310.60	1.30 - 1.60	1.10 - 2.40	307.60
Co	13.60 - 55.50	8.30 - 46.20	12.80 - 38.60	7.30 - 19.20	88.10 - 129.70	15.50 - 21.90	54.60 - 64.80	104.50
Cu	6.07 - 10.00	5.59 - 6.58	3.35 - 7.77	5.06 - 6.75	32.87 - 36.89	1.34 - 1.57	1.55 - 2.16	50.16
Pb	3.20 - 14.50	5.90 - 10.80	3.20 - 6.80	3.10 - 3.80	2.50 - 3.80	2.70 - 3.40	2.60 - 3.70	1.10
Zn	53.00 - 98.00	32.00 - 59.00	55.00 - 142.00	39.00 - 58.00	92.00 - 93.00	70.00 - 72.00	101.00 - 199.00	76.00
Ga	9.33 - 11.27	9.76 - 11.38	9.26 - 12.35	11.87 - 12.34	14.48 - 14.80	9.09 - 10.40	11.18 - 12.66	11.68
Rb	22.67 - 45.88	37.07 - 51.65	18.57 - 30.30	28.23 - 28.77	1.37 - 1.85	23.45 - 30.34	19.83 - 31.71	5.50
Mo	1.50 - 1.79	0.99 - 1.76	1.06 - 3.18	1.18 - 8.47	0.40 - 0.82	1.51 - 2.47	1.71 - 2.27	0.14
Cd	0.03 - 0.13	0.04 - 0.06	0.05 - 0.23	0.03 - 0.07	0.09 - 0.12	0.09 - 0.10	0.08 - 0.64	0.08
In	0.03 - 0.04	0.02 - 0.03	0.04 - 0.07	0.03 - 0.05	0.05 - 0.05	0.06 - 0.07	0.06 - 0.10	0.04
Sn	1.03 - 1.33	0.77 - 1.31	0.79 - 1.31	0.60 - 1.09	0.59 - 0.65	0.96 - 1.14	1.15 - 1.50	0.26
Sb	0.15 - 1.03	0.18 - 0.39	0.11 - 0.41	0.12 - 0.43	0.25 - 0.30	0.19 - 0.38	0.18 - 1.12	0.22
Cs	0.21 - 0.37	0.48 - 0.85	0.21 - 1.02	0.20 - 0.48	0.01 - 0.03	0.42 - 0.73	0.56 - 0.64	0.56
Ba	582.30 - 1088.50	627.60 - 966.80	505.90 - 1104.00	342.00 - 823.50	98.00 - 109.80	159.60 - 445.20	423.10 - 866.10	492.80
Sr	115.20 - 129.90	89.60 - 230.20	58.90 - 185.50	104.70 - 144.30	180.60 - 224.10	45.00 - 54.10	53.80 - 57.60	94.80
Nb	5.95 - 6.51	4.68 - 6.23	3.10 - 6.39	2.56 - 5.39	2.90 - 3.04	4.71 - 4.87	5.64 - 5.88	0.69
Hf	3.26 - 3.50	2.72 - 3.62	2.55 - 3.52	2.35 - 2.85	1.29 - 1.49	2.70 - 2.72	3.11 - 3.26	0.49
Zr	119.00 - 128.00	102.00 - 133.00	91.00 - 128.00	85.00 - 102.00	46 - 54	96.00 - 97.00	111.00 - 114.00	16.00
Y	19.07 - 28.10	14.06 - 23.44	23.42 - 31.46	14.00 - 33.43	14.54 - 16.13	30.08 - 34.20	36.21 - 36.32	10.42
Th	2.45 - 2.68	2.61 - 6.83	1.33 - 2.58	0.95 - 2.27	0.80 - 0.86	1.91 - 1.93	2.16 - 2.29	0.31
U	0.85 - 1.13	0.95 - 1.64	0.53 - 0.98	0.56 - 0.88	0.34 - 0.34	0.86 - 0.91	1.09 - 1.17	0.19
La	9.96 - 15.56	11.15 - 23.51	10.89 - 13.64	6.62 - 16.95	5.91 - 6.85	12.62 - 13.49	14.68 - 14.80	2.34
Ce	24.60 - 32.64	21.31 - 47.59	24.18 - 29.33	14.85 - 34.24	13.34 - 13.78	28.03 - 28.97	32.53 - 32.94	5.55
Pr	2.69 - 4.08	3.09 - 5.29	3.20 - 3.73	2.03 - 4.75	1.81 - 1.99	3.69 - 3.81	4.30 - 4.32	0.79
Nd	10.67 - 16.69	12.95 - 19.21	13.67 - 15.96	8.49 - 20.25	7.86 - 8.47	16.11 - 16.50	18.54 - 18.78	3.82
Sm	2.50 - 3.86	2.84 - 3.47	3.21 - 4.25	2.05 - 4.82	1.99 - 2.11	4.21 - 4.25	4.77 - 4.88	1.20
Eu	0.54 - 0.81	0.56 - 0.90	0.66 - 1.34	0.54 - 1.16	0.64 - 0.65	1.04 - 1.04	1.17 - 1.23	0.51
Gd	2.45 - 3.97	2.76 - 3.60	3.58 - 4.81	2.17 - 5.28	2.22 - 2.43	4.80 - 5.05	5.28 - 5.32	1.52
Tb	0.45 - 0.68	0.41 - 0.61	0.58 - 0.85	0.36 - 0.87	0.38 - 0.41	0.83 - 0.85	0.90 - 0.91	0.27
Dy	3.09 - 4.60	2.51 - 3.97	3.91 - 5.65	2.32 - 5.70	2.59 - 2.85	5.58 - 5.65	6.20 - 6.22	1.82
Ho	0.70 - 1.02	0.51 - 0.86	0.83 - 1.22	0.49 - 1.22	0.56 - 0.62	1.15 - 1.26	1.36 - 1.37	0.40
Er	2.35 - 3.13	1.55 - 2.66	2.59 - 3.64	1.51 - 3.59	1.75 - 1.87	3.41 - 3.91	4.23 - 4.26	1.23
Tm	0.38 - 0.48	0.23 - 0.41	0.38 - 0.54	0.23 - 0.51	0.26 - 0.28	0.51 - 0.60	0.65 - 0.65	0.19
Yb	2.68 - 3.25	1.54 - 2.76	2.51 - 3.64	1.55 - 3.33	1.74 - 1.87	3.31 - 4.00	4.40 - 4.41	1.22
Lu	0.42 - 0.50	0.23 - 0.43	0.39 - 0.56	0.25 - 0.52	0.27 - 0.29	0.49 - 0.62	0.68 - 0.69	0.19
Ta	0.35 - 0.38	0.32 - 0.35	0.18 - 0.30	0.15 - 0.31	0.15 - 0.17	0.26 - 0.27	0.31 - 0.33	0.03
W	0.23 - 0.97	0.22 - 1.69	0.17 - 0.60	0.18 - 0.33	0.09 - 0.15	0.47 - 0.57	0.59 - 0.64	0.09
Tl	0.10 - 0.20	0.15 - 0.30	0.06 - 0.11	0.12 - 0.31	0.01 - 0.01	0.09 - 0.11	0.12 - 0.12	0.03

