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**Geochemistry, Nd, Pb and Sr Isotope Systematics, and U-Pb zircon
ages of the Neoarchean Bad Vermilion Lake Greenstone Belt and
Spatially Associated Granitic rocks, Western Superior Province,
Canada**

By

Tuoyu Wu

A Thesis
Submitted to the Faculty of Graduate Studies
through the Department of Earth and Environmental Sciences
in Partial Fulfillment of the Requirements for
the Degree of Master of Science at the University of Windsor

Windsor, Ontario, Canada

**Geochemistry, Nd, Pb and Sr Isotope Systematics, and U-Pb zircon
ages of the Neoarchean Bad Vermilion Lake Greenstone Belt and
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August 28, 2015

Declaration of Co-Authorship/ Publication

I. Authorship Declaration

This thesis is the product of integrated research on the Neoproterozoic Bad Vermilion Lake greenstone belt in the Superior Province of Canada. Field work was conducted by Dr. Ali Polat. I carried out the laboratory analyses, data interpretation, and manuscripts preparation through cooperation with Dr. Polat and other co-authors. The contribution of other co-authors was primarily through review on the previous versions of the manuscript. Therefore, I certify that I am the major author of this thesis. Meanwhile, I declare that, to the best of my knowledge, my thesis does not infringe upon anyone's copyright nor violate any proprietary rights. All the ideas, techniques, quotations, material from the work of other people included in my thesis, published or otherwise, are fully acknowledged in accordance with the standard referencing practices.

II. Declaration of Publication

The thesis is based on an original paper that has been submitted for publication in *Precambrian Research*, which is an internationally renowned Earth Science journal. The percentage given by the author's name represent the relative scientific contribution of each co-author. Tuoyu Wu (55%), Ali Polat (20%), Robert Frei (10%), Brian J. Fryer (5%), Kunguang Yang (5%), Timothy M. Kusky (5%).

All co-authors provided insightful critique on early versions of this manuscript. This study was possible through contributions of an NSERC grant to Ali Polat. Ali Polat conducted the field work and collected the samples, and provided guidance with the preparation of the manuscript. Robert Frei carried out the Nd, Pb and Sr isotope analysis. Brian J. Fryer provided help with the ICP-MS trace element analyses. Kunguang Yang helped with U-Pb zircon dating at China University of Geosciences (Wuhan). Timothy Kusky provided insights with geodynamic interpretation of the Bad Vermilion Lake greenstone belt. Without their generous help, this study could not be accomplished; therefore, I am here to show my deepest gratitude to them.

Abstract

The Neoarchean (ca. 2720 Ma) Bad Vermilion Lake (BVL) greenstone belt is composed of metamorphosed bimodal tholeiitic to calc-alkaline basalts to rhyolites, volcanoclastic rocks, gabbros, and subordinate sedimentary rocks. All these rocks are intruded by granitic rocks.

The HFSE systematics of the volcanic and volcanoclastic rocks and gabbros are consistent with subduction zone geochemical signatures. The BVL greenstone belt is geochemically similar to Neoarchean subduction-related ophiolites. Two rhyolite samples from the belt have been dated as 2724 ± 23 Ma and 2722 ± 11 Ma, representing approximate age of the arc volcanism. The ca. 2664 Ma Ottertail Lake granite marks the end of tectonic accretion in the study area.

Both the volcanic rocks and gabbros show large ranges of Nd, Pb and Sr isotopic compositions, reflecting post-magmatic alteration. Pb-Pb regression ages of gabbros (2725 ± 83 Ma) agree with the U-Pb ages of the rhyolites, suggesting that the U-Pb system was the most robust isotopic systems.

Keywords: Archean greenstone belt, Superior Province, Western Wabigoon subprovince, Bad Vermilion Lake, Trace element, Radiogenic isotopes

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Last but not least, I am very grateful for my parents' vital support and encouragement during the pursuit of this degree. Without their care,

my M.Sc. experience would not have been joyful and memorable.

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CHAPTER 1.

Introduction

1.1 Backgrounds on Archean greenstone belts

Greenstone belts are empirically described as deformed and metamorphosed volcano-sedimentary successions (Anhaeusser, 2014). The greenstone belts are often enveloped by high-alumina tonalite-trondhjemite-granodiorite (TTG) gneiss and late-tectonic granites to form the granitoid-greenstone terrane (Condie, 1981; 1994). The accretion and amalgamation of many small granitoid-greenstone terranes gradually shape most Archean cratons (Windley, 1995; Kusky and Vearncombe, 1997; Kusky and Polat, 1998; Percival et al., 2012). Accordingly, greenstone belts provide important information on the geological processes in the early Earth.

Greenstone belts usually crop out as elongate slivers of supracrustal successions in most Archean granite-greenstone terranes (Condie, 2007). Most of the exposed greenstone belts range from 5 to 250 km in width, 100 to 300 km in length, and 10-20 km in thickness (Condie, 1981). The volcano-sedimentary successions of Archean greenstone belts usually include 80% ultramafic to felsic volcanic and volcanoclastic rocks as well as 20% chemical and siliciclastic sedimentary rocks (Condie, 1994). In addition, Archean greenstone belts are always related to layered ultramafic-mafic complexes and anorthosite complexes (Anhaeusser, 2014). Metamorphic grades of Archean greenstone belts may increase from prehnite-pumpellyite facies, through greenschist facies, to amphibolite facies (Wilkins, 1997). Due to multiple tectonic deformation and extensive regional metamorphism, nearly all the Archean greenstone belts display various metasomatic alteration effects (Anhaeusser, 2014). Because of the alteration, ultramafic and mafic lithologies are converted to low-grade mineral

assemblages of serpentine, chlorite, epidote and hornblende (Hunter and Stowe, 1997). Although the dating of greenstone belts show a time spanning from 4300 Ma to 517 Ma (summarized by Furnes et al., 2015), but the most widespread belts were formed in Neoarchean between 2700 Ma and 2600 Ma (Condie, 1981). This time slot also corresponds to the major period of gigantic ultramafic to mafic volcanisms, TTG emplacement, as well as the formation of the earliest volcanogenic massive sulphide (VMS) and mesothermal gold deposits in the early earth history (Windley, 1995; Taylor and McLennan, 1995; Kerrich and Wyman, 1996; Polat and Kerrich, 2001; Van Kranendonk, 2007).

Ophiolite represents fragments of oceanic lithosphere that have been emplaced in orogenic belts due to collision or subduction-accretion events (Dewey and Bird, 1971; Coleman, 1977; Nicolas, 1989). The typical Penrose-type ophiolites include, from bottom to top, the following lithologic units: 1) tectonized peridotites; 2) cumulate peridotites and pyroxenites; 3) layered gabbros; 4) sheeted basaltic dikes; 5) pillow basalts; 6) Deep sea sediments (Autonomous, 1972). The Archean greenstone belts do contain two or more parts of Penrose-type ophiolites (e.g., Kusky 1990, 1991; King and Helmstaedt, 1997; de Wit, 2004), which suggest that plate tectonic processes, might be in different styles, were operative in Archean (Kusky and Polat, 1999). Recent research broadened ophiolites' definition as suites of temporally and spatially associated ultramafic to felsic rocks associated with particular tectonic environments (Dilek and Furnes, 2011). Based on the geochemical signature of basaltic components, the ophiolites can be classified as subduction-related type and subduction-unrelated type (Dilek and Furnes, 2011). The subduction-related ophiolites include suprasubduction-zone and volcanic-arc types; while the subduction-unrelated ophiolites include continental-margin, mid-ocean-ridge and plume types (Dilek and

Furnes, 2011, 2014; Furnes, 2015). Some Archean greenstone belts showing intra-oceanic geochemical signatures can represent Precambrian ophiolites (Furnes et al., 2007; Delik and Polat, 2008; Furnes et al., 2009, 2012), the tectonic classification can also apply to the Archean greenstone belts. In that case, the systematic study of the Archean greenstone belts has indispensable implications for the understanding of geodynamics of the early earth.

Granitic intrusions are well-preserved in Archean greenstone belts on all continents (de Wit, 1998). The earliest stage of granitic intrusions is marked by voluminous sodium-rich TTG suites; whereas the latest stage of intrusions are dominated by potassium-rich granites (de Wit, 1998; Anhaeusser, 2014). The TTG suites originate by partial melting of basaltic source, in combination with fractional crystallization of parental melt (e.g., Benn and Moyen, 2008; Moyen et al., 2007). The potassium-rich granites were derived through interaction between TTG melts and evolved mantle peridotites in an extensional environment after major orogenies (Sylvester, 1994; Evans and Hanson, 1997; Moyen, 2009). The Neoarchean sees a dramatic decrease in the abundance of TTG intrusion, with a progressive replacement of potassic granite (Moyen and Martin, 2012). This transformation may be either attributed to the change of the plate tectonic style (Martin, 1993; Stern, 2008), or caused by the temporary shutdown of plate tectonics at the end of Archean (Condie et al., 2009; O'Neil et al., 2007).

The Archean geodynamic processes remains controversial despite the recognition of plate tectonic operation during this time slot (Eriksson and Catuneanu, 2004; Turner, 2014; Furnes et al., 2014, 2015). The main divergence lies to the relative importance of plate tectonics versus thermal convection models in the Archean geodynamic processes (Kerrick and Polat, 2006). The plate tectonic paradigms are

mainly based on field, geochemical and geochronological data from Archean craton worldwide (e.g., Polat et al., 2002; Nutman et al., 2013; Wang, 2013; Backeberg et al., 2014). In contrast, the thermal convection models are generally built upon numerical simulations (Hamilton, 1998; Bédard, 2006; Thebaud and Rey, 2013). Meanwhile, some scientists proposed that both horizontal plate tectonic processes and vertical thermal convection do exist in the Archean (Van Kranendonk et al., 2014; Lin, 2005; Smithies et al., 2007). As a major component of Archean cratons, greenstone belts and associated granitic rocks preserve important geochemical and structural information, which can be utilized to test geodynamic hypothesis of the early earth system.

1.2 Greenstone belts in the Superior Province

The Superior Province covers the largest area among the 21 major Archean crusts in the world (Fig. 1.1). In addition, it preserves many linear volcano-plutonic or metasedimentary subprovinces (Card and Ciesielski, 1986). Moreover, it shows the deepest lithospheric keel in North America (Silver and Chan, 1988). All of these characteristics above make Superior Province an ideal platform to study Precambrian geology. Archean greenstone belts in the Superior Province can be generally divided into two types: (1) subduction related bimodal tholeiitic to calc-alkaline basalt to rhyolite association (e.g. Polat et al., 1998; Polat and Kerrich, 1999; Daigneault et al., 2000); (2) plume-derived komatiite-tholeiite association (e.g., Xie et al., 1993; Tomlinson et al., 1999; Dostal and Muller, 2013). Additionally, minor amounts of arc-related rocks such as boninite, Low-Ti tholeiite, picrite, high-magnesian andesite, adakite, and Nb-enriched basalt can also be found in these greenstone belts (summarized by Kerrich and Polat, 2006; Polat, 2009). Nevertheless, volcanic assemblages with different chemical affinities can coexist together due to plume-arc

interactions (Wyman and Kerrich, 2009). For example, the coexistence of (1) 2750-2700 Ma bimodal tholeiitic to calc-alkaline associations and (2) 2730-2705 Ma tholeiitic basalts and komatiites reflect plume controlled flat subduction in the Abitibi-Wawa greenstone belt (Wyman et al., 2002).

Among all the greenstone belts in the Superior Province, the Bad Vermillion Lake (BVL) greenstone belt in the western Wabigoon subprovince is my targeting object. The BVL belt locates in the Rainy Lake area, near the fault boundary between Quetico metasedimentary province and the granitoid-greenstone terrane of western Wabigoon subprovince (Fig. 1.2). Previous structural studies show that the BVL greenstone belt has experienced at least three deformation events (D_1 - D_3), which have resulted in the prevalent inversion of stratigraphic sequences (Poulsen et al., 1980). The study area has affected by low grade regional metamorphism (Winkler, 1974). Petrographic investigation and geochemical analyses have revealed the composition of mafic to felsic volcanic rocks, mafic dikes, and some felsic intrusions in the BVL greenstone belt (Ashwal, 1983). The latest geochronological studies examined the formation age of major lithologic units (Davis et al., 1989). Based on the subsequent order of volcanic eruption, sedimentation, deformation and granitic intrusions, Davis et al. (1989) pointed out that plate collision play an important role in the formation of the BVL greenstone belt.

Despite many geologists has made advances in understanding the geological evolution in the BVL greenstone belt and associated granitic intrusion (e.g., Ottertail Lake granite), several problems still remain unsolved: (1) geochemical and dating data may not be reliable due to limited precision of contemporaneous experimental facilities; (2) Mineralogical and geochemical composition of siliciclastic rocks from the BVL greenstone belts have not been explored; (3) Effects of metamorphism on

element mobility within the rock units have not been estimated; (4) Petrogenetic links between different rock units in the BVL greenstone belt remain ambiguous; (5) Specific tectonic settings that favored the generation of the BVL greenstone belt and the Ottertail Lake granite have not been ascertained; (6) Tectonic evolution of the western Wabigoon subprovince and its neighbours is still vague. In order to solve these problems, I have done detailed geochemical and geochronological studies on each rock units from the BVL greenstone belts as well as the Ottertail Lake granite to test possible petrogenetic and geodynamic model for this region.

1.3 Purpose of Studies

The principal purposes of conduct this research is to determine the source characteristics and tectonic evolution of the BVL greenstone belt and associated granitic intrusions. This study has profound significance is assessing mantle composition and the style of plate tectonics in Neoarchean. New whole-rock major and trace elements, Nd, Pb, and Sr Isotopes, and U-Pb zircon age data of the major rock units in the BVL greenstone belt and Ottertail Lake granite have been integrated to explore the following scientific questions:

- (1) What were the influences of metamorphic alteration on elemental mobility of the BVL greenstone belt?
- (2) When did the BVL greenstone belt and Ottertail Lake granite form, and how did the formation ages constrain on the regional tectonic evolution?
- (3) What were the source characteristics of the BVL greenstone belt and the Ottertail Lake granite?
- (4) What geodynamic processes shaped the BVL greenstone belt and the Ottertail Lake granite?

- (5) What are the petrogenetic and tectonic implications can the BVL greenstone belt and associated granitic rocks make?

1.4 Structure of Thesis

This thesis is composed of three main chapters. Chapter 1 is the introduction for the thesis. Chapter 2 is a manuscript that has been submitted to a peer reviewed journal. Chapter 3 presents a summary of this study. Among all the chapters, chapter 2 is the most important chapter and undoubtedly the core of the master project research.

A version of Chapter 2 has been submitted as a research article in Precambrian Research. This chapter presents field relationships, petrographic observation, high precision geochemical data, Nd, Sr and Pb isotope systematics, as well as U-Pb zircon data of the major rock units in the BVL greenstone belt and Ottertail Lake granite. Through detailed field work, the major rock units of the BVL greenstone belt and Ottertail Lake granite have been defined and sampled. Based on petrographic investigation, prevalent metamorphic alteration severely modified primary mineralogy and textures in the BVL greenstone belt; while the Ottertail Lake granite remain less altered. High precision major and trace element geochemistry of 4 samples from the BVL greenstone belt and were analyzed to understand the geochemical signature of these rocks. The Nd, Sr and Pb isotopic studies reveal that the severe alteration has devastated the whole-rock Rb-Sr and Sm-Nd isotopic systems, but caused insignificant effects on the U-Pb system. In addition, the isotopic data unravel the source characteristics of the BVL greenstone belt and Ottertail Lake granite. U-Pb zircon dating has constrained the formation ages of both BVL greenstone belt and Ottertail Lake granite, thus providing implications on tectonic evolution of west Wabigoon subprovince.

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Figure 1.1. Global distribution of Archean crusts (dark grey) and underlain Precambrian basement. The major Archean provinces are listed below: 1=Yilgarn, 2= Pilbara, 3=Indian, 4=North China, 5=Aldan-Stanovik, 6=Yenisei, 7=Anabar, 8= Kaapvaal, 9=Zimbabwe, 10=Central African (Tanzanian and northeastern Zaire), 11= Kasai, 12=West African (Liberia, Sierra Leone, Mauritania), 13=Ukrainian, 14= Baltic-Svecofennian (Inari-Kola, Karelian), 15=North Atlantic (Greenland, Scotland), 16=Superior, 17=Wyoming, 18=Slave, 19=São Francisco, 20=Amazonian (Guiana, Guaporé), 21=East Antarctica (modified after Condie, 1981; Goodwin, 1991; Anhaeusser, 2014)

Figure 1.2. Simplified regional geological map of western Wabigoon subprovince, displaying major supracrustal belts (including plutons and greenstone belts) and structure features.

CHAPTER 2

Geochemistry, Nd, Pb and Sr Isotope Systematics, and U-Pb zircon ages of the Neoarchean Bad Vermilion Lake Greenstone Belt and Spatially Associated Granitic rocks, Western Superior Province, Canada

2.1. Introduction

Archean greenstone belts are characterized by multiply deformed and variably metamorphosed supracrustal sequences (Condie, 1981, 1994; Hunter and Stowe, 1997; Polat et al., 2015). These belts are typically intruded by intermediate to felsic rocks displaying mainly a tonalite-trondhjemite-granodiorite (TTG) affinity; greenstone belts and TTG suites together form the composite granitoid-greenstone terranes in Archean cratons (de Wit, 1997; Sylvester et al., 1997; Anhaeusser, 2014). Lithologically, greenstone belts consists of temporally and spatially related, ultramafic to felsic volcanic rocks, ultramafic to mafic intrusions, and subordinate sedimentary rocks (de Wit, 1998, 2004; Kusky and Polat, 1999; Furnes et al., 2013, 2015). The majority of granitoid-greenstone terranes in the world occur as Mesoarchean to Neoarchean basement (Szilas et al., 2012, 2013; Anhaeusser, 2014; Furnes et al., 2015). The Superior Province is the largest Archean craton in the world and consists of many well-preserved elongated granitoid-greenstone terranes (e.g., Thurston et al., 1991; Corfu and Davis, 1992; Henry et al. 1998, 2000; Tomlinson et al., 2002, 2003; Stott, 1997; Percival et al., 2006a, 2012). Given its well-preserved diverse rock types, the Superior Province provides an excellent opportunity for studying the petrogenetic and geodynamic origins of Archean crust (e.g., Kerrich et al., 1999; Sproule et al., 2002; Whalen et al., 2002; Lodge et al., 2013, 2014, 2015).

Greenstone belts in the Archean Superior Province are dominated by two

principal volcanic sequences, which are represented by bimodal tholeiitic to calc-alkaline basalt to rhyolite association and komatiite-tholeiite association, respectively (Polat and Kerrich, 2002; Sproule et al., 2002; Dostal and Mueller, 2013). The bimodal association is characterized by LREE-enriched patterns and pronounced negative anomalies of Nb, Ta, P, and Ti, suggesting a typical intra-oceanic arc magmatism; the komatiite-tholeiite association is featured by high-Mg, Cr, and Ni contents, flat rare earth element, as well as complex Th-U-Nb-LREE systematics, indicating a magmatic origin pertinent to mantle plumes (Condie, 1994; Polat et al., 1999; Polat and Kerrich, 2001a; Kerrich and Polat, 2006; Polat, 2009). Greenstone belts in the western Superior Province, contains both types of volcanic associations (Ayer and Davis, 1997; Dostal et al., 2004; Ujike et al., 2007; Tomlinson et al., 1999; Hollings and Kerrich, 2004, 2006).

Tectonic setting of the greenstone belts in the Wabigoon subprovince are still hotly debated (e.g., Hollings and Wyman, 1999; Tomlinson et al., 1999; Wyman et al., 2000; Backeberg et al., 2014). In order to understand the petrogenesis and geodynamic evolution of the Wabigoon subprovince and especially for its western part, we focus on the BVL greenstone belt and its spatially related Ottetail Lake granitic stock on the northern shore of the Rainy Lake (Fig. 2.1b). Given that all rocks in the BVL greenstone belt have been metamorphosed under greenschist facies conditions, the prefix “meta” will be taken as implicit throughout the paper. In this study, we report new major and trace element data for forty-seven samples from the BVL greenstone belt, including volcanic rocks and gabbros, and the spatially associated Seine siliciclastic sedimentary rocks and the Ottetail Lake granitic stock. Seventeen samples from the volcanic rocks and gabbros were analyzed for Nd, Pb and Sr isotope systematics. In addition, three rhyolite samples and one granite sample

were analyzed by zircon U-Pb dating to constrain the ages of the greenstone belt and the Ottetail Lake stock. Integrated field and petrographic observations, and geochemical, isotopic and geochronological data are used to constrain the petrogenesis and geodynamic evolution for the BVL greenstone belt, and to assess the effects of post-magmatic processes on element mobility.

