Petrology of the Blatchford Lake Intrusive Suite, Northwest
Territories, Canada

by

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in

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“Science is like sex: sometimes something useful comes out, but that is not the reason we are doing it.”

— Richard P. Feynman

Frontispiece

Early morning commute across Thor Lake.

Abstract

The Slave craton of Canada contains a number of alkaline to subalkaline intrusions dated at *ca.* 2180 Ma, collectively known as the Southwest Slave magmatic province. The Blatchford Lake intrusive suite is the largest of this group and is host to the world class Thor Lake rare metal deposits, which includes the Nechalacho REE-Zr-Nb deposit. The Thor Lake rare metal deposits are hosted by a group of peralkaline granite to nepheline syenite phases of the Blatchford Lake intrusive suite, collectively known as the eastern lobe. The eastern lobe rocks crosscut an older alkaline-subalkaline suite of rocks, referred to as the western lobe. The western lobe comprises peridotite, gabbro, and metaluminous granite and syenite phases. Evidence is presented indicating a petrogenetic relationship between the two lobes, whereby the parental melts were derived from the melting of metasomatized isotopically-depleted lithospheric mantle. Interaction between melts from asthenosphere-derived amphibole-rich metasomatic veins, and host depleted lithospheric peridotite can account for the compositional spectrum and isotopic signatures observed in rocks of the eastern and western lobes of the Blatchford Lake intrusive suite, as well as other intrusions in the Southwest Slave magmatic province.

The lithologically distinct phases in the eastern and western lobes represent discrete punctuated pulses from unexposed deep-seated parental systems. Differentiation in the Blatchford Lake intrusive suite was largely controlled by crystal fractionation complemented by a significant degree of crustal assimilation. Crustal assimilants likely consist of lower crustal mafic rocks and local Archean granitoids. The emplacement conditions of granitoid phases of the western lobe suggest an upper crustal emplacement, with pressures of 4 - 4.5 kbar (~16 km).

In the eastern lobe, the transition from the silica-oversaturated Grace Lake granite to the undersaturated Nechalacho layered suite reflects the progressive armouring of magmatic pathways from silica-rich country rocks. The Thor Lake rim syenite, an arcuate feature occurring near the contact of the Grace Lake granite and Thor Lake syenite, represents the basal remnants of an eroded ring dyke.

The two monzonite-diorite intrusive stocks hosted in the Grace Lake granite are chemically unrelated to the Blatchford Lake intrusive suite, and likely represent the northwestern extension of the Compton intrusive suite into the Slave province. Relations between diabase dykes and the intrusive stocks suggest that NW-trending diabase dykes in the region have a complex and protracted history.

Acknowledgements

It is a pleasure to finally thank the many people that have been a part this project as friends, teachers, and colleagues. Brian Cousens, first and foremost, has been all of these. Always giving me the space, trust and just the right amount of guidance to navigate through tricky problems—never saying no to my regular “do you have a minute?” questions. To Hendrik Falck, the spark behind the project, critical coordinator, and the one who was never afraid to throw out lofty ideas with the caveat that I was the one to “figure it out!”.

To John Ketchum and Scott Cairns of the NTGO for their work in navigating the bureaucracy behind the curtains, as well lending a hand and a fishing rod during stints as field mentors. To Steve Geoff, whose ideas lived on throughout the project. To my field assistants, Tania Martin, Melissa Anderson, and Julien Rice, the work and stories from those summers lie in the heart of this project.

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Preface

Method of Presentation

This thesis is presented as six chapters, including an introduction and a conclusion. The main body of this thesis—chapters two to four—were written as individual manuscripts addressing specified geographic localities. The papers are generally isolated and address specific geologic problems within a larger context. While there may be some overlap given the focused nature of this project, redundancies are generally restricted to the introduction of regional geology, previous work, and methodology. Chapter five addresses the relationship between the Blatchford Lake intrusive suite and comparable rocks in the region.

The order of the manuscripts follows the order of assumed publication given that later manuscripts reference work in earlier manuscripts. At the time of thesis submittal, none of the articles had been submitted. The intent is to submit chapters two and four as manuscripts to the *Journal of Petrology*, and chapter three to *Canadian Journal of Earth Sciences*. I will be the primary author on all of the submitted journals.