Note: LOI, loss on ignition.

Table II: Average values for key element ratios for the units of the McLeod Road Birch Lake sequence.

	Unit 1 wispy fragments	Unit 1 QFP breccia 2	Coherent lavas unit 2	Volcaniclastic rocks unit 2	Volcaniclastic rocks unit 3	Coherent lavas unit 4	Volcaniclastic rocks unit 4	Coherent lavas unit 5
Al ₂ O ₃ / Na ₂ O	3.11 - 3.42	3.11 - 4.90	2.67 - 4.07	3.28 - 5.19	4.59 - 5.49	4.70 - 7.27	2.60 - 4.27	3.97
Al ₂ O ₃ / TiO ₂	46.54 - 51.35	44.47 - 47.16	48.08 - 57.52	48.97 - 54.30	31.08 - 31.78	45.52 - 48.30	46.96 - 47.17	31.23
Ti/V	34.31 - 52.20	40.53 - 59.00	61.51 - 308.48	69.45 - 91.47	8.38 - 9.40	685.00 - 803.85	550.83 - 1158.18	7.39
Zr/Y	4.56 - 6.24	5.67 - 7.25	3.89 - 4.07	3.05 - 6.07	3.16 - 3.35	2.84 - 3.19	3.07 - 3.14	1.54
Zr/Ti	0.083 - 0.095	0.091 - 0.086	0.087 - 0.089	0.060 - 0.067	0.021 - 0.018	0.089 - 0.092	0.086 - 0.087	0.01
Nb/Y	0.23 - 0.31	0.27 - 0.33	0.13 - 0.20	0.16 - 0.18	0.19 - 0.20	0.14 - 0.16	0.16 - 0.16	0.07
Ti/Sc	92.87 - 106.61	125.04 - 145.68	73.57 - 87.76	95.50 - 119.92	55.64 - 61.41	86.30 - 94.14	86.97 - 89.09	44.68
Nb/La(mn)	0.40 - 0.58	0.26 - 0.40	0.27 - 0.45	0.31 - 0.37	0.43 - 0.47	0.35 - 0.36	0.37 - 0.38	0.28
Nb/Th (mn)	0.29 - 0.21	0.28 - 0.21	0.28 - 0.30	0.28 - 0.32	0.43 - 0.42	0.29 - 0.30	0.31 - 0.31	0.27
La/Sm (ch)	2.53 - 2.57	2.53 - 4.37	2.07 - 2.19	2.08 - 2.27	1.92 - 2.10	1.93 - 2.05	1.96 - 1.99	1.26
La/Yb (ch)	2.66 - 3.44	5.19 - 6.12	2.69 - 3.11	3.06 - 3.65	2.43 - 2.62	2.42 - 2.73	2.39 - 2.41	1.38
Sm/Yb(ch)	1.03 - 1.32	1.40 - 2.05	1.30 - 1.42	1.30 - 1.47	1.27 - 1.25	1.18 - 1.41	1.20 - 1.23	1.09