2.2. Regional Geology and field characteristics

The Superior Province, nucleus of the North American continent, developed by the amalgamation of many distinct protocontinental and oceanic terranes ranging in age from 3.7 to 2.65 Ga, during five discrete orogenic events between 2720 and 2680 Ma (Percival et al., 2006a and reference therein). The assembly of these accretionary terranes with the rest of Superior craton was initiated by the collision between the 3.0 Ga North Caribou terrane and the 3.7-2.75 Ga North Hudson Bay terrane at 2720 Ma, and ended by welding of the Minnesota River Valley and Pontiac terranes to the Abitibi-Wawa terrane at 2680 Ma, showing an overall orderly north to south progression (Percival et al., 1994, 2006a, b, 2012; Stott, 1997). Seismic reflection and refraction images display common north-dipping structures and variable thickness of 10-15 km among these disparate tectonic fragments (Musacchio et al., 2004; White et al., 2003), supporting the importance of diachronous northward accretionary-collisional process in the formation of the Superior Province. However, plume-derived komatiitic and tholeiitic flows are exposed many locations (Xie et al., 1993; Hollings et al., 1999; Polat et al., 1999; Kerrich et al., 1999; Tomlinson et al., 1999; Sproule et al., 2002; Dostal and Mueller, 2013) in the Superior Province, indicating the important role of mantle plume magmatism in the evolution of the Superior Province. A comparison of eastern and central sections of the western Superior

Province indicates relatively well-preserved east-west trending subprovinces of alternating plutonic, volcanic-plutonic (granitoid-greenstone), high-grade gneissic, and sedimentary rocks. The majority of these linear subprovinces extend along bounding faults for over 1000 km (Fig. 2.1a; Williams, 1990; Stott, 1997; Percival et al., 2006a, b).

The Wabigoon subprovince is a typical granitoid-greenstone composite terrane in the western Superior Province (Fig. 2.1a; Percival et al., 2006a, 2012). It is characterized by ca. 900 km long, and ca. 150 km wide east-west trending greenstone belts and platformal carbonate sequences that are intruded by granitoid batholiths, gabbroic sills and stocks of various compositions (Blackburn et al., 1991; Thurston et al., 1991; Stott, 1997; Kusky and Hudleston, 1999). The lithologies of the greenstone belts in the Wabigoon subprovince are dominated by mafic to felsic volcanic rocks and lesser amounts of komatiites and sedimentary rocks, ranging in ages from ca. 3.0 to 2.7 Ga (Blackburn et al., 1991). On the basis of different lithological, structural, and tectonic evolutionary characteristics, the subprovince is divided into three distinct terranes: (1) the eastern Wabigoon terrane, which is composed predominantly of Mesoarchean to Neoarchean (ca. 3056-2720 Ma) supracrustal successions (Stott and Davis, 1999) intruded by ca. 2770-2680 Ma syn- to post-tectonic plutons, in conjunction with Neoarchean (ca. 2740-2720 Ma) mafic to felsic volcanic rocks (Davis, 1999; Kwok et al., 2000); (2) the central Wabigoon terrane, which is characterized by a number of Mesoarchean greenstone belt remnants intruded by several generations of TTG batholiths (Blackburn et al., 1991), such as the ca. 3075 Ma tonalite at Caribou Lake near its northern margin (Davis et al., 1988) and a ca. 3003 Ma tonalite in the Lumby Lake area, the southern part of the region (Davis and Jackson, 1988); and (3) the western Wabigoon terrane, which is mostly dominated by

large tonalitic to granodioritic batholiths (ca. 2735-2720 Ma; Davis and Edwards, 1982, 1986), surrounded by numerous Neoproterozoic (ca. 2775-2685 Ma) greenstone belts (Blackburn et al., 1991). The western Wabigoon terrane is also distinct from the other two regions in that it shows juvenile Nd isotopic compositions (Ayer and Dostal, 2000; Ujike et al., 2007), and the absence of inherited zircons older than 2710 Ma (Tomlinson et al., 2003). It is noted that the exact location and nature of the boundaries among the three regions remain ambiguous, and correlations of greenstone belts in different regions are not well-defined.

2.2.1. The Bad Vermillion Lake (BVL) greenstone belt

The BVL greenstone belt is bounded to the north by the dextral Quetico fault and the Rainy Lake batholithic complex; while its southern boundary is marked by the dextral Seine River fault, which separates the greenstone belt from the Quetico sedimentary subprovince (Fig. 1b; Wood, 1980; Ashwal et al., 1983; Davis et al., 1989). The Quetico and Seine River faults shape the belt into a triangular wedge block, sharing lithological and structural characteristics of both the Wabigoon and Quetico subprovince along the boundaries (Wood, 1980; Davis et al., 1989). The BVL greenstone belt can be lithologically subdivided into four assemblages: (1) the Keewatin mafic to felsic volcanic rocks (mainly rhyolite and basalt; Fig. 2.2d); (2) the Seine Group pyroclastic rocks (e.g., lapilli tuff and volcanic breccia; Fig. 2.2a), sandstones and conglomerates (Fig. 2.2b); (3) Keewatin gabbros (Fig. 2.2c); and (4) the Coutchiching wackes with minor amounts of mica schist and turbidite (Hart and Davis, 1969; Blackburn et al., 1991). In addition, there are small volumes of felsic sub-volcanic rocks in the belt. Geological mapping indicates that these rock units were inverted and later compressed into an asymmetric synformal anticline (Davis et

al., 1989; Poulsen et al., 1980; Fig. 2.1b). The core of the fold is occupied by the Neoarchean BVL anorthosite complex, which is characterized by calcic-anorthosite (An_{80-95}) with equant plagioclase megacrysts, and two dissimilar gabbroic bodies on its southeastern and northwestern sides. These gabbros include: (1) abundant Fe-Ti oxides, apatite bearing gabbros on the northwestern side (Harris, 1974; Wood et al., 1980); and (2) homogenous and massive gabbros on the southeastern side (Ontario Dept. Mines, 1961). The northeastern and southwestern limbs of the fold are dominated by felsic and mafic volcanic rocks, respectively (Ashwal et al., 1983).

The BVL greenstone belt underwent three phases of deformation (Poulsen et al., 1980). The lower portions of the BVL greenstone belt were structurally overturned and predate the development of dominant (F_2) folds, resulting in that the older Keewatin volcanic rocks superimpose on the younger Coutchiching sediments (Poulsen et al., 1980). All sedimentary and volcanic successions in the Rainy Lake area were subjected to low to medium grade regional metamorphism in the Neoarchean (Winkler, 1974), the intensity of which increases from the southernmost biotite zone to the central staurolite-cordierite zone, and finally reaches the sillimanite-muscovite zone in the north (Poulsen et al., 1980). Anorthosites and associated gabbros have been extensively metamorphosed under upper greenschist facies conditions (Ashwal et al., 1983).

Rubidium-Sr and Sm-Nd dating of the anorthosites provided errorchron ages of 2690 ± 100 Ma and 2740 ± 70 Ma, respectively (Ashwal et al., 1983). The Rb-Sr isotope data from the Keewatin volcanic rocks yielded an errorchron age of 2770 Ma, while the errorchron age for the Coutchiching sedimentary rocks is around 2690 Ma, coinciding with an early stage of metamorphism during the Algoman orogeny (Hart and Davis, 1969). Errorchron ages of the Keewatin volcanic rocks and the

Coutchiching sedimentary rocks are consistent with the zircon intercept age of 2750 Ma (Hart and Davis, 1969). The rhyolite from the northern Keewatin felsic volcanic sequence yielded a crystallization age of about 2728 Ma (Davis et al., 1989; Fig. 2.1b). Another quartz-phyric volcanic rock from the Keewatin sequence several kilometers to the east of the BVL yielded a similar U-Pb zircon age (2727.0 ± 1.2 Ma; Davis et al., 1989). The detrital zircons from the Coutchiching sedimentary rocks display $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 3059 ± 3 Ma to 2704 ± 3 Ma, while a trondhjemite intrusion in the Seine Group defines a maximum depositional age of 2696 Ma (Davis et al., 1989).

2.2.2. *Ottertail Lake granitic stock*

The granitoid complexes in the Wabigoon subprovince can be divided into three major types: (1) Neoarchean (e.g., 2732-2708 Ma in the western Wabigoon terrane) batholiths which are compositionally varying from TTGs through granite to quartz monzonite; (2) Mesoarchean Basement Complex (e.g., ca. 3075 ± 3 Ma tonalitic gneisses; Davis, et al., 1988) mainly from the central Wabigoon terrane; and (3) Neoarchean (2709-2685 Ma) post-tectonic monzonitic to granitic stocks, which chiefly scatter in the west Wabigoon terrane and intrude the supracrustal belts and subjacent internal batholiths (Blackburn et al., 1991). According to Ashwal et al. (1983), the elongated and altered felsic intrusions in the BVL region, which also reveals compositional affinities with local felsic volcanic rocks, were produced during the Laurentian plutonism (ca. 2728-2725 Ma; Davis et al., 1989). However, the unaltered, potassic, and juvenile Ottertail Lake granitic stock (Fig. 2.1b) that intrudes nearly all the lithologic units of the BVL greenstone belts (Fig. 2.2e) was thereby interpreted as a late tectonic Algoman granitoid intrusion by Poulsen et al. (1980).

The Laurentian intrusion provides an Rb-Sr errorchron age of 2520 ± 21 Ma, which is significantly younger than the U-Pb age (2750 Ma) of the Laurentian inherited zircons (Hart and Davis, 1969). Comparatively, the crystallization age of the undeformed Ottetail Lake Stock was interpreted to be $2686 \pm 1/2$ Ma (Davis et al., 1989). It is speculated that the plutons with voluminous tonalitic compositions such as the Laurentian granitoid originated from partial melting of overthickened amphibolite-dominated lower crustal rocks and assimilation of older tonalite gneisses (Whalen et al., 2004). In contrast, the younger Algoman granitic rocks with monzonitic compositions (Fig. 2f), which are analogous to potassium-rich Granodiorite-Granite-Monzogranite (GGMs), were interpreted to have been produced by melting of metasomatized mantle sources (Sutcliffe et al., 1993; Shirey and Hanson, 1986) and emplaced at the terminal stage of cratonization (Anhaeusser and Robb, 1981).

2.3. Petrography

Based on field observations, rocks in the BVL greenstone belt are grouped as mafic (basalt), intermediate (andesite), felsic (rhyolite) volcanic rocks, gabbros, intermediate to felsic volcanoclastic, and siliclastic sedimentary rocks (Figs. 2.2 and 2.3). The volcanoclastic rocks, including tuff, lithic tuff, and quartz-feldspar breccia, are mainly of intermediate to felsic in composition. The intrusive rocks are predominantly gabbros. Primary mineralogy and textures of most igneous rocks have been mostly obliterated by metamorphism and deformation (Figs. 2.4 and 2.5). However, the effects metamorphic alteration and post-tectonic deformation in the spatially associated Ottetail Lake granite are much lower than those in the greenstone belt (Figs. 2.2-2.5).

Mafic volcanic rocks usually contain subhedral to anhedral grains and display well-developed foliation. They are composed mainly of chlorite (30-40%), plagioclase (30-40%), epidote (10-20%), quartz (5-10%), calcite (5-10%), and opaque minerals (<5%) (Fig. 2.4 a-c).

Intermediate volcanic rocks are composed chiefly of fine-grained subhedral to anhedral plagioclase (40-50%), epidote (10-15%), chlorite (15-20%), quartz (10-15%), calcite (5-10%), and opaque minerals (5-10%). Plagioclase is replaced by calcite and epidote.

The majority of felsic volcanic rock outcrops display a porphyritic texture. Phenocrysts (0.5-5 mm) are predominantly blue quartz and alkaline feldspar, whereas matrix (0.02-0.1 mm) chiefly consists of microlite, quartz and some mica (Figs. 2.4d, e). The alkaline feldspars usually display strong albitization and sericitization. The quartz grains are elongated often show irregular boundaries and undulatory extinction.

Pyroclastic rocks in the BVL greenstone belt are composed mainly of tuffs, lithic tuffs, lapilli tuffs and lapilli stones. Some of these rocks also occur within the Seine Group. Our samples are mainly from tuffs and lithic tuffs. These pyroclastic rocks consist of subhedral to anhedral feldspar (30-40%), quartz (40-50%), chlorite (10-20%), calcite (0-5%) and opaque minerals (0-5%). Feldspars in high-strain areas reveal plastic deformation and recrystallization. All major minerals display weak alignment and, are often transected by quartz veins. Alteration in the vesicular tuff is characterized by silicification, albitization and sericitization.

Gabbros are composed of large grains (up to 2 cm) of plagioclase (30-40%), chlorite (20-30%), amphibole (5-10%), epidote (10-15%), calcite (5-10%), quartz (5-10%), and opaque minerals (0-5%) (Fig. 4f). Most plagioclase grains have been altered to epidote, calcite and quartz.

The siliciclastic rocks from the Seine sedimentary rocks are composed of quartz, feldspar, mica, chlorite, calcite, sulphide and rock fragments (Fig. 2.5a, b). Grains are mainly angular and set in fine-grained matrix (Fig. 2.5a, b).

The Ottertail Lake granite consists of biotite (10-20%), plagioclase (10-20%), potassium feldspar (30-40%), quartz (30-40%), and accessory minerals (<5%) such as amphiboles, muscovite, calcite and Fe-opaque phases (Fig. 2.5c, d). It is usually characterized by subhedral equigranular texture with a grain size between 1 and 5 mm. Most grains are undeformed except for quartz, which often exhibits strained boundaries and undulatory extinction. Plagioclase grains are locally altered to epidote and amphibole (Fig. 2.5c, d).

2.4. Sampling and analytical methods

2.4.1. Sampling

Samples were collected from mafic, through intermediate, to felsic volcanic rocks, intermediate to felsic volcanoclastic rocks and gabbros from the Keewatin Group, sedimentary rocks from the Seine Group, and the Ottertail Lake granite. GPS coordinates for sample locations are given in Tables 2.1 and 2.2. Sampling was designed to include outcrops with different degrees of alteration minerals proportions and overall deformation to constrain the effects of post-magmatic alteration on element mobility. The weight of the sample ranges from 2 to 4 kg.

2.4.2. U-Pb zircon geochronology

Zircon U-Pb dating was conducted on three rhyolite (BVL2013-030, BVL2013-031, and BVL2013-034) and one granite (BVL2013-058). Zircon grains were separated at the laboratory of Hebei Institute of Regional Geological Survey and

Mining in Langfang, China, using conventional magnetic separation and heavy liquid techniques. Separated zircons were handpicked using a binocular microscope. Selected zircons were then adhered to a circular resin target in a line, which was prepared for reflected light, transmitted light, and cathodoluminescence (CL) imaging. Clear, stubby and idiomorphic zircons from the resin target were chosen for U-Pb dating on a Laser Ablation Inductively Coupled Plasma Mass Spectrometer (LA-ICP-MS), equipped with 193 nm ArF excimer laser, at the State Key Laboratory of Geological Processes and Mineral Resources, China University of Geosciences, Wuhan.

Detailed operating conditions for the laser ablation system and the ICP-MS instrument data reduction are the same as described by Liu et al. (2008a, b; 2010a, b). Zircon standard 91500, whose age is 1065.4 ± 0.3 Ma (Wiedenbeck et al., 1995), was analyzed twice for every five analyses, serving as an external standard for the derived U-Th-Pb data. Concordia diagrams and weighted mean calculations were made by using Isoplot/Ex_ver3 (Ludwig, 2003). Errors on age-plots are 2σ . A circular spot with a diameter of 32 μm was employed in the U-Pb dating.

2.4.3. Major and trace element analyses

Samples were powered and analyzed for whole-rock major and some trace elements (Ba, Sr, Y, Sc, Zr, Be, V) in Activation Laboratories Ltd. (ATCLABS) in Ancaster, Ontario, using a Thermo Jarrell-Ash ENVIRO II ICP. For the preparation of the ICP analyses, molten samples were instantly fused and digested with a solution of 5% nitric acid containing an internal standard, mixed continuously until completely dissolved (ca. 30 minutes). Loss on ignition (LOI) was determined by measuring the weight loss as resulting from the escape of all volatile (e.g., H_2O , CO_2), by strong

heating of the sample powders to 1100 °C over three hours. Calibration was made by using seven prepared USGS and CANMET certified reference materials. One of the seven standards was used during the analysis for every group of ten samples. Totals of major elements are 100 ± 1 wt.%, and most of these major elements possess high analytical precision of 1-3%. The analytical precision for the trace elements in the ICP analyses are better than 10%.

Concentrations of high-field strength elements (HFSE), large-ion lithophile elements (LILE), and transition metals (e.g., Ni, Co, Cr, Cu, and Zn) in the samples were determined by a high-sensitivity Thermal Elemental X7 Inductively Coupled Plasma Mass Spectrometer (ICP-MS) in the Great Lakes Institute for Environmental Research at the University of Windsor, Canada, adhering to the protocols of Jenner et al. (1990). Approximately 100-120 mg of the sample powders was dissolved in Teflon bombs for HF+HNO₃ acid digestion. Samples were dissolved on a hotplate at temperature between 100 and 120 °C under clean lab conditions. Hawaiian and Icelandic basalt standard (BHVO-1 and BIR-1) were analyzed as reference materials. In this study, the analytical accuracies are estimated as follows: 1-15% for REE, Hf, Th, V, Rb, Sr, Cs, Co, Cr and U; 15-30% for Nb, Ta, Zr and Y; >30% for Ba, Pb and some transitional metals (Supplementary Data Table 1).

Major elements were recalculated to 100 wt.% volatile-free phase for inter-sample comparisons. Mg-number (%) were calculated as the molecular ratio of $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$, where Fe^{2+} is assumed to be 90% of total Fe. Chondrite and N-MORB reservoir compositions used for normalized trace element diagrams are from Sun and McDonough (1989). Europium (Eu/Eu^*), Ce (Ce/Ce^*), Nb (Nb/Nb^*), Ti (Ti/Ti^*), and Zr (Zr/Zr^*) anomalies were calculated relative to their neighboring immobile elements, complying with the principles from Taylor and McLennan

(1985). Initial epsilon-Nd (ϵNd) values were calculated from the present-day parameters of the Chondrite Uniform Reservoir (CHUR), assuming $^{147}\text{Sm}/^{144}\text{Nd}=0.1967$ and $^{143}\text{Nd}/^{144}\text{Nd}=0.512638$. ϵNd values were calculated using zircon U-Pb ages (ca. 2720 Ma) yielded by felsic volcanic rocks in the BVL greenstone belt.

2.4.4. Sm-Nd, U-Th-Pb and Sr isotope analyses

Based on rock types and chondrite-normalized REE patterns, 17 samples have been selected for Nd, Pb and Sr isotope analyses at the Geological Institute, University of Copenhagen, Denmark. The powdered samples were dissolved by standard procedures using concentrated HNO_3 , HCl and HF within SavillexTM beakers on a hotplate at 130 °C for 3 days (see Frei and Polat, 2013). A $^{150}\text{Nd}/^{147}\text{Sm}$ spike was added beforehand. The isotopic ratios of Sm, Nd, Pb and Sr, and of Sm and Nd isotopic dilution concentrations were determined from separately dissolved powder aliquots using a VG Sector 54 IT Thermal Ionization Mass Spectrometer (TIMS) at IGN.

Samples were separated over chromatographic columns charged with 12 ml AG50W-X 8 (100–200 mesh) cation resin, where Sr and REE fractions were collected. REE fractions were further separated over smaller chromatographic columns containing Eichrom'sTM LN resin SPS (Part#LN-B25-S). Strontium cuts were purified applying a standardized 3M HNO_3 - H_2O elution recipe on self-made disposable mini-extraction columns, which consisted of 1 ml pipette tips in which we fitted a frit filter to retain 0.2 ml intensively pre-cleaned mesh 50–100 SrSpecTM (Eichrome Inc.) resin. The elution recipe essentially followed that of Horwitz et al. (1992), scaled to our needs. Strontium was eluted/stripped by pure deionized water and then the eluted

fraction was dried on a hotplate.