Original Contribution

This research was aimed at gaining a better understanding of the petrogenesis of the Blatchford Lake intrusive suite, the nature of its source, and to characterize its relation with the two monzonite-diorite intrusive stocks hosted in the Grace Lake granite. This study was intended to provide answers to large scale questions regarding the Blatchford Lake intrusive suite, complement many of the detailed studies that focus on mineralization at the Thor Lake rare metal deposits, and provide insight into the southwestern Slave magmatic province. This required integrating previously published data with newly acquired geochemical, geochronologic, and structural data. The choice of study areas and research objectives were completely mine. Field work was carried out over three summers (2009-2011), and mapping and sampling was done by myself with the aid of a field assistant. Mapping was done at various scales dependent on individual geologic objectives, and largely complemented earlier work done by the Geological Survey of Canada.

Samples collected during the summer were processed at Carleton University for major, trace element and radiogenic isotope geochemistry, as well as the creation of thin-section. Using diamond rock saws I cut all thin-section pucks, and crushed and powdered samples from the 2009 and 2011 field seasons. Crushing and powdering was assisted by and undergraduate student in 2011. I obtained major element analyses by XRF at the University of Ottawa under the supervision of Tara Kell and Ron Hartree. Trace-element analyses were obtained at the Ontario Geological Survey using inductively coupled plasma mass-spectrometry (ICP-MS). Sm-Nd isotopic analyses were completed at Carleton University. Specimen preparation, including isotope dilution, sample loading, and thermal ionization mass-spectrometry (TIMS) was carried out by myself under the supervision of Brian Cousens and Elizabeth Ann Spencer.

The geochronologic portion of this project was done using two techniques: (1) U-Pb laser ablation ICP-MS at the University of New Brunswick (UNB, Fredericton) and (2) isotope dilution TIMS at the Geological Survey of Canada (GSC, Ottawa). For the U-

Pb zircon dating using laser ablation, I analyzed two specimens. I located and imaged zircons in thin-section for their internal morphology using a scanning electron microscope (SEM) at UNB; imaging was done using backscattered electron (BSE) and cathodoluminescence. Spot locations and laser guiding was done under the supervision of Dr. Chris McFarlane. Data processing was done by Dr. Chris McFarlane. U-Pb zircon dating using isotope dilution TIMS was used to date one sample; crushing and heavy mineral separation of the sample was performed by GSC personnel. I picked the zircons from heavy mineral separates, and interpreted the data under the supervision of Dr. Bill Davis.

Prior to geochemical modeling or barometric estimation using mineral substitution equations, I examined thin-sections using optical microscopy. I acquired compositional data on select minerals with an electron microprobe at Carleton University under the supervision of Peter Jones.

I drafted all figures and prepared all tables in this thesis, unless otherwise cited. This thesis presents a wealth of new field relations and geochemical data, the petrogenetic models proposed in this thesis are the product of my interpretation of these data. Finally, I am wholly responsible for any omissions or inaccuracies in this document.

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1 Chapter: Introduction

1.1 General introduction

The exceptional magnetic and conductive properties possessed by many rare earth elements (REE) and REE-bearing compounds make them ideal for use in electronics. Technological leaps in modern electronic devices over the past 15 - 20 years can be partially attributed to the increased use of REE in various components. This increased demand for REE has put immense pressure on the worldwide supply chain, particularly on China that currently controls ~97% of the world's production. Governments worldwide have designated REE as a strategic resource, and exploration has dramatically increased in recent years in an effort to identify new sources. An important first step in the identification of new deposits is the characterization of known systems. Understanding the conditions governing the genesis and magmatic evolution in these systems facilitates the development of new exploration vectors and targets. Among igneous rocks, peralkaline granitoid systems are one of the most important sources of REE.

Situated in the Canadian Northwest Territories is the world class Nechalacho REE deposit, hosted in a suite of highly evolved silica-saturated to undersaturated peralkaline igneous rocks. These peralkaline rocks (eastern lobe) constitute the younger of two suites in a multiphase intrusive suite known as the Blatchford Lake intrusive suite (also known as the Blachford Lake intrusive suite, Blachford Lake complex, and Blatchford Lake complex). The eastern lobe rocks consist of alkali-feldspar granite, syenite, and nepheline syenite. The older suite of rocks, referred to as the western lobe, is subalkaline-alkaline in