Note: (mn), primitive mantle normalized ratios calculated from Sun and McDonough(1989); (ch), chondrite-normalized ratios using values of Sun and McDonough (1989).

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Table III: Calculated ENd values and Pb Isotopic data for the mafic and felsic units 1- 5 of the McLeod Road Birch Lake sequence.

MB sequence Unit	Measured ppm Nd	Measured ppm Sm	Measured $^{143}\text{Nd}/^{144}\text{Nd}$	Calculated Epsilon Nd (ϵNdT)	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{206}\text{Pb}/^{204}\text{Pb}$
Unit 5 pillow lava	3.6400	0.9510	0.5124	3.8	35.775	15.445	17.482
Unit 4 aphyric rhyolitic lava	16.1100	4.2490	0.5123	3.1	37.126	15.626	19.446
Unit 3 pillow lava	2.8900	0.8550	0.5126	3.2	35.555	15.406	17.500
Unit 3 pillow lava	2.5400	0.8640	0.5129	2.0	35.741	15.544	18.738
Unit 2 plagioclase - porphyritic rhyolitic lava	15.2000	3.4510	0.5121	3.4	36.339	15.436	17.478
Unit 2 plagioclase - porphyritic rhyolitic lava	15.8400	3.7810	0.5121	2.8	36.781	15.701	19.963
Unit 1 amygdaloidal rhyolite sill	6.3700	1.6380	0.5122	0.7	36.108	15.454	17.658
Unit 1 massive dacite	16.6900	3.8600	0.5121	2.6	36.431	15.489	18.080
Unit 1 massive dacite	15.6500	3.6750	0.5121	2.7	37.399	15.758	20.408

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Figure 1. pdf

Figure 2.pdf

Legend

Lithology

- Missi Group (sandstones)
- Burntwood Group (argillites and wackes)
- Birch Lake Basalts

5 Mafic volcanoclastic rocks: monolithic pyroxene and plagioclase - porphyritic lapillistone to tuff breccias: pyroxene - porphyritic pillowed facies

4 Felsic volcanic rocks: aphyric lavas with locally quartz filled amygdules

3 Mafic volcanoclastic rocks and lavas: heterolithic pyroxene and plagioclase - porphyritic lapilli tuff to lapillistone to tuff breccia, minor plagioclase - porphyritic pillowed lavas

2 Felsic volcanic and volcanoclastic plagioclase - porphyritic lavas and flow top breccias

1 Felsic volcanic and volcanoclastic rocks: monolithic to heterolithic quartz and plagioclase - porphyritic lapillistone to tuff breccia with minor aphyric to plagioclase - porphyritic mafic clasts; amygdaloidal plagioclase - porphyritic lavas; plagioclase - porphyritic lapilli tuff to lapillistone with wispy fragments

Symbols

- Limit of mapping
- Thrust fault
- Fault
- MB sequence units 1 - 5
- Antiform
- Synform
- Gold Deposits

Figure 5(a-h).pdf

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Figure. 6a, b. pdf

Figure. 7a, b. pdf

Figure 8(a-f).pdf

Figure 9 (a-e).pdf

Figure 10b.pdf

Figure 10a.pdf

Figure 11 a, b.pdf

Figure 12.pdf

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Figure 13 (a-h).pdf