Samarium isotopes were measured in a static multi-collection mode, whereas Nd isotopes were collected in a multi-dynamic routine, both on a triple Ta-Re-Ta filament setting. The measured Nd isotope ratios were normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.7219$. The mean value of $^{143}\text{Nd}/^{144}\text{Nd}$ ratios for our JNdi standard runs during the period in which the samples were analyzed amounted to 0.512105 ± 5 (2σ ; $n = 8$). Precision for $^{147}\text{Sm}/^{144}\text{Nd}$ ratios is better than 2% (2σ). Chemical separation of Pb from the whole-rock samples was performed over conventional glass stem and subsequently miniature glass stem anion exchange columns containing, respectively, 1 ml and 200 μl of 100–200 mesh Bio-Rad AG 1 $\times$ 8 resin. Lead was analyzed in a static multi-collection-mode where fractionation was controlled by repeated analysis of the NBS 981 standard (using values of Todt et al. 1993). The average fractionation amounted to $0.105 \pm 0.008\%$ (2σ , $n = 5$) per atomic mass unit. Total procedural blanks remained below <200 pg Pb which compared to >100 ng Pb loads, insignificantly affected the measured Pb isotopic ratios of the samples. $^{87}\text{Rb}/^{86}\text{Sr}$ ratios were calculated using ICP-MS Rb and Sr data.

2.5. Results

2.5.1. Zircon geochronology

2.5.1.1. Rhyolite samples (BVL2013-030, BVL2013-031, and BVL2013-034)

Most zircon grains in these three samples show subhedral to anhedral crystal shapes, irregular boundary as well as sporadic occurrence of fractures and fluid or mineral inclusions (Fig. 2.6 a-c). The majority of the grains are characterized by salient magmatic oscillatory zoning with high luminescence in the CL images (Fig. 2.6 a-c); several grains display no zoning (Fig. 2.6b).

Sample BVL2013-030 contains abundant stubby zircon grains (100-150 μm) with subrounded to prismatic edges. They are characterized dominantly by fine oscillatory zoning (Fig. 2.6a). A total of 33 spots on different zircon grains have been analyzed. Thorium and U contents are 12-86 ppm and 28-102 ppm, respectively, with high Th/U ratio of 0.40-0.84 and high REE contents (593-2245 ppm) (Table 3; Supplementary Data Table 2). A cluster of 31 analyses from oscillatory grain cores are concordant and yield a $^{207}\text{Pb}/^{206}\text{Pb}$ mean age of 2722 ± 11 Ma (Fig. 2.7a). The range of the $^{207}\text{Pb}/^{206}\text{Pb}$ ages span from 2808 Ma to 2576 Ma (Table 2.3).

Sample BVL2013-031 yielded small and subrounded grains (50-150 μm) with irregular rims. The small zircons are mostly heterogeneous; whereas the larger grains display complex interiors but with generally undisturbed oscillatory zoning (Fig. 2.6b). A total of 19 spots on different zircon grains have been analyzed. The concentrations of Th and U are 39-1836 ppm and 65-1473 ppm, respectively, yielding elevated Th/U ratios (0.33-1.25) (Table 2.3). Rare earth element contents (1074-16155 ppm) are moderately variable (Supplementary Data Table 2). A cluster of 15 analyses from oscillatory grain zones are concordant and have given a $^{207}\text{Pb}/^{206}\text{Pb}$ mean age of 2698 ± 13 Ma (Fig. 2.7b). Most of the $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages vary from 2733 Ma to 2562 Ma, with four exceptionally low ages bracketed between 2604 Ma and 377 Ma (Table 2.3).

Sample BVL2013-034 is dominated by small subhedral zircon grains (50-100 μm) with subrounded to prismatic edges. Cathodoluminescence imaging reveals distinct cores with wavy, diffusive, and disrupted oscillatory zoning at outer margins of the grains (Fig. 2.6c). Only 7 spots on well-shaped magmatic zircon grains have been analyzed. These grains display large variation in Th (245-1560 ppm) and U (432-1189 ppm) contents, resulting in high Th/U ratios (0.29-1.32; Table 2.3). The

zircon grains are strongly enriched in REE (2836-15578 ppm) (Supplementary Data Table 2). The 7 analyses are basically concordant, and give a $^{207}\text{Pb}/^{206}\text{Pb}$ mean age of 2724 ± 23 Ma (Fig. 2.7c). The $^{207}\text{Pb}/^{206}\text{Pb}$ zircon ages range from 2744 Ma to 2692 Ma (Table 2.3).

2.5.1.2. *Ottertail Lake granite sample (BVL2013-058)*

Sample BVL2013-058 yielded many elongated and prismatic zircons ranging in size from 100 to 200 μm . Cathodoluminescence images exhibit continuous clear oscillatory zoning developed from the internal core to the edge (Fig. 2.6d). A total of 20 spots on different grains have been analyzed. These grains have variable Th (167-557 ppm) and U contents (178-702 ppm) (Table 2.3). The ratios Th/U vary from 0.69 to 1.13. They have high REE concentrations (1059 -3212 ppm) (Supplementary Data Table 2). Nineteen out of the 20 analyses from the oscillatory cores are concordant, and provided a $^{207}\text{Pb}/^{206}\text{Pb}$ mean age of 2664 ± 15 Ma (Fig. 2.7d). One outlier grain yielded a $^{207}\text{Pb}/^{206}\text{Pb}$ age (2868 Ma) and larger standard age deviation ($1\sigma = 40.805$ Ma). The overall $^{207}\text{Pb}/^{206}\text{Pb}$ ages of the zircons are within the bracket of 2868 Ma and 2633 Ma (Table 2.3).

2.5.2. *Major and trace elements*

2.5.2.1 *Mafic volcanic rocks*

The mafic volcanic rocks are basaltic in composition ($\text{MgO} = 3\text{-}10$ wt.%, $\text{SiO}_2 = 48.6\text{-}54.5$ wt.%, $\text{Fe}_2\text{O}_3 = 10.7\text{-}19.8$ wt.%), and characterized by variable concentrations of TiO_2 (0.56-3.70 wt.%), CaO (5.3-11.8 wt.%), P_2O_5 (0.01-0.70 wt.%), Al_2O_3 (12.0-16.7 wt.%), Zr (60-210 ppm), Sc (24-44 ppm), Ni (73-277 ppm), and Cr (9-277 ppm) (Figs. 2.8-2.10; Table 2.1). Mg-numbers vary between 30 and 58. The ratios of

$\text{Al}_2\text{O}_3/\text{TiO}_2$ (3-28) and Ti/Zr (46-167) are subchondritic to superchondritic whereas the Zr/Y (3.9-10.3) ratios are superchondritic (Table 2.1).

The BVL greenstone mafic volcanic rocks plot in the field of subalkaline rocks on the Zr/Ti versus Nb/Y diagram (Fig. 2.8a). On the FeO_T -total alkalis-MgO (AFM) diagram, the Fe- to Mg-rich mafic volcanic rocks show a tholeiitic geochemical affinity (Fig. 2.8b). Most of the Zr/Y ratios (3.9-10.3) are within the range of modern tholeiitic basalts (see Barrett and MacLean, 1994). The Nb/Ta (14-19) ratios are subchondritic to chondritic (Table 2.1).

The mafic volcanic rocks possess near-flat REE patterns at 1 to 10 times N-MORB (Fig. 2.10a). $\text{La}/\text{Sm}_{\text{cn}}$ (1.25-2.28) and $\text{Gd}/\text{Yb}_{\text{cn}}$ (1.45-2.11) ratios show considerable variations. Cerium and Eu anomalies are minimal, but Ta and Nb ($\text{Nb}/\text{Nb}^*=0.15\text{-}0.44$) show salient negative anomalies on the N-MORB-normalized diagram (Fig. 2.11a). They are marked by the following geochemical features: (1) variably negative Zr ($\text{Zr}/\text{Zr}^*=0.61\text{-}0.93$) anomalies; (2) small positive Ce ($\text{Ce}/\text{Ce}^*=1.01\text{-}1.08$) anomalies; (3) slightly variable Eu ($\text{Eu}/\text{Eu}^*=0.81\text{-}1.13$) and highly variable Ti ($\text{Ti}/\text{Ti}^*=0.48\text{-}1.74$) anomalies; and (4) strong enrichments of Th with respect to La (Figs. 2.11a and 2.12a; Table 2.1).

2.5.2.2. *Intermediate volcanic rocks*

Intermediate volcanic rocks only account for a small volume of all the volcanic-related lithologies in the BVL greenstone belt. They are characterized by 59-67 wt.% SiO_2 , 0.65-2.65 wt.% MgO , 2.7-11.6 wt.% Fe_2O_3 , 14.6-23.6 wt.% Al_2O_3 , and 0.7-5.6 wt.% CaO (Figs. 2.8-2.10; Table 2.1). Mg-numbers range from 26 to 40. Like the mafic volcanic rocks, they have a sub-alkaline composition and a tholeiitic affinity (Figs. 2.8a, b). Two samples (BVL2013-026 and 027) show significantly higher MgO

(8.1-9.4 wt.%) and Mg-numbers (60-65), with 62-66 wt.% SiO₂ values than the other three samples (BVL2013-003, 012 and 013) (Table 2.1). The BVL intermediate volcanic rocks have 0.69-1.23 wt.% TiO₂, 11-25 ppm Sc, 60-118 ppm Ni, and 10-190 ppm Cr (Figs. 2.9 and 2.10; Table 2.1). On the chondrite- and N-MORB-normalized diagrams, they are defined by the following features: (1) variably enriched LREE and flat to depleted HREE patterns ($\text{La/Sm}_{\text{cn}}=1.59-4.79$; $\text{Gd/Yb}_{\text{cn}}=1.06-2.69$); (2) strong negative Nb ($\text{Nb/Nb}^*=0.07-0.21$) and Ti ($\text{Ti/Ti}^*=0.23-0.63$); (3) moderately negative Eu anomalies ($\text{Eu/Eu}^*=0.46-0.87$); and (4) negative to positive Zr ($\text{Zr/Zr}^*=0.67-1.05$) anomalies (Figs. 2.11 and 2.12; Table 2.1).

2.5.2.3. *Intermediate to felsic volcanoclastic rocks*

In the field, these rocks have gradational appearance between intermediate and felsic volcanoclastic rocks. Thus, they are called intermediate to felsic rocks. These rocks have moderate variations in SiO₂ (66-78 wt.%), MgO (0.53-3.40 wt.%), CaO (0.09-5.24 wt.%), Al₂O₃ (10.4-16.2 wt.%), Nb (10.9-19.2 ppm), Y (27-90 ppm) and Zr (270-570 ppm) contents (Figs. 2.8-2.10; Table 2.1). Compositionally, they are dacite to rhyodacite (Fig. 2.8a), and reveal a transition from a tholeiitic affinity to a calc-alkaline affinity (Fig. 2.8b). Despite their larger negative Ti anomalies ($\text{Ti/Ti}^*=0.05-0.20$), the intermediate to felsic volcanic rocks display chondrite- and N-MORB-normalized patterns that are similar to those of the intermediate rocks (Figs. 2.11 and 2.12; Table 2.1).

2.5.2.4. *Felsic porphyritic rocks*

The felsic porphyritic rocks in the BVL greenstone belt have similar chemical compositions, and can be geochemically classified as rhyolites (Fig. 2.8a). The

majority of samples show a transition from tholeiitic to calc-alkaline affinities (Fig. 2.8b). They are characterized by high SiO₂ (76-82 wt. %), but low Cr (13-36 ppm), Ni (20-43 ppm), TiO₂ (0.26-0.43 wt.%), MgO (0.12-1.24 wt.%), and Sc (2-8 ppm) concentrations (Figs. 2.8-2.10; Table 2.1). Based on the Zr/Y ratios (3.5-10.4) versus Y (88-115) abundance, they are classified as FII rhyolites (cf., Leshner et al., 1986; Barrie et al., 1993; Barrett and MacLean, 1994; Hart et al., 2004).

On chondrite- and N-MORB-normalized trace element diagrams, the felsic porphyritic volcanic rocks are characterized by: (1) moderately enriched LREE patterns, at 10-50 times N-MORB (La/Sm_{cn}=1.78-2.32; Gd/Yb_{cn}=1.02-1.32; La/Yb_{cn}=2.17-3.17); (2) variably negative to positive Zr anomalies (Zr/Zr*=0.72-1.29); (3) strongly negative Nb (Nb/Nb*=0.16-0.48); and (4) pronounced negative Ti anomalies (Ti/Ti*=0.04-0.08) (Figs. 2.11 and 2.12; Table 2.1).

2.5.2.5. *Gabbros*

Gabbros are compositionally variable at 45-52 wt.% SiO₂, 0.82-2.69 wt.% TiO₂, 11.4-18.2 wt.% Al₂O₃, 13.6-26.1 wt.% Fe₂O₃, 4.3-8.1 wt.% MgO, and 6.0-10.8 wt.% CaO. Large variations in Cr (11-203 ppm), V (300-800 ppm), Zr (34 -220 ppm) and LREE (e.g., La=2.9-14.7 ppm), and moderate variations in Ni (117-197 ppm) and Y (14.8-30.9 ppm) contents. The ratios of Al₂O₃/TiO₂ (4-19) are subchondritic, whereas the ratios of Nb/Ta (14-29), Ti/Zr (60-282), and Zr/Y (1.6-7.1) are subchondritic to superchondritic (Table 2.1).

The gabbros display the following trace element characteristics: (1) near-flat to variably enriched LREE patterns (La/Sm_{cn}=0.93-2.36; La/Yb_{cn}=0.97-4.12) and flat to depleted HREE patterns (Gd/Yb_{cn}=1.06-2.48); (2) minor positive Ce (Ce/Ce*=1.01-1.16) anomalies; (3) moderately negative Eu anomalies (Eu/Eu*=0.60-0.96); (4)

negative to positive Zr ($Zr/Zr^*=0.25-1.25$) and Ti ($Ti/Ti^*=0.87-1.17$) anomalies; and (5) large negative Nb ($Nb/Nb^*=0.09-0.41$) anomalies (Figs. 2.11 and 2.12; Table 2.1).

2.5.2.6. *Siliciclastic sedimentary rocks*

Siliciclastic sedimentary samples from the Seine group are defined as fine-grained sandstones based on the analyses of their grain sizes under microscope (Fig. 2.5). They are distinguished by high SiO_2 (64.2-73.0 wt.%), Al_2O_3 (13.2-18.6 wt. %), LOI (2.9-4.8 wt.%) and low MgO (0.92-0.98 wt.%) concentrations (Table 2.1). These sedimentary rocks show the following characteristics on the chondrite- and N-MORB-normalized trace element diagrams: (1) strongly fractionated REE patterns ($La/Sm_{cn}=4.6-4.8$; $La/Yb_{cn}=23.6-27.3$); (2) large negative Nb ($Nb/Nb^*=0.05-0.08$) and Ti ($Ti/Ti^*=0.20-0.34$) anomalies; and (3) moderately negative Zr ($Zr/Zr^*=0.61-0.68$) anomalies (Figs. 2.10f and 2.11f; Table 2.1).

2.5.2.7. *Ottertail Lake granite*

The Ottertail Lake granite is characterized by 65.5-74.8 wt.% SiO_2 , 3.9-4.5 wt.% Na_2O , 3.6-4.6 wt.% K_2O and low volatile contents (0.4-0.7 wt.%) compared with rock units in the BVL greenstone belt (Table 2.2). The Rittmann Serial Index [$\sigma = (N_2O+K_2O)^2 / (SiO_2-43)$] (Rittmann, 1957) is consistent with a calc-alkaline affinity ($\sigma < 3.3$). The Al_2O_3 , N_2O , K_2O and CaO contents are consistent with metaluminous to slightly peraluminous affinities (Table 2.2).

The Ottertail granite has the following trace element characteristics: (1) strong fractionation of REE ($La/Sm_{cn}=4.4-8.6$; $La/Yb_{cn}=14.3-35.5$); (2) negative anomalies of Eu ($Eu/Eu^*=0.72-0.83$), Zr ($Zr/Zr^*=0.6-0.9$), Nb ($Nb/Nb^*=0.04-0.13$), and Ti ($Ti/Ti^*=0.11-0.22$) (Figs. 2.11 and 2.12; Table 2.2). Overall, the trace element patterns

of the granites are similar to the siliciclastic sedimentary rocks from the Seine Group (Figs. 2.11 and 2.12; Table 2.2). They plot in the VAG+syb-COLG and VAG fields on Y versus Nb and Y+Nb versus Rb tectonic discrimination diagrams, respectively (Fig. 2.13).

2.5.3. Radiogenic isotopes

2.5.3.1. Sm-Nd isotopes

All rock types, including mafic volcanic rocks ($\epsilon_{\text{Nd}} = +1.4$ to $+3.5$), gabbros ($\epsilon_{\text{Nd}} = +1.5$ to $+3.8$), intermediate volcanic rocks ($\epsilon_{\text{Nd}} = +3.1$ to $+4.0$), intermediate to felsic volcanoclastic rocks ($\epsilon_{\text{Nd}} = +0.8$ to 2.5), and porphyritic felsic volcanic rocks ($\epsilon_{\text{Nd}} = +2.0$ to $+2.6$) have variably positive initial (2720 Ma) ϵ_{Nd} values, and display similar $^{147}\text{Sm}/^{144}\text{Nd}$ ratios (Table 2.4). Depleted mantle model ages range from 2.76 to 3.18 Ga (Table 2.4). All samples have yielded an errorchron age of 2921 ± 200 Ma (MSWD=170) (Fig. 2.14). Mafic rocks (mafic volcanic rocks and gabbros) together have yielded an errorchron age of 2987 ± 260 Ma (MSWD=63) (Fig. 2.14), whereas the intermediate to felsic rocks have given an age of 2763 ± 480 Ma (MSWD=218).

The majority of major and elements do not show any significant correlations with $^{143}\text{Nd}/^{144}\text{Nd}$ ratios (Fig. 2.15). On some trace element diagrams (e.g., La, Y, Zr, Nb, Nd), the mafic rocks (e.g., mafic volcanic rocks and gabbros) and intermediate to felsic volcanic and volcanoclastic rocks plot as separate groups (Fig. 2.15).

2.5.3.2. Pb isotopes

All rock types in the BVL greenstone belt display large variations in $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$ isotope ratios (Table 2.5). A porphyritic rhyolite sample (BVL2013-030) has the highest $^{206}\text{Pb}/^{204}\text{Pb}$ (60.672), $^{207}\text{Pb}/^{204}\text{Pb}$ (23.404), and

$^{208}\text{Pb}/^{204}\text{Pb}$ (85.100) values, whereas gabbroic sample BVL2013-025 exhibits the lowest $^{206}\text{Pb}/^{204}\text{Pb}$ (13.805), $^{207}\text{Pb}/^{204}\text{Pb}$ (14.606), and $^{208}\text{Pb}/^{204}\text{Pb}$ (33.655) values in the belt (Table 2.5). All rock types have collectively yielded an errorchron age of 2661 ± 60 Ma (MSWD=880) (Fig. 2.14b). The mafic volcanic rocks and the gabbros together have yielded an age of 2725 ± 83 Ma (MSWD=63) (Fig. 2.14c), whereas the intermediate to felsic rocks have given an age of 2661 ± 100 Ma (MSWD=1573). There are no obvious correlations between rock types and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios for most major and trace element concentrations (Fig. 2.16).

2.5.3.3. *Sr isotopes*

$^{87}\text{Sr}/^{86}\text{Sr}$ ratios display large variations in mafic volcanic rocks (0.701512–0.730744), intermediate to felsic volcanoclastic rocks (0.722065–0.940511) and porphyritic felsic volcanic rocks (0.732422–1.011538), whereas they have smaller ranges in gabbros (0.701481–0.705468) and intermediate volcanic rocks (0.724179–0.724386) (Table 2.6). As a group, the gabbros have the lowest whereas the porphyritic rhyolites have the highest $^{87}\text{Sr}/^{86}\text{Sr}$ values (Table 2.6). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ ranges from 0.625650 to 0.769642. The BVL greenstone belt rocks have yielded an $^{87}\text{Rb}/^{86}\text{Sr}$ – $^{87}\text{Sr}/^{86}\text{Sr}$ errorchron age of 2229 ± 350 Ma (MSWD=59) (Fig. 2.14d). Like Nd and Pb isotopes, Sr isotopes do not display strong correlations with major and trace element concentrations (Fig. 2.17).