nature, and consists of ultramafic cumulates, granite, and syenite. Volumetrically, the western lobe is dominated by ultramafic to mafic rocks, and has been identified as having strong Ni-Cu-PGE potential. The Blatchford Lake intrusive suite is the largest (~230 km²) in a group of alkaline/subalkaline intrusions in the southern Slave craton emplaced at ca. 2180 Ma (Table 1.1). These intrusions are collectively referred to as the Southwest Slave magmatic province (SWSMP, Bleeker & Hall, 2007, Buchan *et al.*, 2010), and consist of the Big Spruce Lake alkaline intrusion, Blatchford Lake intrusive suite, Dogrib diabase dykes, Duck Lake sill, and the Squalus Lake intrusion (Fig. 1.1). The Simpson Island Dyke (also known as the Easter Island dyke) is situated 35 km south of the Blatchford Lake intrusive suite, in the East Arm of Great Slave Lake; workers have suggested a connection between the Simpson Island Dykes and the SWSMP based on temporal and petrologic similarities (Badham, 1979, Mumford *et al.*, 2012b). The SWSMP marks the end of a nearly 300 Ma period of igneous quiescence in the Slave craton, and the subsequent break-up of Scandia (Bleeker & Hall, 2007). Studies on the SWSMP may provide insight into regional tectonics and driving forces behind the break-up (i.e., presence of a mantle plume). The differentiation trends and spectrum of rock types present in the Blatchford Lake intrusive suite closely resembles those observed throughout the SWSMP, making the Blatchford Lake intrusive suite an excellent research site to gain insight into the formation of the entire magmatic province.

Davidson (1978) was the first to map and describe the eastern and western lobe as a single plutonic complex, i.e., the Blatchford Lake intrusive suite. Work on the Blatchford Lake intrusive suite since then has been largely restricted to studies

Unit	Age (Ma)	Mineral	Method	Reference
Dogrib diabase	2193 +/-2	Baddeleyite	Multi-grain U-Pb TIMS	Bleeker et al. (2012)
Big Spruce Complex	2188 +/-10	Baddeleyite	Multi-grain U-Pb TIMS	Cavell and Baadsgaard (1986)
Duck Lake sill	2181 +/-2	Baddeleyite	Multi-grain U-Pb TIMS	Bleeker and Kamo (2003)
Simpson Island dyke	2219 +/-3.7	Baddeleyite	Multi-grain U-Pb TIMS	Mumford et al. (2012)
Squalus Lake intrusion	2180 +/-1	Zircon	Multi-grain U-Pb TIMS	Villeneuve and van Breeman (1994)
Caribou Lake gabbro	2184 +/-2	Zircon	Multi-grain U-Pb TIMS	Mumford et al. (2012)
Thor Lake syenite	2176 +/-1.6	Zircon	Single-grain U-Pb TIMS	Chapter 2
Grace Lake granite	2176.2 +/-1.3	Zircon and Monazite	Multi-grain U-Pb TIMS	Sinclair et al. (1994)
Nechalacho layered suite	2164 +/-11	Zircon	In situ LA-MC-ICP-MS	Chapter 2

Table 1.1 - Summary of radiometric ages determined for the Southwest Slave magmatic province

concerning mineralization in the Thor Lake rare metal deposits, including the Nechalacho deposit (e.g., Pinckston & Smith 1995, and Taylor and Pollard 1996).

However, in order to properly interpret these studies the context of the overall evolution of the Blatchford Lake intrusive suite is required. Information regarding the parental melt composition, differentiation mechanisms, and emplacement conditions are crucial elements to the development of a model to describe the formation of the mineralized systems. This study aims to decipher the petrogenesis of the Blatchford Lake intrusive suite using improved geologic mapping combined with petrography and mineralogy, geochemistry, radiogenic isotope studies, and geochronology. In addition to the work unraveling the petrogenesis of the Blatchford Lake intrusive suite and its relation to the SWSMP, interest also rests on two late intrusive bodies occurring within the eastern lobe. Located approximately two kilometers west of the Thor Lake rare metal deposits, detailed mapping of two small intrusive stocks identified previously undocumented field relations, including cross-cutting diabase dykes and rhythmically layered gabbroic rafts. These observed relations called into question the temporal (and therefore the petrogenetic) association proposed by Davidson (1978) between the Compton Intrusive suite sills located in the East Arm and the two intrusive stocks hosted in the Blatchford Lake intrusive suite. If the Blatchford stocks are related to the Compton intrusive suite; they mark the only Compton occurrences north of the Hearne Channel in the Archean Slave craton and have important implications regarding timing of local mafic dyke swarms. The origin of the rhythmically layered gabbroic rafts is also of great interest, given their strong resemblance to the mafic rocks of the western lobe of the Blatchford Lake intrusive suite.

Figure 1.1 - Map of the Slave craton and the locations of intrusions of the SWSMP.