2.6. Discussion

2.6.1. *Effects of metamorphism on element mobility*

Metamorphic alteration has a strong impact on element mobility in Archean greenstone belts (Condie et al., 1977; Rubin, 1993; Polat and Hoffmann, 2003; Polat

et al., 2003, 2007). All major lithologic units of the BVL greenstone belt have undergone polyphase deformation and ubiquitous greenschist metamorphism that modified primary textures and minerals (Figs. 2.2-2.5). It is therefore necessary to understand the effects of alteration on the geochemical composition of the BVL greenstone belt before considering its petrogenetic origin and geodynamic setting. Altered samples are identified by the presence of Ce anomalies ($Ce/Ce^* < 0.9$ or $Ce/Ce^* > 1.1$) on chondrite-normalized REE diagrams and carbonate and silica (quartz) enrichment $> 2\%$ (Table 2.1) (see Polat and Hoffman, 2003). These samples are not used in petrogenetic interpretation.

Widespread occurrence of chlorite and epidote contributes to the enrichment of volatile phases (LOI: 3.37-9.21 wt.%) in the Bad Vermilion Lake greenstone belt, suggesting that they underwent extensive hydrothermal alteration (Figs. 2.2-2.5; Table 2.1), as seen in other Archean greenstone belts (Ludden et al., 1982; Xie et al., 1993; Kerrich et al., 1999; Polat et al., 2002; Polat and Hoffmann, 2003; Polat, 2009). Elements that were most resistant to alteration during metamorphism are HFSE (e.g., Nb, La-Lu) and transition metals (e.g. Sc, Ni), since they show moderate correlations with Zr on variation diagrams (Figs. 2.9 and 2.10).

Large scatter on the Sm–Nd, Pb–Pb and Rb–Sr regression diagrams and isotopic ratios is consistent with the mobility of these elements in some samples (Fig. 2.14; Tables 2.4-2.6). The 2225 ± 350 Ma $^{87}\text{Rb}/^{86}\text{Sr}$ – $^{87}\text{Sr}/^{86}\text{Sr}$ errorchron age yielded by the BVL greenstone belt is significantly lower than the zircon U–Pb ages (2722 ± 11 and 2724 ± 23 Ma) from the porphyritic rhyolites, suggesting that the Rb–Sr isotope system was mainly open during the hydrothermal alteration. In contrast, the $^{147}\text{Sm}/^{144}\text{Nd}$ – $^{143}\text{Nd}/^{144}\text{Nd}$ (2921 ± 200 Ma) and $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$ (2661 ± 60 Ma) plots have yielded errorchron ages that are closer to zircon U–Pb ages of the porphyritic rhyolites,

indicating that the Sm–Nd and U–Pb isotope systems were less susceptible to metamorphic recrystallization than the Rb–Sr system. Given that the U–Pb system among all three isotope systems has yielded the closest regression ages (2661 ± 60 Ma for all rocks; 2725 ± 83 Ma for mafic rocks) to the zircon ages, this isotope system appears to be the least affected by metamorphism.

2.6.2. *New age constraints and their implications*

Except for one inherited zircon grain with a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 2808 ± 24 Ma, magmatic zircons in sample BVL2013-030 have given a mean crystallization age of 2722 ± 11 Ma (Fig. 2.5a). Similarly, magmatic zircons from sample BVL2013-034 have yielded a crystallization age of 2724 ± 23 Ma (Fig. 2.5c). Therefore, these ages are interpreted as the crystallization of the porphyritic rhyolites in the BVL greenstone belt. These ages agree with the previously reported zircon age ($\sim$ ca. 2727 ± 1 Ma; Davis et al., 1989) on the felsic volcanic rocks in the BVL greenstone belt, reflecting the timing of the bimodal volcanism in the study area. The 2725 ± 83 Ma $^{206}\text{Pb}/^{204}\text{Pb}$ – $^{207}\text{Pb}/^{204}\text{Pb}$ errorchron age yielded by the mafic rocks (gabbros and basalts) can also be considered as the approximate age of the belt. The BVL greenstone belt and the anorthosite complex are intruded by the 2716 ± 18 Ma granitic rocks, constraining the minimum age of the BVL greenstone belt (Zhou et al., 2015).

Four structureless and homogenous zircons with lower $^{207}\text{Pb}/^{235}\text{U}$ and $^{206}\text{Pb}/^{238}\text{U}$ ratios in sample BVL 2013-031 have much younger $^{207}\text{Pb}/^{206}\text{Pb}$ ages ranging from 377 Ma to 2604 Ma (Table 2.3); these ages may be attributed to Pb loss during later tectonothermal events.

The Ottertail Lake granite (Fig. 2.7d) has yielded a relatively concordant crystallization age of ca. 2664 Ma, which marks the termination of deposition of

volcanic and sedimentary rocks in the BVL greenstone belt. Given that the majority of tholeiitic to calc-alkaline volcanic rocks in the western Wabigoon terrane were deposited between 2745 and 2720 Ma (Davis et al., 1988; Corfu and Davis, 1992), it is speculated that the cessation of the volcanism in the BVL greenstone belt marks the migration of arc magmatism farther south in the southern boundary of the West Wabigoon terrane. The majority of the large TTG intrusions in the western Wabigoon terrane were emplaced into the bimodal volcanic association between 2735 Ma and 2710 Ma (Davis and Edwards, 1982, 1986). Since Laurentian granitoids are geochemically similar to the spatially associated rhyolites (Ashwal et al., 1983), both the granitoids and the felsic volcanic rocks can be treated as a proxy for the early syn-volcanic tonalitic-dioritic-gabbroic batholith (ca. 2735-2720 Ma; Davis and Edwards, 1982, Corfu and Davis, 1992; Whalen et al., 2004) in the western Wabigoon terrane. Because the Bad Vermilion Lake anorthosite complex is intruded by 2716 Ma and 2649 Ma old granitic rocks (Zhou et al., 2015), it can be considered as contemporaneous with the bimodal volcanism in the BVL greenstone belt. Deposition of the juvenile Coutchiching Group and the immature Seine sedimentary rocks (conglomerates and sandstone) mark rapid uplifting and erosion in the region.

2.6.3. Source characteristics and tectonic setting of the BVL greenstone belt

Despite the effect of metamorphism, the Nd isotope compositions ($\epsilon_{\text{Nd}} = +0.8$ to $+4.0$) of the BVL greenstone belt rocks are similar to those of Neoarchean greenstone belts in other parts of the Superior Province (see Vervoort et al., 1994; Stevenson, 1995; Henry et al., 1998; Polat and Kerrich, 2002; Polat, 2009; Lodge et al., 2015), consistent with a depleted mantle source. The N-MORB-normalized trace element patterns (Fig. 2.12) indicate that the Neoarchean Bad Vermilion Lake volcanic rocks

were derived from a subarc mantle wedge (see Pearce and Peate, 1995; Murphy, 2007). Flat to slightly depleted HREE patterns (Fig. 8a-c) are consistent with a shallow (<90 km) mantle source (see Xie et al., 1993; Polat et al., 2005; Van Westrenen et al., 2001). Mafic rocks (basalts and gabbros) and intermediate and felsic rocks plot in two different fields on $^{143}\text{Nd}/^{144}\text{Nd}$ versus La, Nd, Nb and Y; this may reflect two different sources for the BVL greenstone belt rocks (Fig. 2.15).

The following observations suggest that the Bad Vermilion Lake volcanic rocks share the geochemical characteristic of Phanerozoic bimodal volcanic arcs: (1) the Bad Vermilion Lake volcanic rocks show a magmatic evolution trend from basalt to rhyolite on the SiO_2 versus Zr/TiO_2 diagram (Fig. 2.8a), such trend is analogous to volcanic rocks in Tonga trench (Ewart and Bryant, 1972; Ewart et al., 1973); (2) on the AFM diagram, they show a transition from tholeiitic to calc-alkaline series (Fig. 2.8b); (3) the Nb/Ta (12 to 19) ratios in the mafic volcanic rocks are similar to those in the modern arc and backarc systems (see Munker, 1998); (4) on the Th/Yb versus Nb/Yb binary diagram (not shown), the mafic volcanic rocks show geochemical similarities to Cenozoic oceanic island arc basalts (cf., Pearce, 2008); and (5) the mafic samples with lower contents of trace elements ($\sum\text{REE}=10\text{-}30 \times \text{chondrite}$) have higher Mg-number (40-60); while those with higher contents of trace elements ($\sum\text{REE}=10\text{-}30 \times \text{chondrite}$) possess lower Mg-number (20-40), reflecting various degrees of fractional crystallization or partial melting (cf., Greene, 2006).

The Bad Vermilion Lake felsic rocks share the negative Eu ($\text{Eu}/\text{Eu}^*=0.46\text{-}0.84$) and Ti ($\text{Ti}/\text{Ti}^*=0.03\text{-}0.08$) anomalies of felsic volcanic rocks in the Winston Lake greenstone belt, Wawa subprovince, which have been interpreted as arc-back arc volcanic rocks (Polat, 2009; Kerrich et al., 2008; Lodge et al., 2014, 2015).

2.6.4. Source characteristics of the Ottertail Lake granite

The Ottertail Lake granite has strongly fractionated REE patterns ($\text{La/Sm}_{\text{cn}}=4.4\text{--}8.6$, $\text{Gd/Yb}_{\text{cn}}=1.7\text{--}3.2$) and negative Nb, Ta, Ti, and Eu anomalies (Figs. 2.10 and 2.11). The Y versus Nb and Y+Nb versus Rb tectonic discrimination diagrams suggest that the Ottertail Lake granite (Fig. 2.13) originated in a syn-collisional arc setting at about 2664 Ma. It is compositionally akin to Archean granodiorite-granite-monzogranite (GGM)-type post-kinematic granitoids, which are usually interpreted as product of partial melting of Archean TTG crust and associated sediments in an extensional environment following a major orogeny (cf., Hart et al., 1981; Robb and Anhaeusser, 1983; Sylvester, 1994).

2.6.5. Geodynamic and petrogenetic implications

The BVL greenstone belt volcanic association is characterized by a bimodal tholeiitic to calc-alkaline suite displaying subduction geochemical signatures ($\text{Nb/Nb}^*=0.07\text{--}0.48$). The spatially associated layered gabbros and anorthosite complex also have subduction zone geochemical signatures ($\text{Nb/Nb}^*=0.04\text{--}0.99$) (Zhou et al., 2015). The field relationship (Figs. 2.2 and 2.3) and subduction zone geochemical signatures of all rock associations (Fig. 2.12) are consistent with the tectonic evolution of the region at a convergent plate margin (e.g., Percival et al., 2012).

Ophiolites are defined as fragments of oceanic crust and uppermost mantle, recording the opening and closure of ancient oceans in the framework of the Wilson cycles of plate tectonics (Şengör, 1990; Dilek and Furnes, 2014; Furnes et al., 2015). According to the Penrose definition, the stratigraphic sequence of ophiolites include, from bottom to top, mantle peridotites, layered gabbros, sheeted dykes, pillow basalts

and sedimentary covers (Anonymous, 1972). However, the Penrose definition of ophiolite has major limitations in defining ophiolites in the Archean rock record that is typically characterized by multiple phases of deformation, metamorphism and intrusion (Kusky, 2004; Kusky et al., 2014; Şengör and Natal'in, 2004; Dilek and Polat, 2008; Dilek and Furnes, 2011; Furnes et al., 2015). Given the inadequacy of the Penrose ophiolite definition in Precambrian orogenic belts, Dilek and Furnes (2011) redefined ophiolite as "suites of temporally and spatial associated ultramafic to felsic rocks related to separate melting episodes and processes of magmatic differentiation in particular tectonic environments". Dilek and Furnes (2011, 2014) reclassified ophiolites as: (1) subduction-related ophiolites originating in backarc, forearc and arc tectonic settings; and (2) subduction-unrelated ophiolites forming in rifted continental margins, mid-ocean ridges and oceanic plateaus. Lithological and geochemical characteristics of the BVL greenstone are consistent with being a subduction-related Archean ophiolite.

The Seine Group is bounded by unconformity with the underlying Keewatin and Coutchiching sequence. It is a Timiskaming-type deposit dominated by conglomerates and sandstones and siltstone with a maximum deposition age of around 2696 Ma (Wood, 1980; Davis et al., 1989), implying a shallow water alluvial-fan terrestrial depositional environment (Hyde, 1980; Mueller and Corcoran, 1998). Field observations suggest that the boulders and pebbles in the Timiskaming deposit (Figs. 2.2 and 2.3) were originated from the BVL greenstone belt and associated granitic rocks, suggesting that the region underwent uplift and erosion during Timiskaming deformation. Similarly, the trace element compositions of the Seine Group sandstones (Figs. 2.11 and 2.12) are similar to the volcanic and granitic rocks in the area, suggesting a proximal source area.

The BVL greenstone belt originated during the Central Superior orogeny (at ~2710-2700 Ma; Percival et al., 2006a). Based on the tectonic implications of each lithologic unit in the BVL region, a life cycle of intra-oceanic setting can be summarized as follows: (1) rifting of the Winnipeg River-Marmion terrane contributed to the build-up of western Wabigoon mafic oceanic crust spanning from 2775 to 2720 Ma (see Blackburn et al., 1991); (2) formation of the island arc bimodal volcanic association as well as spatially associated anorthosite and TTGs were mainly produced around ca. 2720 Ma due to oblique subduction of the oceanic western Wabigoon terrane underneath the oceanic crust of the Winnipeg River terrane (see Percival et al., 2006a); (3) the immature clastic sediments (e.g., the Coutchiching Group) were likely deposited in a marginal ocean basin or extended forearc basin between 2720 and 2710 Ma (see Percival et al., 2012); and (4) collision between the western Wabigoon terrane and the continental Winnipeg River terrane generated the oceanic-island-arc complex between 2710 and 2700 Ma (Corfu, 1988; Davis and Smith, 1991; Ayer and Dostal, 2000), which not only produced a large amount of intermediate volcanic rocks (Savant-Sturgeon greenstone belt; Sanborn-Barrie and Skulski, 2006 and reference therein), but also caused uplifting, erosion, deformation and local stratigraphic inversion in the BVL greenstone belt (Davis et al., 1989; Poulsen et al., 1980).

Due to the ca. 2690 Ma accretion of the Quetico sedimentary prism on the southern margin of the western Wabigoon terrane (Percival, 1989; Percival and Williams, 1989; Williams, 1990; Zaleski et al., 1999), the relative location of the BVL greenstone belt was transformed from the interior of the west Wabigoon terrane to the boundary between the Wabigoon and Quetico subprovinces.

The Ottetail Lake granite intruded in an extensional environment after the

Minnesotan (2.68 Ga) orogeny, when all the belt-like subprovinces had been assembled to form the Superior Province (Percival, 2006a, b, 2012). Collectively, the geodynamic processes that formed the supracrustal rocks in the BVL greenstone belt are consistent with an allochthonous rather than autochthonous origin, resulting from modern-style plate tectonic processes in the Mesoarchean to Neoarchean (see Williams, 1990; Williams et al., 1991; Percival et al., 2004; Backeberg et al., 2014; Kusky et al., 2014).

2.7. Conclusions

On the basis of new field observations, zircon U-Pb ages, whole-rock major and trace element, and Nd, Pb and Sr isotope data, the following conclusions are drawn for the Neoarchean Bad Vermilion Lake (BVL) greenstone belt and the spatially associated Ottertail Lake granite and the Timiskaming type Seine Group sedimentary rocks:

1. The Neoarchean (ca. 2720 Ma) BVL greenstone belt is composed of subduction-derived tholeiitic to calc-alkaline volcanic and volcanoclastic rocks including basalts, andesites and rhyolites. On the basis of new ophiolite classifications (Dilek and Furnes, 2011; Furnes et al., 2015), the BVL greenstone belt is defined as a subduction-related ophiolite. Positive initial ϵNd values (+0.8 to +4.0) in the BVL greenstone belt lithologies are consistent with a long-term depleted mantle source or sources. These ϵNd values are similar to those in other Neoarchean greenstone belts in the Superior Province.
2. Zircon U-Pb ages indicate that the porphyritic rhyolites in the BVL greenstone belt formed at ca. 2725 Ma, constraining the age of the belt and subduction zone

- processes, northerly subduction of oceanic crust beneath the Western Wabigoon and Marmion terrane in the region.
3. Based on the U-Pb zircon dating, the BVL greenstone belt is intruded by 2716, 2664 and 2649 Ma granitic rocks and overlain unconformably by 2696 Ma Timiskaming-type clastic sedimentary rocks.
 4. The emplacement of the late- to post-tectonic Ottertail Lake granite at ca. 2664 Ma marked the end of accretionary tectonic process between the Western Wabigoon and Marmion, Quetico and Wawa-Abitibi terranes. High SiO₂ (65-75 wt.%) and K₂O (3.9-4.5 wt.%) contents, negative Eu anomalies ($Eu/Eu^*=0.72-0.83$), and recycled older zircons (ca. 2868 Ma) in the Ottertail Lake granitic rocks suggest that they were derived from older felsic rocks. The origin of these rocks is attributed to an extensional tectonic regime following the collision between the Western Wabigoon and Marmion, Quetico and Wawa-Abitibi terranes.
 5. Petrographic observations, major and trace element, and Nd, Pb and Sr isotope data indicate that the BVL greenstone belt underwent intense hydrothermal alteration, resulting in mobilization of many elements (e.g., K, Rb, Ba, Sr, Na, and Pb). The REE (La-Lu), HFSE (e.g., Nb, Zr, Y), and some transitional metals (e.g., Ni and Sc) were among the least mobile elements. Hydrothermal alteration appears to have disturbed the Rb-Sr isotope system in all samples, and Sm-Nd and U-Pb isotope systems in some samples, resulting in 2229 ± 350 Ma, 2935 ± 280 Ma, and 2661 ± 60 Ma errorchron ages, respectively. The Pb-Pb regression ages in all rocks (2661 ± 60 Ma) and in the basalts and gabbro (2725 ± 25 Ma) are closer to the zircon U-Pb ages yielded by the porphyritic rhyolites (2722-2724 Ma) than those yielded by Sm-Nd and Rb-Sr systems, suggesting that during metamorphism the U-Pb system was the least affected system among the three isotope systems.

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2.9. References

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Figure 2.1. (a) Simplified tectonic map of the Superior Province (modified from Card and Ciesielski, 1986). (b) Regional geological map of the Rainy Lake area, Wabigoon subprovince, showing the location of the BVL greenstone belt and spatially related Ottertail Lake Stock and Bad Vermilion Lake anorthosite complex (modified from Blackburn et al., 1991).

Figure 2.2. Field photographs illustrating the lithological characteristics and field relationships of the Bad Vermilion Lake greenstone belt. (a) Foliated and folded mafic volcanic rock (basalt). (b) Foliated and folded mafic volcanic rock (basalt). (c) Felsic volcanic rock (rhyolite). (d) Layered gabbro. (e) Massive gabbro. (f) Polymictic conglomerate, consisting of greenstone, gabbro, and gneiss boulders.

Figure 2.3. Field photographs illustrating the lithological characteristics and field relationships of the Seine Group (Timiskaming-type) and Ottertail Lake granite. (a) Polymictic conglomerate, consisting of greenstone, pyroclastic, gabbro, and gneiss boulders. (b) Foliated and folded sandstone (greywacke). (c) Intrusive contact between the BVL greenstone belt and the Ottertail Lake granite. (d) Intrusive contact between the BVL greenstone belt and the Ottertail Lake granite. (e) Ottertail Lake granite. (f) Ottertail Lake granite.

Figure 2.4. Photomicrographs illustrating the petrographic characteristics of the BVL greenstone belt. (a) Mafic volcanic rock (basalt) consisting mainly of plagioclase and chlorite, and minor quartz. (b) Mafic volcanic rock (basalt) consisting mainly of plagioclase, chlorite, and opaque mineral. (c) Altered mafic volcanic rock consisting mainly of calcite and quartz. (d) Felsic volcanic rock (rhyolite) including quartz phenocrysts. (e) Felsic volcanic rock (rhyolite) including quartz phenocrysts. (f) Gabbro characterized by altered plagioclase, chlorite, and amphibole.

Figure 2.5. Photomicrographs illustrating the petrographic characteristics of the BVL greenstone belt. (a) Seine Group sandstone dominated by quartz. (b) Seine Group sandstone consisting mainly of plagioclase, calcite and opaque minerals. (c) Ottertail Lake granite consisting mainly of muscovite, quartz and feldspar. (d) Ottertail Lake granite characterized by muscovite, feldspar and quartz.

Figure 2.6. Cathodoluminescence images over representative zircons from the rhyolite samples (i.e., (a) BVL2013-030, (b) BVL2013-031, (c) BVL2013-034 in the Keewatin sequence, as well as (d) the granite sample BVL2013-058 in the Ottertail Lake Stock. Ellipse and circles with adjacent number denote spot positions, spot number and $^{207}\text{Pb}/^{206}\text{Pb}$ ages.

Figure 2.7. U-Pb Concordia diagrams for the analyzed zircons illustrating the ages of the samples BVL2013-030, BVL2013-031, BVL2013-034 in the BVL greenstone belt, and the Ottertail Lake granite sample BVL2013-058.

Figure 2.8. (a) Zr/TiO_2 versus SiO_2 (after Winchester and Floyd, 1977) and (b) FeO_T -total alkalis ($\text{Na}_2\text{O}+\text{K}_2\text{O}$)- MgO diagram (after Irvine and Baragar, 1971) chemical classification diagram for volcanic rocks from the BVL greenstone belt. In the diagram, ‘TrAn’ denotes Trachyte-Andesite; ‘Ab’ denotes Alkaline-Basalt; ‘Tonga’ represents the relative distribution of volcanic products from Tonga trench, a typical intra-oceanic arc setting.

Figure 2.9. (a-f) Variation diagrams of Zr versus TiO_2 (wt.%), Al_2O_3 (wt.%), MgO (wt.%), P_2O_5 (wt.%), Fe_2O_3 (wt.%), and CaO (wt.%), for mafic to felsic volcanic and volcaniclastic rocks in the BVL greenstone belt.

Figure 2.10. Variation diagrams of Zr versus Nb (ppm), Ni (ppm), La (ppm), Sc (ppm), Cr (ppm), and Y (ppm) for mafic to felsic volcanic and volcanoclastic rocks in the BVL greenstone belt.

Figure 2.11. Chondrite-normalized REE diagrams for (a) mafic volcanic rocks (mostly basalt), (b) intermediate volcanic rocks, (c) intermediate to felsic volcanic rocks, (d) prophyritic felsic volcanic rocks (rhyolites), (e) felsic volcaniclastic rocks, (f) gabbros, (g) siliciclastic sedimentary rocks, and (h) the Ottertail Lake granite. Normalization values are from Sun and McDonough (1989).

Figure 2.12. N-MORB-normalized trace element diagrams for (a) mafic volcanic rocks (mostly basalt), (b) intermediate volcanic rocks, (c) intermediate to felsic volcanic rocks, (d) porphyritic felsic volcanic rocks (rhyolites), (e) felsic volcaniclastic rocks, (f) gabbros, (g) siliciclastic sedimentary rocks, and (h) the Ottertail Lake granite. Normalization values are from Sun and McDonough (1989).

Figure 2.13. (a) Nb versus Y and (b) Rb versus Y+Nb tectonic discriminant diagrams for the Ottertail Lake granite (after Pearce et al., 1984). VAG: Volcanic Arc Granite; WPG: Within Plate Granite; ORG: Ocean Ridge Granite; syn-COLG: syn-Collision Granite.

Figure 2.14. (a) $^{147}\text{Sm}/^{144}\text{Nd}$ versus $^{143}\text{Nd}/^{144}\text{Nd}$, (b) $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$, (c) $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$, and (d) $^{87}\text{Rb}/^{86}\text{Sr}$ versus $^{87}\text{Sr}/^{86}\text{Sr}$ plots for the BVL greenstone belt rocks.

Figure 2.15. (a-f) $^{143}\text{Nd}/^{144}\text{Nd}$ versus SiO_2 (wt.%), Nb (ppm), Y (ppm), MgO (wt.%), Ni (ppm) and La (ppm) plots for the BVL greenstone belt rocks.

Figure 2.16. (a-f) $^{206}\text{Pb}/^{204}\text{Pb}$ versus SiO_2 (wt.%), TiO_2 (wt.%), K_2O (wt.%), MgO (wt.%), La (ppm), and Ni (ppm) plots for the BVL greenstone belt rocks.

Figure 2.17. $^{87}\text{Sr}/^{86}\text{Sr}$ versus SiO_2 (wt.%), TiO_2 (wt.%), La (wt.%), MgO (wt.%), K_2O (wt.%), and Zr (ppm) plots for the BVL greenstone belt rocks.

Table 2.1. Major (wt.%) and trace (ppm) element concentrations and significant element ratios for the Bad Vermilion Lake greenstone belt volcanic, volcanoclastic, and sedimentary rocks.

	Mafic volcanic rocks							
	BVL2013-001	BVL2013-002 ^a	BVL2013-009	BVL2013-010	BVL2013-011	BVL2013-021	BVL2013-022	BVL2013-023
SiO ₂	52.5	53.4	48.5	54.2	49.3	54.5	48.6	49.0
Al ₂ O ₃	13.0	15.8	16.7	13.1	15.7	13.4	12.0	13.4
Fe ₂ O ₃ (T)	17.9	10.7	14.4	16.3	14.5	17.3	19.8	17.4
MnO	0.21	0.22	0.24	0.21	0.14	0.23	0.27	0.24
MgO	3.39	5.56	2.97	5.31	10.07	3.08	5.20	5.80
CaO	7.36	9.36	11.81	6.28	5.34	6.11	7.90	7.43
Na ₂ O	2.89	4.19	3.03	1.93	3.35	1.81	1.65	3.22
K ₂ O	0.33	0.11	0.90	0.83	0.03	1.54	0.24	0.23
TiO ₂	2.11	0.56	1.37	1.67	1.47	1.60	3.70	2.81
P ₂ O ₅	0.37	0.01	0.13	0.24	0.12	0.41	0.70	0.55
LOI	8.67	9.70	10.04	7.32	4.25	9.21	3.37	7.34
Total	100.2	98.2	99.6	99.6	99.9	100.6	99.6	99.9
Mg-number	30	54	31	42	58	26	34	40
Cr	22	103	278	19	250	9	9	53
Co	49	23	61	47	58	38	51	48
Ni	198	73	277	132	264	86	227	193
Rb	6.2	2.2	20.7	16.3	0.4	30.5	4.9	3.4
Sr	81	90	144	115	90	108	194	133
Cs	0.19	0.08	0.69	0.78	0.13	0.39	0.32	0.15
Ba	88	54	235	270	9	462	68	66
Sc	35	24	25	34	27	27	44	38
V	163	156	272	374	307	94	471	464
Ta	0.29	0.19	0.12	0.38	0.110	0.443	0.349	0.251
Nb	5.31	2.21	1.66	5.45	1.61	6.89	5.88	4.45
Zr	166	59	59	159	56	209	133	106
Th	3.88	1.83	0.39	2.49	0.38	3.02	0.82	0.64
Y	16.16	12.21	15.10	17.80	13.6	29.9	25.8	18.7
U	0.63	0.40	0.08	0.51	0.07	0.64	0.18	0.14
La	15.89	6.34	4.20	16.79	4.07	23.80	12.13	11.25
Ce	44.22	16.20	10.74	39.82	9.83	55.28	30.27	26.74
Pr	6.35	2.44	1.55	5.14	1.40	7.12	4.26	3.59
Nd	28.12	11.42	7.55	21.76	6.72	30.15	19.76	16.20
Sm	6.05	2.90	2.17	5.07	1.90	6.75	4.95	3.97
Eu	1.55	0.82	0.90	1.35	0.70	1.76	1.75	1.46
Gd	4.65	2.78	2.72	4.73	2.37	6.53	5.49	4.31
Tb	0.62	0.45	0.46	0.69	0.39	0.91	0.81	0.63
Dy	3.42	2.67	2.84	3.72	2.46	5.37	4.91	3.68
Ho	0.66	0.50	0.57	0.51	0.51	1.14	0.98	0.74
Er	2.01	1.38	1.65	2.19	1.48	3.55	2.82	2.11
Tm	0.27	0.19	0.22	0.33	0.21	0.51	0.38	0.28
Yb	1.82	1.28	1.42	2.32	1.35	3.47	2.38	1.80
Lu	0.30	0.19	0.21	0.40	0.20	0.54	0.35	0.27
Cu	139	19	125	74	23	20	48	111
Zn	138	752	138	191	102	208	283	268
Pb	2.87	2.14	3.63	4.51	1.08	2.49	6.13	5.89
Al ₂ O ₃ /TiO ₂	6	28	12	8	11	8	3	5
Nb/Ta	19	12	14	14	15	16	17	18
Zr/Y	10.3	4.8	3.9	8.9	4.1	7.0	5.2	5.7
Ti/Zr	76	57	139	63	157	46	167	159
Y/Ho	25	25	26	26	27	26	26	25
La/Sm _{cn}	1.70	1.41	1.25	2.14	1.38	2.28	1.58	1.83
La/Yb _{cn}	6.26	3.56	2.12	5.20	2.16	4.91	3.65	4.49
Gd/Yb _{cn}	2.11	1.80	1.58	1.69	1.45	1.55	1.91	1.98
Ce/Ce*	1.08	1.01	1.03	1.05	1.01	1.04	1.03	1.03
Eu/Eu*	0.90	0.88	1.13	0.84	1.01	0.81	1.03	1.08
Zr/Zr*	0.75	0.61	0.86	0.90	0.93	0.87	0.80	0.78
Ti/Ti*	0.98	0.48	1.38	0.84	1.70	0.59	1.74	1.66
Nb/Nb*	0.16	0.15	0.31	0.20	0.30	0.19	0.44	0.39

^a: Altered; cn: Chondrite-normalized

Table 2.1. (Continued)

	Intermediate volcanic rocks				
	BVL2013-003	BVL2013-012	BVL2013-013	BVL2013-026	BVL2013-027
SiO ₂	66.6	59.1	62.7	62.3	65.9
Al ₂ O ₃	14.6	14.6	23.6	13.0	12.7
Fe ₂ O ₃ (T)	6.2	11.6	2.7	12.3	8.9
MnO	0.15	0.21	0.02	0.08	0.04
MgO	2.13	2.65	0.65	9.44	8.16
CaO	4.37	5.63	0.68	0.74	0.75
Na ₂ O	3.70	4.19	0.75	0.03	1.67
K ₂ O	1.60	0.71	7.41	0.50	0.27
TiO ₂	0.54	1.03	1.05	1.23	1.22
P ₂ O ₅	0.14	0.29	0.48	0.44	0.44
LOI	4.81	5.99	3.00	4.96	4.20
Total	100.0	98.4	100.0	100.9	100.5
Mg-number	40	31	32	60	65
Cr	47	15	17	12	10
Co	15	25	6	11	13
Ni	59	85	78	65	60
Rb	54	21	242	9.0	4.6
Sr	458	97	121	7	20
Cs	2.43	0.57	4.04	0.12	0.04
Ba	633	165	1227	110	89
Sc	11	23	23	25	25
V	104	117	287	4	4
Ta	0.490	0.331	0.656	0.420	0.594
Nb	5.17	4.64	12.04	8.01	8.26
Zr	159	134	305	283	214
Th	6.26	1.78	19.98	6.54	3.41
Y	14.3	18.3	28.6	77.0	27.6
U	1.31	0.40	4.85	0.71	0.49
La	27.03	14.69	79.51	20.34	24.64
Ce	54.64	35.34	162.62	49.00	55.40
Pr	6.03	4.57	17.67	6.70	7.43
Nd	22.66	19.50	65.15	30.60	32.98
Sm	4.20	4.17	11.19	8.26	8.18
Eu	1.00	1.11	2.70	1.39	1.16
Gd	3.46	3.87	8.07	10.52	7.35
Tb	0.50	0.56	1.02	1.91	0.99
Dy	2.77	3.32	5.25	13.32	5.47
Ho	0.53	0.68	1.00	2.89	1.08
Er	1.62	2.15	3.13	8.67	3.36
Tm	0.23	0.32	0.39	1.25	0.50
Yb	1.43	2.18	2.48	8.20	3.47
Lu	0.22	0.35	0.41	1.20	0.58
Cu	36	33	21	12	11
Zn	70	152	186	164	129
Pb	7.91	1.95	30.50	7.00	10.91
Al ₂ O ₃ /TiO ₂	27	14	23	11	10
Nb/Ta	11	14	18	19	14
Zr/Y	11.1	7.3	10.7	3.7	7.8
Ti/Zr	21	46	21	26	34
Y/Ho	27	27	29	27	26
La/Sm _{cn}	4.15	2.27	4.59	1.59	1.94
La/Yb _{cn}	13.58	4.83	22.95	1.78	5.09
Gd/Yb _{cn}	2.01	1.47	2.69	1.06	1.75
Ce/Ce*	1.05	1.06	1.06	1.03	1.00
Eu/Eu*	0.80	0.84	0.87	0.46	0.46
Zr/Zr*	0.96	0.88	0.67	1.05	0.77
Ti/Ti*	0.35	0.63	0.27	0.32	0.39
Nb/Nb*	0.09	0.21	0.07	0.16	0.21
North	532351	535091	535997	522085	520799
East	5399420	5399610	5399400	5400301	5399678

Table 2.1. (Continued)

	Intermediate to felsic volcaniclastic rocks							
	BVL2013-004	BVL2013-005	BVL2013-006	BVL2013-007	BVL2013-008	BVL2013-015	BVL2013-024	BVL2013-036 ^a
SiO ₂	74.2	74.6	76.5	73.5	72.3	66.7	67.3	77.2
Al ₂ O ₃	10.4	11.1	11.1	10.9	11.3	16.2	10.6	11.4
Fe ₂ O ₃ (T)	10.4	7.8	5.9	11.9	6.8	4.8	17.7	2.7
MnO	0.04	0.07	0.08	0.06	0.26	0.09	0.08	0.03
MgO	3.40	1.19	0.93	1.86	0.83	0.98	3.05	0.53
CaO	0.09	1.35	1.06	0.09	5.24	2.85	0.19	0.41
Na ₂ O	0.09	2.93	3.18	0.14	0.87	3.52	0.03	2.18
K ₂ O	0.96	0.56	0.82	1.21	2.04	3.77	0.32	5.40
TiO ₂	0.34	0.34	0.34	0.36	0.35	0.74	0.63	0.24
P ₂ O ₅	0.04	0.04	0.04	0.04	0.04	0.35	0.12	0.01
LOI	2.89	2.58	2.21	2.62	6.04	4.41	3.09	0.25
Total	99.6	100.9	100.2	98.4	98.5	100.6	99.5	99.6
Mg-number	42.1	25.4	26	26	21	29	25	31
Cr	23	21	23	11	16	52	22	18
Co	5	2	2	4	2	12	15	1
Ni	26	26	25	27	26	72	43	23
Rb	19	12	19	21	41	116	4.7	93
Sr	15	25	34	11	32	532	6	39
Cs	0.77	0.54	0.9	0.76	1.49	3.04	0.09	0.66
Ba	384	69	137	482	212	1172	103	1134
Sc	3	3	3	3	3	11	11	2
V	7	6	4.4	4.5	5.5	84	33	0.59
Ta	1.07	1.18	1.22	1.09	1.02	0.67	0.82	1.35
Nb	15.14	16.71	17.11	15.58	16.47	12.37	11.81	19.19
Zr	529	572	562	526	544	274	383	573
Th	6.06	6.77	6.60	6.24	6.66	15.31	4.99	8.49
Y	55	71	60	59	60	27	41	79
U	1.31	1.41	1.54	1.32	1.41	3.31	1.05	2.22
La	45.11	47.69	41.36	35.83	43.68	76.49	33.12	52.23
Ce	108.72	113.23	99.43	91.16	104.46	163.97	79.32	142.78
Pr	14.08	14.54	12.76	11.29	13.59	18.22	10.30	16.82
Nd	61.97	64.03	55.94	49.36	59.68	66.32	45.13	71.96
Sm	15.35	16.01	14.22	12.60	14.46	10.76	11.35	18.25
Eu	2.79	3.18	2.76	3.24	2.67	2.04	1.86	3.09
Gd	12.58	14.33	12.57	11.07	11.58	7.67	9.73	18.78
Tb	1.62	1.94	1.69	1.61	1.55	0.97	1.29	2.95
Dy	9.34	11.73	9.94	9.89	9.56	4.96	7.46	17.25
Ho	2.07	2.65	2.23	2.20	2.19	0.94	1.57	3.45
Er	7.15	9.05	8.03	7.54	7.72	3.07	5.16	10.41
Tm	1.15	1.44	1.33	1.21	1.24	0.39	0.82	1.48
Yb	8.36	10.39	10	8.86	9.36	2.32	6.11	9.99
Lu	1.39	1.70	1.7	1.47	1.55	0.38	1.03	1.53
Cu	5.01	5.72	6.5	7.65	7.90	22	7	4
Zn	71.25	124.42	145	135.55	151.67	145	208	63
Pb	7.66	2.26	1.32	4.18	11.46	21.52	4.28	5.00
Al ₂ O ₃ /TiO ₂	31	33	33	30	32	22	17	47
Nb/Ta	14	14	14	14	16	18	14	14
Zr/Y	9.5	8.0	9.4	8.9	9.1	10.3	9.4	7.2
Ti/Zr	4	4	4	4	4	16	10	3
Y/Ho	27	27	27	27	27	28	26	23
La/Sm _{cn}	1.90	1.92	1.88	1.84	1.95	4.59	1.88	1.85
La/Yb _{cn}	3.87	3.29	2.94	2.90	3.35	23.62	3.89	3.75
Gd/Yb _{cn}	1.24	1.14	1.03	1.03	1.02	2.73	1.32	1.55
Ce/Ce*	1.06	1.05	1.06	1.11	1.05	1.08	1.05	1.18
Eu/Eu*	0.61	0.64	0.63	0.84	0.63	0.69	0.54	0.51
Zr/Zr*	1.02	1.06	1.18	1.25	1.10	0.61	1.00	0.94
Ti/Ti*	0.06	0.05	0.06	0.08	0.07	0.20	0.15	0.03
Nb/Nb*	0.22	0.22	0.24	0.25	0.23	0.08	0.22	0.21
North	533170	533659	533342	533630	533693	536776	525528	514160
East	5399620	5399659	5399662	5399666	5399650	5399101	5400865	5394956

Table 2.1. (Continued)