1.2 Location and Access

The Blatchford lake intrusive suite is centered at 62°7' N latitude and 112°37' W longitude along the northern shore of the Hearne Channel of the East Arm in Great Slave Lake, Northwest Territories, Canada. The intrusive suite is situated along the southwestern margin of the Archean Slave Province, approximately 100 km southeast of the city of Yellowknife. The low relief topography of the field area is typical for the Canadian Shield at this latitude, comprising boreal forests with abundant wetlands and lakes. Outcrop exposure generally ranges from roughly 15 – 40%, increasing to > 80% in close proximity to the Hearne Channel shoreline. Access to the area was provided by float plane and helicopter from Yellowknife. A short airstrip has been built adjacent to Thor Lake to service the exploration camp and can be accessed by select aircraft with wheels. A dirt road connects the exploration camp at Thor Lake to a landing at Great Slave Lake.

1.3 Tectonic Setting

The entire Blatchford Lake intrusive suite is hosted in Archean metasediments, granite and granodiorite plutons along the southern margin of the Slave craton, adjacent to the Athapuscow Aulacogen (Bowring *et al.*, 1984, Hoffman, 1973, Hoffman *et al.*, 1974) of the East Arm of Great Slave Lake. The southern margin of the Athapuscow Aulacogen is separated from the Taltson Magmatic Zone by the Great Slave Lake Shear Zone (Fig. 1.1). Other major structures in the region include the Beaulieu River Fault Zone and the Yellowknife River Fault Zone (Fig. 1.1) that are both Archean strike-slip fault zones. The Blatchford Lake intrusive suite is relatively undeformed, exhibiting only

a weak localized foliation (sub-vertical, NW-trending) and rare Proterozoic north-south trending sub-vertical faults of low displacement.

Paleoproterozoic tectonic reconstructions suggest that deformation along the southern margin of the Slave craton was controlled by either: (1) largely transpressional forces along an oblique crustal-scale boundary (Bleeker & Hall, 2007, Hanmer *et al.*, 1992, Hoffman, 1987), or (2) a failed rift margin (Bowring *et al.*, 1984, Hoffman, 1973, Hoffman *et al.*, 1974). Both mechanisms involve crustal thinning that could initiate decompression melting and deep structures to act as conduits for deep crustal or mantle derived melts.

1.4 Previous Work

The mafic rocks of the western portion of the Blachford Lake intrusive suite were first examined in the 1930's by Stockwell (1932), Jolliffe (1936), and Henderson (1938), as part of a Geological Survey of Canada regional mapping program. For his master's thesis Buckham (1936) studied the petrology, of what he referred to as the Francois River Gabbro, now known as the Caribou Lake gabbro of the Blatchford Lake intrusive suite.

However, until Davidson (1972, 1978) studied granites in the southern Slave province it was not considered that the western mafic suite might be related to the adjacent atypical granitoid rocks. As his first publication on the igneous rocks comprising the Blatchford Lake intrusive suite, Davidson (1972) briefly described the various phases, their mineralogy and field relations, as well as creating a regional-scale map of the complex. Davidson (1978, 1981, 1982) further expanded on his original work on the Blatchford Lake intrusive suite, producing a more detailed map and a brief geochemical

analysis of the main phases comprising the Blatchford Lake intrusive suite. Most of the subsequent work done within the Blatchford Lake intrusive suite has focused on the Be-REE-Nb-Y mineralization around Thor Lake. These include publications by Cerny & Trueman (1985) on the polyolithionite micas, De St Jorre & Smith (1988) on Ga-rich feldspars, Smith *et al.* (1991) on zonally metamict zircons, Sinclair *et al.* (1994) concerning the U-Pb age of the Grace Lake Granite, Pinckston & Smith (1995) on the mineralogy of the Lake zone, and Taylor & Pollard (1996) on Be-Y-REE mineralization at the T-zone. Birkett *et al.* (1994) completed a ground based gravity survey (1-2 km station spacing) across the Blatchford Lake intrusive suite. With the recent increased worldwide demand for rare earth elements, there has been a resurgence of research focused on the Thor Lake rare-metal deposits. Most of these studies have examined various aspects of the Nechalacho REE-deposit (formerly known as the Lake zone) in detail including the mineralogy (Gilgen, 2010, Sheard *et al.*, 2012) and chemistry (Feng & Samson, 2010a, Feng & Samson, 2010b, MacWilliam & Williams-Jones, 2011, Möller & Williams-Jones, 2011, Williams-Jones *et al.*, 2010).

From 2004 to 2007 Kodiak Exploration Ltd. actively explored the Caribou Lake gabbro for Cu-Ni-PGE mineralization. Deposit models focused on sulfide banding near the basal contact or higher in the intrusions associated with magnetite-rich reefs (Marmont, 2007). Drilling programs during 2006-2007 resulted in over 16,000 m of drill core. Limited success was achieved during the 2006 drilling, where an 8 m thick massive sulfide lens was intersected (Marmont, 2006).