	Volcaniclastic rocks		Porphyritic felsic rocks (rhyolite)				
	BVL2013-038	BVL2013-039	BVL2013-030	BVL2013-031	BVL2013-033	BVL2013-034	BVL2013-037
SiO ₂	65.5	66.0	79.0	73.7	82.3	76.7	76.2
Al ₂ O ₃	12.3	12.0	11.0	10.9	9.2	10.1	12.2
Fe ₂ O ₃ (T)	11.7	11.5	3.3	6.2	2.1	6.1	4.7
MnO	0.13	0.11	0.07	0.08	0.05	0.13	0.06
MgO	2.54	2.28	0.33	0.66	0.12	0.36	1.24
CaO	2.19	2.34	1.12	2.47	2.15	1.65	0.32
Na ₂ O	4.00	4.12	2.99	3.01	2.70	2.48	1.97
K ₂ O	0.58	0.50	1.92	2.41	1.01	2.14	3.08
TiO ₂	0.85	0.88	0.29	0.43	0.31	0.33	0.26
P ₂ O ₅	0.19	0.21	0.02	0.05	0.03	0.04	0.01
LOI	1.21	0.72	1.06	1.44	0.78	0.86	1.14
Total	100.8	100.0	100.2	100.7	99.5	100.5	98.0
Mg-number	30	28	17	17	10	10	34
Cr	15	29	18	15	36	28	13
Co	13	13	1	3	1	2	1
Ni	55	59	24	33	20	43	20
Rb	10.4	9.7	39	70	20	52	52
Sr	43	53	20	55	67	32	15
Cs	0.31	0.30	0.32	0.97	0.25	0.86	0.54
Ba	87	81	248	581	178	275	1034
Sc	16	17	4	8	3	4	2
V	43	45	1	3	1	1	0
Ta	0.72	0.83	1.305	1.520	0.833	0.813	1.401
Nb	10.93	11.51	18.09	21.43	12.71	28.19	19.94
Zr	403	398	594	405	512	506	598
Th	4.98	5.20	9.07	9.86	9.76	5.79	9.56
Y	83	90	115.0	115.8	82.0	94.0	88.4
U	1.13	1.16	2.00	2.16	1.33	1.25	2.13
La	29.48	31.05	51.88	58.24	35.60	32.99	56.03
Ce	69.59	74.51	120.02	132.39	84.85	77.67	133.27
Pr	9.27	9.74	15.10	16.34	11.04	10.18	16.71
Nd	41.53	43.53	64.40	67.75	48.62	45.25	69.92
Sm	11.09	11.61	15.98	16.18	12.59	11.99	16.92
Eu	2.46	2.54	3.08	2.94	2.76	2.60	2.61
Gd	13.58	14.34	18.15	17.87	14.57	14.54	17.82
Tb	2.25	2.42	3.07	3.06	2.46	2.50	2.86
Dy	14.69	15.87	20.14	20.06	15.63	16.65	17.29
Ho	3.18	3.43	4.43	4.31	3.23	3.62	3.51
Er	9.76	10.51	13.80	13.46	9.72	11.11	10.91
Tm	1.43	1.54	2.02	1.97	1.39	1.63	1.64
Yb	9.56	10.24	13.54	13.20	9.10	10.93	11.89
Lu	1.47	1.56	2.02	2.01	1.32	1.62	1.94
Cu	8	8	11	4	8	41	5
Zn	212	149	95	101	440	176	129
Pb	8.59	5.06	3.03	5.84	36.53	3.30	6.06
Al ₂ O ₃ /TiO ₂	14	14	38	25	30	31	46
Nb/Ta	15	14	14	14	15	35	14
Zr/Y	4.9	4.4	5.2	3.5	6.2	5.4	6.8
Ti/Zr	13	13	3	6	4	4	3
Y/Ho	26	26	26	27	25	26	25
La/Sm _{cn}	1.72	1.73	2.10	2.32	1.83	1.78	2.14
La/Yb _{cn}	2.21	2.18	2.75	3.17	2.81	2.17	3.38
Gd/Yb _{cn}	1.18	1.16	1.11	1.12	1.32	1.10	1.24
Ce/Ce*	1.03	1.05	1.05	1.05	1.05	1.04	1.07
Eu/Eu*	0.61	0.60	0.55	0.53	0.62	0.60	0.46
Zr/Zr*	1.11	1.05	1.10	0.72	1.23	1.29	1.03
Ti/Ti*	0.17	0.17	0.04	0.06	0.06	0.06	0.04
Nb/Nb*	0.21	0.21	0.20	0.21	0.16	0.48	0.20
North	514940	514940	518966	518921	515548	515525	514671
East	5394460	5394460	5399537	5399556	5395295	5395228	5394823

Table 2.1. (Continued)

	Gabbros								
	BVL2013-018 ^a	BVL2013-019	BVL2013-020	BVL2013-025	BVL2013-028	BVL2013-029	BVL2013-032	BVL2013-035	BVL2013-040
SiO ₂	44.7	49.6	48.1	50.4	52.2	49.3	50.3	48.3	49.8
Al ₂ O ₃	11.4	17.9	18.2	15.3	13.0	13.3	15.6	14.6	13.5
Fe ₂ O ₃ (T)	26.1	16.0	15.2	16.4	16.9	16.6	13.6	15.4	17.7
MnO	0.23	0.16	0.15	0.23	0.22	0.22	0.21	0.27	0.22
MgO	5.58	4.67	4.64	8.01	4.26	5.64	5.84	6.64	4.25
CaO	9.05	5.96	10.09	7.13	7.72	10.52	10.84	8.87	8.37
Na ₂ O	0.04	4.37	1.80	1.59	2.79	2.17	2.13	3.07	2.65
K ₂ O	0.01	0.09	0.04	0.05	0.82	0.33	0.54	1.35	0.86
TiO ₂	2.69	1.12	1.60	0.82	1.83	1.73	0.90	1.38	2.18
P ₂ O ₅	0.19	0.12	0.10	0.06	0.27	0.16	0.06	0.09	0.43
LOI	8.85	6.73	4.52	4.03	1.48	2.26	2.08	1.08	0.99
Total	100.1	100.3	100.9	100.5	100.4	100.8	100.5	99.5	99.1
Mg-number	32	39	40	52	33	40	46	46	32
Cr	11	39	22	203	70	50	196	191	11
Co	83	53	49	50	47	58	47	55	49
Ni	197	117	137	144	149	167	118	196	153
Rb	0.62	1.37	1.04	1.26	19	7.1	18	46	22
Sr	58	41	154	160	161	182	127	128	242
Cs	0.08	0.05	0.12	0.12	0.55	0.22	0.32	1.78	0.64
Ba	5.30	24.24	12.82	19	233	91	109	437	236
Sc	43	38	32	47	34	37	42	31	31
V	803	418	602	305	405	590	303	311	433
Ta	0.20	0.11	0.05	0.07	0.265	0.184	0.084	0.200	0.310
Nb	3.33	1.45	1.51	1.26	4.83	3.27	1.31	2.85	4.98
Zr	83	55	34	46	162	96	47	76	219
Th	1.21	0.83	1.14	2.20	3.79	4.90	0.46	0.55	1.84
Y	16.22	14.79	20.70	18	30	22	19	17	31
U	0.34	0.33	0.42	0.06	0.45	0.27	0.04	0.09	0.36
La	10.08	4.04	14.21	2.98	14.36	9.88	2.88	4.90	14.65
Ce	37.27	13.57	32.43	7.46	34.19	23.00	7.19	13.08	35.17
Pr	6.20	2.25	3.94	1.08	4.48	3.02	1.06	1.97	4.68
Nd	28.70	10.91	16.22	5.34	19.58	13.36	5.41	9.82	20.93
Sm	6.11	2.81	3.89	1.78	4.79	3.35	1.82	3.00	5.17
Eu	1.25	0.56	0.80	0.57	1.46	1.11	0.70	0.95	1.76
Gd	5.26	2.94	4.10	2.51	5.52	3.85	2.71	3.75	6.13
Tb	0.74	0.48	0.66	0.44	0.89	0.63	0.48	0.57	0.94
Dy	3.89	2.99	4.17	3.05	5.60	4.02	3.23	3.52	5.85
Ho	0.71	0.62	0.86	0.67	1.17	0.84	0.71	0.69	1.21
Er	2.02	1.74	2.49	2.06	3.49	2.49	2.15	1.94	3.55
Tm	0.27	0.23	0.33	0.30	0.49	0.35	0.32	0.25	0.49
Yb	1.76	1.47	2.12	1.95	3.14	2.26	2.12	1.61	3.12
Lu	0.28	0.21	0.30	0.28	0.47	0.33	0.31	0.24	0.47
Cu	122.94	26.49	94.38	88.67	88	115	129	17	46
Zn	158.81	118.94	120.61	245.55	354	166	187	201	224
Pb	2.32	1.58	7.46	45.73	137.2	7.27	4.02	4.30	3.57
Al ₂ O ₃ /TiO ₂	4	16	11	19	7	8	17	11	6
Nb/Ta	17	14	29	17	18	18	16	14	16
Zr/Y	5.1	3.7	1.6	2.6	5.3	4.4	2.5	4.5	7.1
Ti/Zr	194	122	282	107	68	108	114	109	60
Y/Ho	23	24	24	26	26	26	26	25	26
La/Sm _{cn}	1.07	0.93	2.36	1.08	1.94	1.90	1.02	1.06	1.83
La/Yb _{cn}	4.12	1.98	4.82	1.10	3.28	3.14	0.97	2.18	3.37
Gd/Yb _{cn}	2.48	1.66	1.60	1.07	1.45	1.41	1.06	1.92	1.62
Ce/Ce*	1.16	1.10	1.06	1.02	1.04	1.03	1.01	1.03	1.04
Eu/Eu*	0.67	0.60	0.62	0.83	0.87	0.95	0.96	0.87	0.96
Zr/Zr*	0.37	0.59	0.25	0.88	0.99	0.85	0.89	0.83	1.25
Ti/Ti*	1.17	0.96	0.98	0.95	0.87	1.18	0.99	1.01	0.95
Nb/Nb*	0.22	0.19	0.09	0.12	0.15	0.11	0.27	0.41	0.23
North	528315	528258	528234	522085	519577	519577	518907	514229	514903
East	5400675	5400787	5400790	5400301	5399550	5399550	5399558	5394913	5393900

Table 2.1. (Continued)

	Siliciclastic rocks		
	BVL2013-014	BVL2013-015	BVL2013-016
SiO ₂	73.0	66.7	64.3
Al ₂ O ₃	13.2	16.2	18.6
Fe ₂ O ₃ (T)	4.5	4.8	5.3
MnO	0.08	0.09	0.08
MgO	0.92	0.98	0.93
CaO	2.06	2.85	2.58
Na ₂ O	3.52	3.52	2.63
K ₂ O	2.02	3.77	4.59
TiO ₂	0.54	0.74	0.69
P ₂ O ₅	0.15	0.35	0.27
LOI	2.85	4.41	4.79
Total	100.3	100.6	99.4
Mg-number	29	29	26
Cr	163	52	190
Co	19	12	19
Ni	93	72	118
Rb	74	116	137
Sr	227	532	380
Cs	2.83	3.04	4.02
Ba	455	1172	1060
Sc	10	11	13
V	87	84	96
Ta	0.266	0.672	0.728
Nb	3.98	12.37	10.02
Zr	119	274	252
Th	10.73	15.31	15.58
Y	10.3	26.5	20.5
U	2.03	3.31	3.50
La	33.03	76.49	65.64
Ce	66.26	163.97	137.62
Pr	7.34	18.22	15.13
Nd	27.08	66.32	54.35
Sm	4.47	10.76	8.84
Eu	1.07	2.04	1.68
Gd	3.33	7.67	5.95
Tb	0.41	0.97	0.77
Dy	2.04	4.96	3.88
Ho	0.38	0.94	0.73
Er	1.18	3.07	2.41
Tm	0.14	0.39	0.31
Yb	0.87	2.32	1.90
Lu	0.14	0.38	0.31
Cu	62	22	59
Zn	206	145	99
Pb	106.4	21.5	19.2
Al ₂ O ₃ /TiO ₂	24	22	27
Nb/Ta	15	18	14
Zr/Y	11.6	10.3	12.3
Ti/Zr	5.3	3.1	4.0
Y/Ho	27	28	28
La/Sm _{cn}	4.8	4.6	4.8
La/Yb _{cn}	27.3	23.6	24.8
Gd/Yb _{cn}	3.2	2.7	2.6
Ce/Ce*	1.04	1.08	1.07
Eu/Eu*	0.85	0.69	0.71
Zr/Zr*	0.64	0.61	0.68
Ti/Ti*	0.34	0.20	0.23
Nb/Nb*	0.05	0.08	0.07
North	535952	536776	536365
East	5399449	5399101	5399243

Table 2.2. Major (wt.%) and trace (ppm) element concentrations and significant element ratios for the Ottetail Lake granite.

	Ottetail Lake granite						
	BVL2013-056	BVL2013-057	BVL2013-058	BVL2013-059	BVL2013-060	BVL2013-061	BVL2013-062
SiO ₂	65.5	67.0	70.0	70.6	73.5	74.2	74.8
Al ₂ O ₃	15.0	15.1	14.9	15.1	14.7	14.3	14.3
Fe ₂ O ₃ (T)	4.8	4.2	3.3	2.7	1.6	1.4	1.5
MnO	0.07	0.06	0.06	0.04	0.04	0.03	0.03
MgO	2.42	1.96	1.14	0.94	0.33	0.22	0.21
CaO	3.41	3.23	2.32	2.16	1.45	1.01	0.98
Na ₂ O	3.89	4.02	4.24	4.47	4.46	4.11	4.29
K ₂ O	4.19	3.77	3.58	3.57	3.74	4.55	3.71
TiO ₂	0.54	0.49	0.36	0.30	0.14	0.12	0.10
P ₂ O ₅	0.20	0.19	0.16	0.12	0.05	0.02	0.02
LOI	0.68	0.64	0.41	0.66	0.41	0.44	0.45
Total	99.1	100.6	100.8	100.7	100.7	99.9	99.9
Mg-number	50	48	41	41	28	24	22
Cr	86	71	41	24	16	20	10
Co	13.0	11.5	7.1	5.3	2.0	1.3	1.2
Ni	70	64	38	29	13	11	8
Rb	101	103	100	96	115	134	100
Sr	890	977	920	802	628	299	575
Cs	1.3	2.1	3.8	1.6	2.5	5.2	2.8
Ba	1300	1247	1190	1234	1293	953	1297
Sc	8.0	6.0	4.0	3.0	2.0	1.0	1.0
V	65	55	33	25	8	6	4
Ta	0.7	0.7	0.5	0.5	0.6	0.4	0.3
Nb	9.2	8.1	5.7	5.3	5.5	4.4	3.6
Zr	199	186	150	132	93	90	79
Th	9.4	10.3	8.6	8.4	5.4	14.5	4.6
Y	17.8	15.6	12.0	10.3	8.3	7.4	7.0
U	2.1	2.1	1.9	1.1	1.9	3.0	0.8
La	51.9	46.4	38.4	33.6	18.5	37.5	21.6
Ce	112.6	100.7	78.9	69.1	37.1	65.5	38.9
Pr	12.9	11.3	9.5	7.7	4.1	6.4	4.1
Nd	47.7	40.9	35.1	28.0	14.5	20.1	13.6
Sm	7.7	6.4	5.6	4.4	2.4	2.8	2.2
Eu	1.6	1.4	1.2	1.0	0.5	0.6	0.5
Gd	5.6	4.7	4.1	3.1	1.9	2.2	1.7
Tb	0.7	0.6	0.5	0.4	0.3	0.3	0.2
Dy	3.5	3.0	2.4	1.9	1.4	1.3	1.2
Ho	0.7	0.6	0.4	0.4	0.3	0.3	0.2
Er	2.1	1.8	1.5	1.2	0.9	0.9	0.8
Tm	0.3	0.2	0.2	0.2	0.1	0.1	0.1
Yb	1.6	1.4	1.1	0.9	0.9	0.8	0.8
Lu	0.2	0.2	0.2	0.2	0.1	0.1	0.1
Cu	17.0	14.6	6.6	5.4	5.6	3.7	3.9
Zn	113	110	93	126	61	66	176
Pb	20.3	19.8	17.1	15.8	21.2	27.7	23.3
Al ₂ O ₃ /TiO ₂	28	31	42	51	102	124	143
Nb/Ta	13	12	11	11	9	10	13
Zr/Y	11.2	11.9	12.5	12.8	11.2	12.1	11.2
Y/Ho	27.1	27.7	27.2	28.3	29.1	29.0	28.2
Ti/Zr	16	16	14	13	9	8	8
La/Sm _{cn}	4.4	4.7	4.5	5.0	4.9	8.6	6.5
La/Yb _{cn}	23.1	23.6	26.0	25.8	14.3	35.5	19.8
Gd/Yb _{cn}	2.9	2.7	3.2	2.7	1.7	2.4	1.8
Ce/Ce*	1.1	1.1	1.0	1.1	1.0	1.0	1.0
Eu/Eu*	0.7	0.8	0.8	0.8	0.8	0.8	0.8
Zr/Zr*	0.6	0.7	0.6	0.7	0.9	0.7	0.9
Ti/Ti*	0.2	0.2	0.2	0.2	0.2	0.1	0.1
Nb/Nb*	0.10	0.09	0.07	0.07	0.13	0.04	0.09
North	516902	516642	515178	514355	513131	512005	510582
East	5399375	5399284	5399275	5399043	5398644	5398281	5397721

Table 2.3. Results of zircon U-Pb isotope analyses

BVL2013-030, Rhyolite from the Keewatin sequence in the Bad Vermillion Lake greenstone belt (North: 518966 and East: 5399537)																
	Element concentrations		Isotopic ratios							Ages (Ma)						
	Th (ppm)	U (ppm)	Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	Concordance
BVL-030-32	54	81	0.66	0.1978	0.0051	15.800	0.404	0.576	0.0070	2808	24	2865	24	2934	28	97%
BVL-030-17	29	49	0.58	0.1933	0.0060	14.170	0.423	0.530	0.0082	2771	27	2761	28	2743	34	99%
BVL-030-19	12	28	0.43	0.1932	0.0073	14.782	0.563	0.555	0.0089	2770	38	2801	36	2846	37	98%
BVL-030-31	38	64	0.59	0.1931	0.0053	14.557	0.416	0.543	0.0066	2769	29	2787	27	2796	28	99%
BVL-030-18	15	34	0.44	0.1930	0.0063	14.107	0.470	0.529	0.0085	2768	31	2757	32	2739	36	99%
BVL-030-15	37	63	0.60	0.1926	0.0056	15.377	0.420	0.578	0.0071	2765	27	2839	26	2939	29	96%
BVL-030-13	35	70	0.49	0.1915	0.0060	15.077	0.473	0.569	0.0063	2755	34	2820	30	2902	26	97%
BVL-030-29	14	32	0.45	0.1911	0.0067	15.718	0.570	0.597	0.0123	2752	31	2860	35	3017	50	94%
BVL-030-9	14	33	0.42	0.1911	0.0072	15.118	0.541	0.578	0.0100	2751	34	2823	34	2940	41	95%
BVL-030-12	42	71	0.59	0.1909	0.0072	15.829	0.586	0.602	0.0106	2750	35	2867	35	3039	43	94%
BVL-030-20	32	56	0.57	0.1904	0.0061	15.480	0.515	0.585	0.0084	2746	33	2845	32	2968	34	95%
BVL-030-33	21	40	0.52	0.1894	0.0055	14.076	0.423	0.537	0.0071	2737	30	2755	29	2771	30	99%
BVL-030-23	16	36	0.43	0.1892	0.0069	14.931	0.524	0.575	0.0082	2735	36	2811	33	2928	34	95%
BVL-030-30	86	102	0.84	0.1884	0.0047	15.532	0.399	0.594	0.0069	2728	25	2848	25	3008	28	94%
BVL-030-14	18	39	0.45	0.1877	0.0062	14.036	0.474	0.540	0.0074	2722	35	2752	32	2782	31	98%
BVL-030-28	53	77	0.68	0.1877	0.0049	15.515	0.419	0.596	0.0075	2722	26	2847	26	3015	30	94%
BVL-030-16	26	52	0.49	0.1873	0.0059	14.757	0.482	0.568	0.0082	2719	32	2800	31	2899	34	96%
BVL-030-3	20	43	0.46	0.1862	0.0059	14.408	0.474	0.563	0.0094	2709	30	2777	31	2881	39	96%
BVL-030-21	14	33	0.40	0.1861	0.0061	15.049	0.504	0.587	0.0102	2708	30	2818	32	2979	42	94%
BVL-030-11	16	38	0.42	0.1860	0.0058	13.847	0.448	0.539	0.0081	2707	31	2739	31	2781	34	98%
BVL-030-7	30	53	0.57	0.1857	0.0062	13.817	0.457	0.541	0.0071	2704	34	2737	31	2789	30	98%
BVL-030-2	27	50	0.53	0.1855	0.0051	13.680	0.392	0.535	0.0069	2703	28	2728	27	2762	29	98%
BVL-030-22	42	72	0.59	0.1855	0.0052	14.927	0.417	0.581	0.0066	2702	29	2811	27	2953	27	95%
BVL-030-10	30	55	0.55	0.1851	0.0057	14.078	0.448	0.549	0.0068	2699	33	2755	30	2823	28	97%
BVL-030-25	64	85	0.76	0.1848	0.0052	15.921	0.453	0.622	0.0071	2697	29	2872	27	3117	28	91%
BVL-030-27	39	64	0.61	0.1846	0.0056	14.598	0.442	0.572	0.0077	2694	30	2789	29	2916	32	95%
BVL-030-26	50	79	0.63	0.1843	0.0053	15.254	0.462	0.596	0.0077	2692	31	2831	29	3014	31	93%
BVL-030-8	13	29	0.47	0.1841	0.0065	13.638	0.477	0.542	0.0084	2690	35	2725	33	2793	35	97%
BVL-030-4	36	63	0.56	0.1834	0.0069	13.917	0.500	0.555	0.0091	2684	35	2744	34	2846	38	96%
BVL-030-1	34	58	0.59	0.1832	0.0069	13.016	0.495	0.521	0.0110	2682	33	2681	36	2703	46	99%
BVL-030-24	28	55	0.51	0.1831	0.0051	14.937	0.425	0.591	0.0085	2681	26	2811	27	2995	34	93%
BVL-030-5	29	52	0.56	0.1805	0.0069	13.749	0.508	0.558	0.0093	2657	36	2733	35	2859	38	95%
BVL-030-6	14	32	0.43	0.1719	0.0064	12.483	0.493	0.528	0.0079	2576	42	2641	37	2732	33	96%