1.5 Study Objectives

The primary objective of this study is to describe the origin and evolution of the Blatchford Lake intrusive suite and the two small intrusive stocks hosted within it. Chapter two addresses the formation and evolution of rocks in the peralkaline eastern lobe. Field relations and improved geochronology are combined with geochemistry to describe the nature of contacts between key intrusive units, interpret intra-phase associations, and provide insight regarding the source composition. The third chapter examines the rocks of two atypical intrusive stocks located two kilometers to the west of the Thor Lake rare metal deposits. To decipher the origin of the two intrusive stocks, the geochemistry and geochronology of these rocks are compared to rocks from the Blatchford Lake intrusive suite and the Compton intrusive suite. New field relations are presented, and their implications relating to regional diabase dyke swarms are considered. The fourth chapter is focused on the petrology of the western lobe rocks. Geochemical characterization of the major phases provides a basis for determining intra-phase associations, and constraining the parental magma composition. Geothermobarometry is employed to place constraints on the pressure and temperature of emplacement of granitoid phases. Evidence indicating a relationship between the eastern and western lobes is reviewed, and potential mechanisms linking them are evaluated. Finally, the fifth chapter presents a limited comparison between the Blatchford Lake intrusive suite and rocks of the SWSMP and the Simpson Island dyke. Details regarding the petrogenesis of the Blatchford Lake intrusive suite described in chapters two and four are used to assess the origin of the SWSMP.

1.6 Methodology

1.6.1 Field investigations

The Blatchford Lake intrusive suite has been subject of mapping at various scales since the 1930's (Buckham, 1936, Jolliffe, 1936, Stockwell, 1932) however, prior to this study the Blatchford Lake intrusive suite was only mapped as a single entity once (Davidson, 1972, Davidson, 1978). Many geochronologic studies in the region are older, generally using K-Ar methods (Wanless *et al.*, 1979) or relatively unrefined U-Pb methods (Bowring *et al.*, 1984). Given the large surficial extent of the Blatchford Lake intrusive suite, a more thematic and focused approach to the area was undertaken. The field investigations targeted a) mapping key/problematic areas identified as a result of preliminary work and from geophysical anomalies, and b) collecting representative geochemical and geochronologic samples. Four months of field work was performed over three field seasons (2009-2011). While the focus of the study was primarily on surficial geologic relations, limited time was spent investigating and sampling drill core. Access to drill core was provided by Kodiak Exploration Ltd. (phases of Caribou Lake gabbro) and by Avalon Rare Metals Inc. (rocks related to the Thor Lake rare metal deposits). I also had viewing access to rock samples stored at the Geological Survey of Canada, Ottawa that were collected by Davidson (1972, 1978).

Brief field visits were also made to the other intrusions of the Southwest Slave magmatic province (Big Spruce Lake alkaline complex, Dogrib diabase dykes, Duck Lake sill, Squalus Lake intrusion) as well as the Simpson Island dyke. Individual investigations typically consisted of one to four days of verifying previous observations,

characterizing major rock types, and collecting representative samples from major lithologies.

1.6.2 Petrography

The mineralogy and textures of rocks were examined in ~210 thin-sections from rocks collected during this study. These observations were used to characterize rock types and lay the foundations for subsequent mineral chemical analyses and geochronologic investigations.

1.6.3 Electron Microprobe

The major and minor element compositions of the constituent minerals were determined using a Cameca Camebax MBX electron microprobe in wavelength-dispersion mode at Carleton University (Canada). For silicate minerals a beam current of 20 nA and an acceleration voltage of 20 kV was used. Beam sensitive minerals such as feldspar were analyzed using a rastered electron beam 10 by 10 microns in size. Peak counting times for analyzed elements were: 15-50 seconds or 40,000 accumulated x-ray counts. Background measurements were made at 50% of the peak counting time on each side of the analyzed peak. Peak and background spectrometer positions were carefully selected to avoid instances of overlap. Raw x-ray data were converted to elemental weight % by the Cameca PAP matrix correction program. Natural and synthetic phases were used as calibration standards. Analyses are accurate to 1-2 % relative for major elements, (>10 wt %); 3-10 % relative for minor elements (<10 wt %, >0.5 wt %). As

detection limit is approached (<0.1 wt %), relative errors approach 100 %. Mineral chemistry data are presented in Appendix B.

1.6.4 *Geothermobarometry*

Conventional geothermobarometry is used in this study to constrain the emplacement conditions of the Blatchford Lake intrusive suite. Prior to this study there had been no attempt to constrain the depth of emplacement or temperature of crystallization of units in the Blatchford Lake intrusive suite. This is partially attributed to the distinct dearth of thermometers or barometers applicable to peralkaline rocks, such as those that comprise the eastern lobe where most investigations of the Blatchford Lake intrusive suite have been focused. Efforts during this study were made to assess the viability of various thermometers on rocks from the eastern lobe, including the Ti-in-zircon thermometer (Ferry & Watson, 2007, Hayden & Watson, 2007, Watson *et al.*, 2006), Zr saturation thermometer (Hancher & Watson, 2003, Watson & Harrison, 1983) and hornblende-plagioclase thermometer (Blundy & Holland, 1990, Holland & Blundy, 1994). Results from these thermometers exhibited an extremely wide range and/or geologically unrealistic values.

Geothermometry was done on rocks of the western lobe using the Al-in-hornblende barometer (Schmidt, 1992) and the plagioclase-hornblende thermometer (Anderson & Smith, 1995, Blundy & Holland, 1990, Holland & Blundy, 1994). For plagioclase-hornblende thermometry the temperature-corrected calibration of Anderson and Smith (1995) using the second temperature calibration of Holland and Blundy was used (1994; compare Anderson, 1996). This calibration is based on the thermodynamic

equilibria of edenite + albite = richerite + anorthite. Uncertainty in pressure and temperature is reported as 1σ precision error as in Anderson and Smith (1995). In order to test whether or not the determined mineral compositions represent equilibrium conditions, core and rim analyses were determined. It was interpreted that equilibrium existed at the thin-section scale when the compositional variation between rims of analyzed mineral phases was less than five percent. Geothermometry data are presented in Table 4.3.

1.6.5 Whole rock major and trace-element geochemistry

Rocks samples collected were at least 12 x 12 x 12 cm, with the exception of drill core samples which were at least 20 cm in length. Samples were slabbed, altered surfaces trimmed off, crushed in a Bico Chipmunk jaw crusher, and ground to a fine-powder in a chrome-steel ring mill. Between samples, the jaw crusher and the chrome-steel ring mill were cleaned thoroughly using water, compressed air, and ethyl alcohol. The fine powder was mixed, and aliquots were separated for analysis. Replicate analyses through the chrome-steel ring mill and agate ring mill have been compared, indicating only minor Cr contamination (Cousens, personal communication 2011). Whole rock major and trace element contents were determined by fused-disc X-ray fluorescence spectrometry (XRF; University of Ottawa and ALS Geochemistry, Vancouver) and solution mode inductively coupled plasma mass spectrometry (ICP-MS; Ontario Geological Survey, Sudbury and ALS Geochemistry, Vancouver). The precisions of the data, based on replicate analyses of samples and blind standards are listed with the data presented in Appendix A.1 – A.4. Sample locations are illustrated in Figure 1.2. Detection limits indicate the minimum

Figure 1.2 - Sample locations, for geologic legend see Figure 2.2.

concentration that can be distinguished from a blank specimen; values were calculated by personnel at the Ontario Geological Survey Geoscience Laboratories.

1.6.6 Whole rock Sm-Nd isotopic analyses

Based on major and trace-element compositions, a subset of samples was selected for Nd isotopic analyses. All Sm-Nd analyses and sample preparations, including weighing, spiking, acid washing, dissolution, column chromatography, filament loading, and mass spectrometry were performed at the Isotope Geochemistry and Geochronology Research Centre (IGGRC) at Carleton University, Ottawa, Canada. Due to the strong rare-earth element (REE) enrichment in many of the samples, care was taken to avoid over-saturation of the chromatography columns. This was done by limiting sample size, based on the concentration of Nd determined by ICP-MS. Spike was added to the sample (enriched ^{148}Nd - ^{149}Sm) so that the precise concentration of Nd and Sm could later be determined by isotope dilution. Chemical procedures following the methodology described by Cousens (2000) are outlined below. Sample and spike were dissolved in Teflon beakers in three steps: 50% HF + 16N HNO₃, 7N HNO₃, 6N HCL; between stages samples were dried. Following dissolution, the samples were taken up into 2.5N HCL and centrifuged. Ion-exchange column chromatography was used to isolate the Sm and Nd. The precipitate free liquid was added into 14 mL Bio-Rad borosilicate glass chromatography Sr columns with Dowex 50-X8 cation resin. The REE were separated from the Sr columns using 6N HCL. The REE fraction was dried, then re-dissolved in 0.26N HCL and loaded into 14-ml Eichrom chromatographic column containing Teflon powder coated with HDEHP [di(2-ethylhexyl) orthophosphoric acid, (Richard *et al.*,