Table 2.3. (Continued)

BVL2013-031, Rhyolite from the Keewatin sequence in the Bad Vemillion Lake greenstone belt (North: 518921 and East: 5399556)															
Element concentrations			Isotopic ratios						Ages (Ma)						
Th (ppm)	U (ppm)		Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	Concordance
BVL-031-2	68	122	0.55	0.1873	0.0028	15.305	0.349	0.592	0.0057	2718	24	2834	22	2997	97%
BVL-031-17	93	150	0.57	0.1870	0.0035	15.160	0.458	0.581	0.0083	2716	28	2825	29	2954	92%
BVL-031-4	74	125	0.56	0.1868	0.0030	15.222	0.382	0.591	0.0063	2714	26	2829	24	2995	94%
BVL-031-14	86	147	0.62	0.1866	0.0031	16.056	0.429	0.619	0.0075	2713	26	2880	26	3107	95%
BVL-031-11	98	165	0.60	0.1863	0.0031	14.550	0.392	0.563	0.0071	2710	25	2786	26	2878	94%
BVL-031-1	341	473	0.59	0.1858	0.0026	13.641	0.361	0.531	0.0087	2706	22	2725	25	2745	92%
BVL-031-15	101	162	0.59	0.1857	0.0031	14.597	0.407	0.566	0.0080	2705	25	2789	27	2892	96%
BVL-031-9	72	110	0.72	0.1852	0.0029	15.290	0.369	0.598	0.0062	2700	24	2833	23	3023	99%
BVL-031-16	39	65	0.62	0.1851	0.0037	15.441	0.499	0.607	0.0091	2699	31	2843	31	3056	96%
BVL-031-7	113	182	0.65	0.1845	0.0032	15.509	0.409	0.610	0.0065	2694	27	2847	25	3070	93%
BVL-031-3	40	75	0.53	0.1840	0.0032	15.458	0.416	0.610	0.0069	2690	28	2844	26	3071	92%
BVL-031-18	204	314	0.60	0.1836	0.0032	14.561	0.420	0.571	0.0081	2685	26	2787	27	2910	92%
BVL-031-10	162	255	0.62	0.1821	0.0025	15.936	0.365	0.631	0.0069	2672	21	2873	22	3155	92%
BVL-031-6	50	92	0.65	0.1815	0.0042	13.356	0.472	0.536	0.0079	2667	35	2705	33	2769	95%
BVL-031-13	71	125	0.64	0.1816	0.0033	15.181	0.449	0.601	0.0082	2667	28	2827	28	3034	90%
BVL-031-8	756	804	0.94	0.1748	0.0043	11.943	0.420	0.496	0.0062	2604	38	2600	33	2594	98%
BVL-031-12	426	605	0.70	0.1705	0.0027	10.563	0.346	0.446	0.0099	2562	25	2485	30	2380	95%
BVL-031-5	1836	1473	1.25	0.1453	0.0021	7.638	0.194	0.381	0.0052	2291	24	2189	23	2082	94%
BVL-031-19	162	493	0.33	0.0542	0.0025	0.390	0.023	0.053	0.0007	377	98	334	17	330	98%

BVL2013-034, Rhyolite from the Keewatin sequence in the Bad Vemillion Lake greenstone belt (North: 515525 and East: 5395228)															
Element concentrations			Isotopic ratios						Apparent ages (Ma)						
Th (ppm)	U (ppm)		Th/U	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	±1σ	²⁰⁷ Pb/ ²⁰⁶ Pb	±1σ	²⁰⁷ Pb/ ²³⁵ U	±1σ	²⁰⁶ Pb/ ²³⁸ U	Concordance
BVL-034-03	1052	1189	0.88	0.1891	0.0036	14.576	0.2665	0.553	0.0043	2744	31	2788	17	2836	98%
BVL-034-05	245	856	0.29	0.1887	0.0033	14.310	0.2593	0.545	0.0050	2731	30	2770	17	2803	98%
BVL-034-02	393	432	0.91	0.1885	0.0041	14.040	0.2944	0.534	0.0046	2729	35	2752	20	2757	99%
BVL-034-07	1560	1186	1.32	0.1880	0.0032	14.306	0.3005	0.548	0.0082	2725	28	2770	20	2818	98%
BVL-034-04	999	891	1.12	0.1880	0.0034	14.365	0.2568	0.549	0.0045	2724	30	2774	17	2819	98%
BVL-034-06	483	546	0.89	0.1868	0.0034	14.145	0.2726	0.545	0.0061	2715	30	2759	18	2805	98%
BVL-034-01	561	688	0.82	0.1843	0.0042	13.665	0.3031	0.531	0.0050	2692	38	2727	21	2745	99%

Table 2.3. (Continued)

BVL2013-058, Granite from the Ottertail Lake Stock (North: 515178 and East: 5399275)																
	Element concentrations		Isotopic ratios							Ages (Ma)						
	Th (ppm)	U (ppm)	Th/U	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{206}\text{Pb}$	$\pm 1\sigma$	$^{207}\text{Pb}/^{235}\text{U}$	$\pm 1\sigma$	$^{206}\text{Pb}/^{238}\text{U}$	$\pm 1\sigma$	Concordance
BVL-058-10	179	259	0.69	0.205	0.0051	15.479	0.5623	0.531	0.0090	2868	41	2845	35	2744	38	96%
BVL-058-04	171	208	0.82	0.182	0.0040	12.658	0.2778	0.505	0.0052	2733	36	2655	21	2634	22	99%
BVL-058-13	235	221	1.06	0.183	0.0046	13.435	0.3448	0.530	0.0061	2681	41	2711	24	2741	26	98%
BVL-058-03	301	392	0.77	0.183	0.0036	13.217	0.2718	0.521	0.0053	2680	32	2695	19	2705	22	99%
BVL-058-01	167	178	0.94	0.182	0.0040	13.054	0.2826	0.517	0.0055	2676	36	2684	20	2688	23	99%
BVL-058-02	350	507	0.69	0.182	0.0034	13.119	0.2489	0.519	0.0048	2674	32	2688	18	2696	21	99%
BVL-058-07	202	239	0.84	0.182	0.0041	13.321	0.3061	0.529	0.0055	2674	38	2703	22	2737	23	98%
BVL-058-19	477	680	0.70	0.182	0.0037	12.683	0.2478	0.500	0.0043	2668	33	2656	18	2615	19	98%
BVL-058-18	204	279	0.73	0.181	0.0039	13.244	0.2760	0.524	0.0045	2666	35	2697	20	2715	19	99%
BVL-058-05	424	569	0.74	0.181	0.0037	13.000	0.2732	0.518	0.0050	2665	35	2680	20	2692	21	99%
BVL-058-06	269	238	1.13	0.181	0.0043	13.072	0.3118	0.523	0.0055	2661	39	2685	23	2712	23	99%
BVL-058-20	436	572	0.76	0.181	0.0040	13.286	0.2805	0.526	0.0045	2661	32	2700	20	2726	19	99%
BVL-058-17	557	702	0.79	0.181	0.0033	13.013	0.2356	0.517	0.0043	2658	30	2681	17	2687	18	99%
BVL-058-09	468	574	0.81	0.180	0.0034	12.541	0.2399	0.502	0.0043	2655	31	2646	18	2623	19	99%
BVL-058-11	252	368	0.69	0.180	0.0036	12.965	0.2722	0.520	0.0055	2655	33	2677	20	2697	23	99%
BVL-058-15	420	517	0.81	0.180	0.0038	13.068	0.2834	0.522	0.0055	2655	34	2685	21	2709	23	99%
BVL-058-12	281	307	0.91	0.179	0.0039	12.812	0.2905	0.515	0.0052	2648	36	2666	21	2679	22	99%
BVL-058-08	463	494	0.94	0.179	0.0037	11.619	0.2572	0.471	0.0062	2643	34	2574	21	2486	27	96%
BVL-058-14	423	559	0.76	0.179	0.0041	12.862	0.3008	0.518	0.0050	2643	37	2670	22	2689	21	99%
BVL-058-16	238	295	0.81	0.177	0.0035	12.530	0.2693	0.509	0.0057	2633	32	2645	20	2652	24	99%

Table 2.4. Sm-Nd isotope composition of the volcanic rocks and gabbros in the Neoarchean Bad Vermillion Lake greenstone belt.

Sample	Rock type	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{147}\text{Sm}/^{144}\text{Nd}$	Sm (ppm)	Nd (ppm)	ϵ_{Nd} (2720 Ma)	$T_{\text{DM}} - \text{Ga}$ (de Paolo, 1981)
BVL-2013-010	Mafic volcanic rock	0.511682±07	0.1396	5.19	22.52	1.4	3.03
BVL-2013-011	Mafic volcanic rock	0.512287±21	0.1672	2.07	7.48	3.5	2.84
BVL-2013-021	Mafic volcanic rock	0.511646±09	0.1368	7.04	31.14	1.6	2.99
BVL-2013-019	Gabbro	0.512011±09	0.1575	2.79	10.73	1.5	3.10
BVL-2013-020	Gabbro	0.511813±09	0.1428	3.81	16.15	2.8	2.88
BVL-2013-025	Gabbro	0.512849±09	0.1978	1.74	5.32	3.8	2.89
BVL-2013-029	Gabbro	0.511876±09	0.1480	3.49	14.29	2.2	2.97
BVL-2013-013	Intermediate volcanic rock	0.511600±09	0.1300	4.30	20.01	3.1	2.83
BVL-2013-027	Intermediate volcanic rock	0.512319±09	0.1676	9.17	33.12	4.0	2.76
BVL-2013-006	Intermediate to felsic volcanoclastic rock	0.512045±07	0.1569	14.88	57.40	2.4	2.98
BVL-2013-008	Intermediate to felsic volcanoclastic rock	0.511996±07	0.1538	15.75	61.94	2.5	2.95
BVL-2013-036 ^a	Intermediate to felsic volcanoclastic rock	0.511924±09	0.1547	18.90	73.96	0.8	3.18
BVL-2013-038	Intermediate to felsic volcanoclastic rock	0.512088±09	0.1600	11.72	44.31	2.1	3.02
BVL-2013-030	Porphyritic felsic rock (rhyolite)	0.511881±09	0.1471	15.85	65.23	2.6	2.91
BVL-2013-031	Porphyritic felsic rock (rhyolite)	0.511770±09	0.1427	16.86	71.46	2.0	2.98
BVL-2013-033	Porphyritic felsic rock (rhyolite)	0.512056±09	0.1569	13.79	53.16	2.6	2.95
BVL-2013-037	Porphyritic felsic rock (rhyolite)	0.511842±09	0.1452	17.42	72.62	2.5	2.92

^a: Altered

Table 2.5. Pb isotope compositions of the volcanic rocks and gabbros in the Neoproterozoic Bad Vermillion Lake greenstone belt.

Sample	Rock type	$^{206}\text{Pb}/^{204}\text{Pb}$	$\pm 2s$	$^{207}\text{Pb}/^{204}\text{Pb}$	$\pm 2s$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\pm 2s$	U (ppm)
BVL-2013-010	Mafic volcanic rock	16.595	0.009	15.094	0.010	35.772	0.029	0.507
BVL-2013-011	Mafic volcanic rock	18.609	0.015	15.551	0.014	39.195	0.040	0.069
BVL-2013-021	Mafic volcanic rock	23.076	0.028	16.274	0.021	43.486	0.059	0.645
BVL-2013-019	Gabbro	26.607	0.033	17.013	0.022	40.250	0.055	0.332
BVL-2013-020	Gabbro	27.295	0.026	17.146	0.018	39.020	0.047	0.416
BVL-2013-025	Gabbro	13.805	0.013	14.660	0.015	33.655	0.038	0.065
BVL-2013-029	Gabbro	29.472	0.034	17.608	0.021	51.296	0.067	0.272
BVL-2013-013	Intermediate volcanic rock	20.263	0.012	15.754	0.011	39.531	0.033	4.846
BVL-2013-027	Intermediate volcanic rock	17.623	0.018	15.392	0.017	38.695	0.046	0.493
BVL-2013-006	Intermediate to felsic volcanoclastic rock	45.258	0.031	20.339	0.016	64.815	0.058	1.537
BVL-2013-008	Intermediate to felsic volcanoclastic rock	20.374	0.011	15.780	0.010	40.357	0.031	1.410
BVL-2013-036 ^a	Intermediate to felsic volcanoclastic rock	36.157	0.024	18.858	0.014	55.270	0.050	2.222
BVL-2013-038	Intermediate to felsic volcanoclastic rock	41.164	0.033	19.774	0.018	64.600	0.065	1.131
BVL-2013-030	Porphyritic felsic rock (rhyolite)	60.672	0.037	23.404	0.017	85.100	0.070	1.997
BVL-2013-031	Porphyritic felsic rock (rhyolite)	35.985	0.025	18.556	0.015	57.772	0.052	2.165
BVL-2013-033	Porphyritic felsic rock (rhyolite)	14.405	0.008	14.753	0.010	34.430	0.030	1.329
BVL-2013-037	Porphyritic felsic rock (rhyolite)	54.948	0.041	21.568	0.018	75.369	0.074	2.130

^a: Altered

Table 2.6. Rb-Sr isotope compositions of the volcanic rocks and gabbros in the Neoproterozoic Bad Vermillion Lake greenstone belt.

Sample	Rock type	$^{87}\text{Sr}/^{86}\text{Sr}$	Rb	Sr	$^{87}\text{Rb}/^{86}\text{Sr}$
BVL-2013-010	Mafic volcanic rock	0.716155±09	16.27	114.50	0.410
BVL-2013-011	Mafic volcanic rock	0.701512±09	0.38	89.88	0.012
BVL-2013-021	Mafic volcanic rock	0.730744±09	30.48	107.50	0.819
BVL-2013-019	Gabbro	0.704741±24	1.37	41.41	0.095
BVL-2013-020	Gabbro	0.701481±10	1.04	153.82	0.020
BVL-2013-025	Gabbro	0.701896±07	1.26	159.87	0.023
BVL-2013-029	Gabbro	0.705468±08	7.09	182.33	0.112
BVL-2013-013	Intermediate volcanic rock	0.724386±09	4.91	193.95	0.073
BVL-2013-027	Intermediate volcanic rock	0.724179±13	4.63	20.38	0.657
BVL-2013-006	Intermediate to felsic volcanoclastic rock	0.759619±09	19.43	34.29	1.637
BVL-2013-008	Intermediate to felsic volcanoclastic rock	0.840242±10	41.16	31.58	3.765
BVL-2013-036 ^a	Intermediate to felsic volcanoclastic rock	0.940511±11	93.19	39.38	6.836
BVL-2013-038	Intermediate to felsic volcanoclastic rock	0.722065±12	10.41	43.20	0.696
BVL-2013-030	Porphyritic felsic rock (rhyolite)	0.837695±10	39.27	19.53	5.807
BVL-2013-031	Porphyritic felsic rock (rhyolite)	0.913308±09	69.98	55.41	3.648
BVL-2013-033	Porphyritic felsic rock (rhyolite)	0.732422±09	19.75	67.45	0.846
BVL-2013-037	Porphyritic felsic rock (rhyolite)	1.011538±12	52.39	15.44	9.799

^a: Altered

CHAPTER 3

Conclusions, Implications and Suggestions for future studies

3.1. Conclusions and implications

This thesis is mainly aimed to define the geology of the BVL greenstone belt on the basis of previous pioneers' work and newly acquired geochemical and geochronological data. Based on these resources, we can basically restore the petrogenetic and geodynamic processes of the BVL greenstone belt and associated granitic intrusions. The following conclusions are considered to be the major contribution to this thesis project:

- (1) The BVL greenstone belt is made up of bimodal tholeiitic to calc-alkaline basalts to rhyolite association, gabbros, and Seine group siliciclastic rocks. The greenstone belt was intruded by diachronous granitic intrusions.
- (2) The BVL greenstone belt originated from partial melting of subarc mantle wedge, showing an affinity with subduction-related ophiolite.
- (3) The Ottetail Lake granitic magma was produced by partial melting of pre-existing Laurentian granitoid and Seine Group sedimentary rocks in a syn-collisional arc setting. The intrusion was later emplaced in an extensional basin.
- (4) In the context of regional tectonics, the BVL greenstone belt and associated layered anorthosite complex were generated at around ca. 2.5 Ga, which was caused by the northerly subduction processes underneath the west Wabigoon terrane and Marmion terrane. The emplacement of Ottetail Lake granite at ca. 2.64 Ga marks the end of the major collision among the Wabigoon, Marmion, and Quetico and Abitibi-Wawa terrane.

3.2. Implications

Alteration can be caused by a series of geological processes such as sea-floor hydrothermal activities, regional metamorphism and late granitic intrusions (Polat et al., 2003, 2007; Terabayashi et al., 2003; Weiershauser and Spooner, 2005; Ordóñez-Calderón et al., 2008). Although the BVL greenstone belt experienced low-grade greenschist metamorphism, it still suffers significant hydrothermal alteration. Because of the alteration, some primary mineralogy and textures in the BVL greenstone volcanic rocks have been obscured. In that case, only Ce anomalies on chondrite-normalized diagram and carbonate-quartz enrichment (Polat and Hoffman, 2003) can be employed as alteration standards. In addition, the Nd, Sr, Pb isochrons have been used to examine the alteration of the greenstone samples. It is fortunate to see most samples still preserves trace element patterns that resemble those of unaltered Phanerozoic counterparts. The trace element patterns can help us to discriminate various geodynamic environments related to the greenstone formations.

The integrated studies of the BVL greenstone belt and associated layered intrusions imply the existence of magmatic arcs in the Neoarchean Era. This conclusion supports the operation of subduction processes in the Archean. Although komatiites have been found in Steep Rock-Lumby Lake area in the west Wabigoon terrane, it is still a rare volcanic sequence and corresponds to a short interval of basement generation and crustal rifting (Hollings and Wyman, 1999). Above all, it is convincing that horizontal motions of plate tectonics are the dominant force to shape early Earth (Eriksson et al., 2004; Kerrich and Polat, 2006; Polat et al., 2015).

3.3. Suggestions for future studies

Recommendations for further study of the BVL greenstone belt and associated

granitic rocks are made as follows:

- (1) Greenstone belts are exceptional host rocks for nickel sulphide, volcanogenic massive sulphide Cu-Zn-Pb (VMS), lode gold, iron formation and some other deposits (Condie, 1981; Herrington et al., 1997), it is advisable to make a detailed study of the resource potential of ore deposits in the BVL greenstone belts
- (2) Savant-Sturgeon and Finlayson greenstone belts in the west Wabigoon subprovince also show arc affinities (Sanborn-Barrie and Skulski, 2006; Backeberg et al., 2014). Comparative studies between the BVL greenstone belt and these greenstone belts may significantly contribute to the reconstruction of geodynamic processes of Western Superior Province.
- (3) The Nd, Pb, and Sr isotopic systems shed light on the source characteristics of the BVL greenstone belt. Prevalent hydrothermal alterations have made the interpretation of the Nd, Pb and Sr data a little more complicated. Hf in the zircon are exceptionally immobile, so it is suggested to incorporate zircon Hf isotopic data to the whole rock Sm-Nd and Rb-Sr systems to distinguish juvenile mantle from older crustal sources (Patchett, 1983).