1976)]. Nd was eluted using 0.26N HCl, followed by Sm with 0.5N HCl. Samples were loaded with H₃PO₄ on one side of a Re double filament, and run at temperatures of 1780-1825°C. Analyses were made using a Thermo-Finnigan Triton T1 thermal ionization mass spectrometer in static mode. Nd isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd}=0.72190$. The La Jolla standard produced $^{143}\text{Nd}/^{144}\text{Nd}=0.512668 \pm 20$, n=26 (Feb 2005 – June 2007). During the same period an internal standard produced $^{143}\text{Nd}/^{144}\text{Nd}=0.511818 \pm 8$, n=28 (Feb 2005 – June 2007). The internal standard was then run during the course of this study and produced $^{143}\text{Nd}/^{144}\text{Nd}=0.511821 \pm 9$, n=35 (Jan 2010 – June 2012). All quoted uncertainties are 2-sigma standard deviations of the mean.

1.6.7 *U-Pb spot analyses of zircon*

U-Pb spot analyses of zircon were done using laser ablation – inductively coupled plasma – mass spectrometer (LA-ICP-MS) at the University of New Brunswick (UNB), Fredericton. Individual zircon grains were analyzed *in situ* in a standard polished thin-section. Prior to analysis, zircons were imaged using a JEOL JSM6400 Digital SEM equipped with Geller dPict digital image acquisition software and Gatan ChromaCL Cathodoluminescence imaging system (also at UNB). Backscattered electron and cathodoluminescence images were used to characterize internal zircon morphology and guide ablation. Standards and samples were simultaneously loaded into a two-volume low-volume Laurin Technic Pty sample cell that was repeatedly evacuated and backfilled with He to remove traces of air from the cell after each sample exchange. The cell was subsequently pressurized using high-purity He cell gas (~750 mL/min) that was mixed downstream of the cell with 650 mL/min Ar and 2.8 mL/min N₂. All gas lines were fitted

with VICI Metronics high-flow Hg traps that maintain the ^{204}Hg gas background at <150 cps.

Output energy from the Resonetics M-50-LR 193 nm Excimer laser was set and regulated at 120 mJ corresponding to a fluence of $\sim 5 \text{ J/cm}^2$ on target. Standards and unknowns were ablated using a 32 μm diameter (23 μm for NS sample) crater using a repetition rate of 4 Hz. A single long ablation sequence was constructed for each sample, and consisted of at least 15 analyses of the 91500 zircon standard ($^{206}\text{Pb}/^{238}\text{U}$ age = $1062.4 \pm 0.4 \text{ Ma}$; $^{207}\text{Pb}/^{206}\text{Pb}$ age = $1065.4 \pm 0.3 \text{ Ma}$; Wiedenbeck *et al.*, 1995). Measurements of the 91500 zircon standard were interspersed with the unknown target grains, and used as an external standard to correct for instrument drift, down-hole fractionation, and mass-bias. Each ablation sequence consisted of 30 seconds of gas background collection, followed by 30-35 seconds of ablation. Time-resolved intensities were collected using an Agilent 7700x quadrupole ICP-MS configured with dual external rotary pumps. Laser-induced Pb/U fractionation corrections, corrected isotope ratios, and elemental abundances were calculated offline using Iolite™ version 2.13 (February 1, 2011) and VizualAge™ (Petrus & Kamber, 2012). Time-slices with constant $^{207}\text{Pb}/^{235}\text{U}$, $^{206}\text{Pb}/^{238}\text{U}$, and $^{207}\text{Pb}/^{206}\text{Pb}$ ratios were initially chosen because these represent constant age domains. The VizualAge™ plugin, which projects the location of each analysis on a ‘live’ concordia, was then used to fine-tune the limits of the time-slices to determine the most concordant portion of the analysis.

The exported data were inspected using Isoplot™ v3.71 (Ludwig, 2003). The accuracy of the LA-ICP-MS data was verified by periodically analysing the $416 \pm 1 \text{ Ma}$ Temora zircon standard (416 Ma: Black *et al.*, 2003) under the same analytical

conditions. The long-term (2 years) concordant age for Temora zircon obtained at the UNB laser ablation is 415.5 ± 2.5 Ma confirming the accuracy of the analytical technique.