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Appendix A: Supplementary Data Table 1

Supplementary Data Table 1 Measured and recommended trace element concentrations for the standard samples (BHVO-1 and BIR-1)

Element	BIR				BHVO-1			
	Measured (n=1)	Recommended	Reference	Deviation (%)	Measured (n=1)	Recommended	Reference	Deviation (%)
Cr	364.55	370	a	1.47	260.94	289	a	9.71
Co	52.33	52	a	0.63	46.57	45	a	3.48
Ni	219.26	170	a	28.98	273.88	120	a	128.23
Rb	0.22	0.24	a	7.30	8.90	9.5	a	6.30
Sr	101.93	110	b	7.34	441.10	403	b	9.45
Cs	0.006	0.005	b	11.99	0.10	0.10	a	3.10
Ba	8.48	7.00	b	21.14	138.11	139	b	0.64
V	316.34	313	b	1.07	304.11	317	b	4.07
Ta	0.04	0.06	b	32.42	0.89	1.20	b	26.19
Nb	0.50	0.55	b	9.06	12.43	19	b	34.58
Zr	12.71	14.50	a	12.35	141.21	179	b	21.11
Hf	0.57	0.56	a	1.03	3.92	4.4	b	10.91
Th	0.11	0.300	a	62.45	1.22	1.1	b	10.60
Y	13.38	16	b	16.35	22.50	28	b	19.64
U	0.01	0.01	a	10.38	0.40	0.42	a	4.29
La	0.57	0.58	a	1.14	14.41	16.00	b	9.94
Ce	1.80	1.85	a	2.55	36.04	39.00	b	7.60
Pr	0.36	0.37	a	3.75	5.07	5.45	a	6.90
Nd	2.18	2.35	a	7.33	23.17	25.00	b	7.34
Sm	1.04	1.10	a	5.90	5.80	6.20	b	6.40
Eu	0.49	0.52	a	5.51	1.95	2.06	b	5.13
Gd	1.89	1.97	a	3.83	6.16	6.40	b	3.72
Tb	0.34	0.38	a	10.95	0.89	0.96	b	7.40
Dy	2.42	2.50	a	3.30	5.00	5.20	b	3.89
Ho	0.53	0.57	a	7.11	0.92	0.99	b	7.40
Er	1.59	1.70	a	6.70	2.49	2.42	b	2.92
Tm	0.23	0.24	a	3.51	0.30	0.33	b	8.74
Yb	1.54	1.60	a	3.99	1.83	2.00	b	8.62
Lu	0.23	0.25	a	7.10	0.26	0.29	b	11.74
Cu	119.51	125	b	4.39	149.80	136	a	10.15
Zn	124.36	70	b	77.66	174.82	105	b	66.50
Pb	6.64	3	b	121.28	6.51	2.6	b	150.40

For the reference, a denotes that the recommended values are from the Geochemical Reference Materials and Certificates of the United States Geological Survey in 2002; b denotes the values are based on Eggins et al. (1997).

Appendix B: Supplementary Data Table 2

Supplementary Data Table 2. Measured element concentration data in analyzed zircons from the rhyolite sample BVL2013-030, BVL2013-031, BVL2013-034 and the Ottertail Lake granite sample BVL2013-058

Sample BVL2013-030.														
Spot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
²⁹ SiO ₂	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7
⁴⁹ Ti	21.0	25.3	23.0	27.2	7.1	24.8	50.4	19.7	9.8	7.7	28.0	31.4	11.8	25.9
⁸⁹ Y	2497	1427	1066	1181	1193	951	1529	1136	822	2156	921	1336	1308	1094
⁹³ Nb	1.9	1.9	2.2	1.5	1.6	1.8	2.6	1.5	2.2	1.9	2.1	3.5	6.3	2.1
¹³⁹ La	1.8	0.2	0.1	0.0	0.4	0.4	0.0	0.0	0.0	0.1	0.0	0.1	0.0	0.0
¹⁴⁰ Ce	8.8	3.2	3.3	3.6	3.8	3.6	3.5	2.4	2.7	3.5	2.7	4.5	7.9	3.1
¹⁴¹ Pr	1.0	0.1	0.0	0.0	0.1	0.2	0.1	0.1	0.0	0.3	0.1	0.3	0.0	0.0
¹⁴⁶ Nd	7.2	1.2	1.5	0.0	1.1	1.4	1.9	2.0	1.1	2.5	0.6	1.6	0.6	1.5
¹⁴⁷ Sm	8.9	4.4	0.9	2.5	4.0	1.5	3.9	2.0	0.9	5.2	1.9	2.7	1.8	3.1
¹⁵¹ Eu	2.2	0.9	0.8	0.3	0.7	1.0	1.0	0.9	0.2	1.2	0.7	0.7	0.7	0.6
¹⁵⁷ Gd	56	28	21	24	22	19	27	23	14	45	16	24	22	20
¹⁵⁹ Tb	18	10	7	8	8	6	11	8	5	16	6	9	8	7
¹⁶³ Dy	230	123	93	102	104	84	140	105	70	198	80	119	117	100
¹⁶⁵ Ho	85	48	35	39	40	33	52	38	27	72	31	43	45	37
¹⁶⁶ Er	362	219	166	183	183	149	230	176	133	326	145	207	204	172
¹⁶⁹ Tm	74	46	35	39	39	32	49	37	27	66	32	43	43	37
¹⁷² Yb	643	434	336	363	370	305	462	357	271	611	323	425	415	370
¹⁷⁵ Lu	115	75	60	63	66	52	78	58	47	95	51	68	66	58
¹⁷⁸ Hf	7852	8097	7886	6251	7423	8569	7747	7961	7684	7648	8185	6524	8959	8140
¹⁸¹ Ta	0.8	1.1	1.0	1.0	0.7	1.1	1.2	0.7	0.9	0.9	1.0	1.7	2.8	0.9
²⁰⁴ Pb	631	164	23	147	0	438	223	0	11	0	132	0	0	0
²⁰⁶ Pb	79	68	60	91	75	41	73	39	47	75	50	105	97	51
²⁰⁷ Pb	63	56	50	74	60	32	60	32	39	60	39	85	77	40
²⁰⁸ Pb	149	121	95	191	141	56	127	61	65	134	81	249	158	84
Pb _{Total}	120	94	76	141	105	52	101	48	54	102	65	174	123	65
²³² Th	34	27	20	36	29	14	30	13	14	30	16	42	35	18
²³⁸ U	58	50	43	63	52	32	53	29	33	55	38	71	70	39
Σ REE	1612	994	760	827	842	688	1059	809	599	1442	690	948	933	810

Supplementary Data Table 1. (*Continued*)

Sample BVL2013-030.															
Spot No.	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
²⁸ SiO ₂	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7
⁴⁹ Ti	9.0	5.6	5.1	13.5	28.0	4.3	32.2	16.5	0.0	0.0	14.6	11.7	22.4	18.8	9.1
⁸⁹ Y	2043	912	946	1512	803	1317	898	1446	1539	3201	2451	1490	898	1862	2678
⁹³ Nb	1.4	2.1	1.8	3.3	1.3	3.1	1.4	2.9	4.5	2.2	2.2	2.9	2.5	4.6	2.0
¹³⁹ La	0.0	0.0	0.0	74.9	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.2	0.0	0.1
¹⁴⁰ Ce	3.5	2.3	2.7	224.0	2.8	5.1	2.7	4.4	5.4	3.7	3.7	4.2	2.9	6.3	4.3
¹⁴¹ Pr	0.1	0.1	0.2	34.6	0.1	0.0	0.1	0.4	0.1	0.1	0.1	0.1	0.0	0.0	0.1
¹⁴⁶ Nd	4.0	0.0	0.5	221.8	1.1	1.4	0.4	2.4	1.0	5.3	2.9	1.8	2.3	1.0	2.8
¹⁴⁷ Sm	7.6	2.2	2.8	67.9	1.1	3.7	1.5	3.5	4.0	9.9	7.5	4.6	1.9	4.4	7.4
¹⁵¹ Eu	1.8	0.6	0.7	7.8	0.5	0.7	0.4	0.4	0.9	2.5	1.4	0.9	0.5	0.6	1.3
¹⁵⁷ Gd	46	15	15	107	14	25	15	27	27	72	53	30	14	34	59
¹⁵⁹ Tb	16	6	6	19	5	9	5	10	10	24	18	9	5	12	20
¹⁶³ Dy	195	82	79	168	69	112	77	123	134	294	225	131	73	163	244
¹⁶⁵ Ho	70	30	32	52	27	44	29	48	52	109	83	49	29	62	91
¹⁶⁶ Er	304	143	144	212	125	207	139	218	231	477	362	221	136	283	401
¹⁶⁹ Tm	62	31	31	42	27	43	29	46	49	97	74	47	29	56	80
¹⁷² Yb	600	310	311	414	275	420	301	451	470	884	692	463	288	553	744
¹⁷⁵ Lu	92	51	50	63	44	68	49	74	77	142	115	77	51	93	119
¹⁷⁸ Hf	8476	8732	7977	6990	7152	7122	7432	7717	7440	7485	7806	7031	8312	7305	8757
¹⁸¹ Ta	0.7	0.9	1.0	1.2	1.0	1.3	0.8	0.9	1.4	1.2	1.2	1.1	0.8	1.7	1.0
²⁰⁴ Pb	34	0	0	17	81	178	0	0	0	78	218	0	72	98	0
²⁰⁶ Pb	63	43	37	79	46	102	50	77	125	110	86	109	45	143	82
²⁰⁷ Pb	51	35	30	64	37	80	40	62	102	89	69	88	37	115	67
²⁰⁸ Pb	114	66	55	153	65	209	73	139	321	228	169	253	61	396	155
Pb _{Total}	87	52	44	114	54	154	59	105	221	167	128	178	52	269	116
²³² Th	29	15	12	32	14	42	16	28	64	50	39	53	14	86	38
²³⁸ U	49	34	28	56	33	72	36	55	85	79	64	77	32	102	64
Σ REE	1401	673	677	1708	593	938	650	1007	1061	2121	1638	1040	632	1270	1773

Supplementary Data Table 2. (*Continued*)

Sample BVL2013-031																	
Spot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
²⁹ SiO ₂	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7	32.7
⁴⁹ Ti	0.0	24.5	0.0	39.5	166.7	15.3	1.4	3.0	3.9	12.1	58.4	3089.4	23.1	23.0	21.4	30.1	9.7
⁸⁹ Y	7104	1997	2467	2485	23296	1535	2998	12725	2986	3818	3279	3776	2226	2599	3037	1389	2249
⁹³ Nb	21.3	8.3	2.3	6.7	366.7	3.1	10.2	31.9	6.6	8.7	7.3	322.5	4.9	6.1	5.9	4.7	10.0
¹³⁹ La	0.0	0.0	0.0	0.0	122.4	0.8	0.9	0.9	318.0	0.1	0.0	31.8	19.3	0.0	0.7	59.1	0.5
¹⁴⁰ Ce	34.8	8.1	3.4	6.9	548.5	7.9	13.8	97.8	880.1	15.5	8.5	97.0	52.3	11.1	13.7	149.7	10.8
¹⁴¹ Pr	0.4	0.0	0.1	0.4	41.8	0.8	0.0	2.2	138.2	0.2	0.0	11.7	7.1	0.2	0.6	21.7	0.2
¹⁴⁶ Nd	9.2	2.0	2.9	2.9	236.8	3.4	3.8	28.6	812.1	7.4	4.5	66.3	41.2	2.6	5.4	122.0	5.9
¹⁴⁷ Sm	18.5	4.5	6.9	7.3	142.6	5.7	7.2	46.7	256.2	12.8	9.2	47.9	16.5	8.1	11.9	35.0	9.3
¹⁵¹ Eu	2.6	0.6	2.5	0.8	9.5	0.4	0.8	4.4	16.5	1.5	2.1	20.0	2.0	0.8	2.2	2.8	0.9
¹⁵⁷ Gd	140	34	52	49	455	30	54	296	339	70	63	187	57	47	69	55	44
¹⁵⁹ Tb	48	13	18	17	154	10	20	99	57	26	22	62	16	18	24	12	16
¹⁶³ Dy	636	167	230	216	2012	134	270	1198	424	339	283	621	196	230	295	141	202
¹⁶⁵ Ho	235	65	83	82	749	49	99	436	105	127	109	159	75	88	105	47	76
¹⁶⁶ Er	1055	306	368	377	3463	238	457	1899	375	577	495	556	338	397	455	207	347
¹⁶⁹ Tm	203	64	73	75	715	50	91	363	65	116	99	115	69	80	90	42	69
¹⁷² Yb	1819	594	675	698	6519	466	860	3082	570	1079	917	1227	654	772	836	405	653
¹⁷⁵ Lu	299	102	114	120	986	78	142	494	86	171	157	210	106	120	131	66	107
¹⁷⁸ Hf	8276	9019	7206	8139	7463	8152	8426	8162	8547	8002	8234	15947	8258	8403	8161	6806	7377
¹⁸¹ Ta	5.7	3.1	1.5	2.5	14.6	2.4	3.7	6.5	2.8	3.5	3.0	274.1	2.1	2.3	2.0	1.1	2.8
²⁰⁴ Pb	4	0	3	80	0	28	0	108	48	32	31	0	110	0	121	0	0
²⁰⁶ Pb	677	180	115	188	1495	123	283	1022	164	412	239	748	196	231	245	102	233
²⁰⁷ Pb	486	131	82	136	849	88	205	725	120	294	173	495	138	166	173	72	170
²⁰⁸ Pb	1808	358	221	411	4223	234	664	3515	392	1024	515	1243	423	524	570	250	579
Pb _{Total}	1218	260	162	292	2761	172	461	2250	272	701	366	941	301	367	398	172	397
²³² Th	341	68	40	74	1836	50	113	756	72	162	98	426	71	86	101	39	93
²³⁸ U	473	122	75	125	1473	92	182	804	110	255	165	605	125	147	162	65	150
Σ REE	4500	1359	1628	1653	16155	1074	2019	8046	4442	2542	2168	3411	1649	1774	2040	1366	1540

Supplementary Data Table 2. (*Continued*)

Sample BVL2013-034.							
Spot No.	1	2	3	4	5	6	7
²⁹ SiO ₂	93.6	94.7	91.9	93.2	95.2	93.2	89.2
⁴⁹ Ti	290.3	20.9	162.8	269.8	13.8	110.2	218.9
⁸⁹ Y	11556	9199	15610	12348	3361	15237	29468
⁹³ Nb	55.0	27.0	120.0	90.0	179.9	28.1	81.4
¹³⁹ La	11.7	0.2	2.6	3.6	0.3	0.3	1.2
¹⁴⁰ Ce	98.5	40.1	187.5	94.9	24.0	60.7	187.3
¹⁴¹ Pr	6.6	0.4	2.8	2.2	0.1	1.3	2.5
¹⁴⁶ Nd	52.3	8.8	25.2	19.2	2.5	18.9	34.1
¹⁴⁷ Sm	53.3	24.3	45.7	33.1	3.5	43.9	69.0
¹⁵¹ Eu	22.3	4.9	9.2	10.0	0.7	7.0	7.7
¹⁵⁷ Gd	241	169	309	223	33	323	467
¹⁵⁹ Tb	81	59	109	77	14	109	167
¹⁶³ Dy	1035	796	1414	1039	210	1395	2251
¹⁶⁵ Ho	367	294	495	385	92	497	829
¹⁶⁶ Er	1659	1361	2222	1817	538	2223	3743
¹⁶⁹ Tm	308	256	403	351	130	404	680
¹⁷² Yb	2995	2460	3730	3412	1533	3763	6254
¹⁷⁵ Lu	471	386	538	534	256	562	886
¹⁷⁸ Hf	28674	25876	32491	27842	29883	27549	31298
¹⁸¹ Ta	28.2	9.9	34.3	30.0	256.4	8.5	19.4
Pb _{common}	70	0	0	14	5	27	5
Pb _{Total}	1778	1130	3243	2679	1073	1575	4545
²³² Th	561	393	1052	999	245	483	1560
²³⁸ U	688	432	1189	891	856	546	1186
Σ REE	7401	5861	9492	8002	2836	9410	15578

Supplementary Data Table 2. (*Continued*)

Sample BVL2013-058.																	
Spot No.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
²⁹ SiO ₂	95.8	94.8	95.1	95.8	95.0	95.6	95.5	94.6	94.8	95.2	95.3	95.3	96.0	94.9	94.9	95.0	94.8
⁴⁹ Ti	62.9	18.2	12.0	36.5	6.1	27.5	50.2	39.9	22.1	256.8	58.4	16.8	53.7	24.6	26.3	27.1	14.8
⁸⁹ Y	1415	1591	1306	1659	1860	2759	1740	3371	2535	1340	1280	1859	2450	1718	2330	1548	2008
⁹³ Nb	3.5	4.7	3.1	3.2	5.2	2.6	2.4	6.5	7.9	4.6	4.4	3.7	2.3	5.5	6.3	4.7	7.1
¹³⁹ La	0.7	1.5	0.1	0.9	0.3	0.2	4.4	143.4	0.0	9.6	0.4	40.3	0.1	69.9	11.6	0.1	0.2
¹⁴⁰ Ce	126.6	143.2	89.7	78.6	121.7	78.1	103.2	454.7	151.6	185.9	90.7	187.4	71.7	249.0	205.9	79.9	151.6
¹⁴¹ Pr	1.3	1.7	0.2	0.9	0.0	0.6	2.5	38.0	0.5	3.1	0.2	11.4	0.6	11.7	9.3	0.1	0.4
¹⁴⁶ Nd	10.8	13.1	2.4	7.5	3.0	12.6	21.4	170.9	4.2	19.8	2.3	47.4	11.3	42.5	57.8	2.9	3.8
¹⁴⁷ Sm	11.4	8.9	4.6	8.7	5.8	18.1	12.1	48.3	11.9	9.2	3.2	14.1	15.8	11.2	31.5	7.9	6.9
¹⁵¹ Eu	2.7	3.1	1.3	2.4	2.2	4.3	3.3	10.2	2.3	3.7	1.1	2.3	4.2	3.0	10.6	1.2	1.8
¹⁵⁷ Gd	36.5	30.2	26.7	37.0	29.5	75.0	45.3	101.1	47.6	32.3	22.6	41.9	67.8	32.3	71.0	34.9	36.6
¹⁵⁹ Tb	10	9	8	11	10	20	12	26	15	8	7	12	18	9	18	10	11
¹⁶³ Dy	117	110	92	139	131	228	133	278	184	99	93	145	207	119	195	116	135
¹⁶⁵ Ho	40	44	36	49	49	80	50	95	71	37	36	52	69	45	66	44	54
¹⁶⁶ Er	193	235	188	231	270	384	244	470	361	189	189	262	338	251	324	221	295
¹⁶⁹ Tm	41	53	42	48	62	78	53	99	81	41	42	55	70	57	68	48	68
¹⁷² Yb	445	666	490	542	747	822	567	1082	921	474	479	615	749	702	762	529	826
¹⁷⁵ Lu	82	135	97	101	154	146	107	196	173	87	92	114	140	138	139	96	161
¹⁷⁸ Hf	31397	37256	36182	31246	35153	30494	32857	34979	35066	35644	35071	34054	27618	35996	34758	37173	35226
¹⁸¹ Ta	1.3	2.0	1.5	1.2	2.1	1.2	1.4	2.3	3.1	1.5	1.8	1.9	1.2	1.8	2.7	1.9	2.5
Pb _{common}	0	0	39	0	33	0	60	20	10	69	54	41	73	19	0	60	0
Pb _{Total}	439	1054	856	475	1251	736	622	1217	1346	727	806	794	660	1272	1294	682	1620
²³² Th	167	350	301	171	424	269	202	463	468	179	252	281	235	423	420	238	557
²³⁸ U	178	507	392	208	569	238	239	494	574	259	368	307	221	559	517	295	702
Σ REE	1117	1452	1078	1257	1585	1948	1357	3212	2024	1200	1059	1600	1762	1742	1969	1191	1751

Vita Auctoris

Tuoyu Wu was born in June 1987 in Qianjiang, Hubei Province, China. He did his undergraduate studies in a joint program between China University of Geosciences and University of Waterloo, and acquired bachelor degree from both sides in 2010 and 2011 respectively. In September 2013, he moved on to the University of Windsor, where he started his M.Sc. and is currently a master candidate. He hopes to graduate in August 2015.