1.6.8 TIMS U-Pb zircon dating

All crushing and mineral separation was performed at the Geological Survey of Canada, Ottawa, using standard crushing, heavy liquid, and magnetic-separation techniques. All zircon fractions were chemically abraded using the techniques of Mattinson (2005) to anneal and leach the discordant zones of zircon grains. Isotopic and U-Pb compositional data were determined by isotope dilution thermal ionization mass spectrometry (TIMS) at the Geochronology laboratory, Geological Survey of Canada. Sample dissolution and chemical methods are described in Parrish *et al.* (1987). Individual crystals were selected under binocular microscope to avoid inclusions and other imperfections, spiked with a mixed ^{205}Pb - ^{233}U - ^{235}U tracer solution calibrated to $\pm 0.1\%$ against a gravimetric solution, and dissolved in high-pressure bombs in HF-HNO₃. Data reduction and error propagation follow methods outlined in Roddick (1987). U and Pb isotopic ratios were measured using a Triton mass spectrometer operated in static multi-collection mode. The ^{205}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb isotopes were measured simultaneously in Faraday collectors, with ^{204}Pb in an axial secondary electron multiplier. Faraday-multiplier gain was monitored and corrected by peak jumping ^{205}Pb into the axial cup. A Pb mass fractionation correction of $0.1 \pm 0.04\%$ /amu was applied as determined by replicate analyses of the NBS981 standard. U fractionation was corrected using the ^{233}U - ^{235}U double spike and was typically in the range of 0.12% /amu.

2 Chapter: Petrology of the eastern lobe of the Blatchford Lake intrusive suite

2.1 Introduction

Peralkaline igneous rocks, characterized by $\text{Al}_2\text{O}_3 < (\text{Na}_2\text{O} + \text{K}_2\text{O})$ and high contents of incompatible elements, are eagerly sought after as a potential source of rare-earth elements (REE) (Castor, 2008, Sorensen, 1992). The plutonic peralkaline system that hosts the Thor Lake deposits of the Northwest Territories, Canada, constitutes one of the world's largest resources of rare-earth elements (Castor, 2008). Much of the research and attention at Thor Lake has focused on the various polymetallic rare-metal deposits, since their discovery in the 1970s (Pinckston & Smith, 1995, Taylor & Pollard, 1996, Trueman *et al.*, 1988). However, almost no work has been done to address the petrogenesis of the host system, the Blatchford Lake intrusive suite (BLIS; also known as the Blachford Lake intrusive suite, Blachford Lake complex, and Blatchford Lake complex) since Davidson (1972, 1978, 1981, 1982). Phases of the BLIS can be separated based on crosscutting relations and chemistry into two groups: the western and eastern lobes. The older subalkaline-alkaline western lobe is composed of mafic and ultramafic rocks, and metaluminous granites and syenites. The eastern lobe comprises peralkaline granite, syenite, and nepheline syenite, and is host to multiple unusual igneous features, including a localized coeval olivine rich-body and an inverse trend of degree of silica-saturation, decreasing from rim to core of the intrusion. In addition to this work on the petrogenesis of the eastern lobe of the BLIS, numerous concurrent studies are focused on addressing complexities associated with the mineralization of the Thor Lake deposits

(Feng & Samson, 2010b, MacWilliam & Williams-Jones, 2011, Möller & Williams-Jones, 2011, Sheard, 2010, Williams-Jones *et al.*, 2010) as well as the petrogenesis of the western lobe (Chapter four).

While the association between alkaline igneous rocks (miaskitic and agpaitic) and rare-metal mineralization is well documented (Marks *et al.*, 2011, Marks *et al.*, 2008, Richardson & Birkett, 1996, Schmitt *et al.*, 2002, Steenfelt, 1991), there remain many questions regarding the conditions, processes and mechanisms that concentrate rare-metals to economic levels. The proposed factors can be roughly sub-divided into three components: melt source, magmatic processes, and post-magmatic hydrothermal processes, with a continuum likely between these end-members likely. However, in order to separate and individually evaluate the influences of magmatic and magmatic-hydrothermal processes we must have a solid understanding of the genesis of parental melts and constraints on the conditions governing magmatic evolution.

Using trace-element geochemistry, geochronology, and radiogenic isotopes, this study aims to reveal the petrogenetic context in which the mineralization can be evaluated, and gain insight into the composition and origin of the parental melts. As well, the significance of the inverse trend in degree of silica-saturation and the nature of the localized coeval olivine rich-body will both be addressed with respect to the evolution of the BLIS. Finally, we will resolve outstanding geochronological issues in the eastern lobe relating to the age of the Nechalacho layered suite.

2.2 Geological setting and previous work

The Blatchford Lake intrusive suite is located in the Northwest Territories, about 100 km southeast of the city of Yellowknife, Canada. The intrusive suite occurs at the southeastern margin of the Slave craton, along the north shore of the Hearne Channel of Great Slave Lake (Fig. 2.1, 2.2). The entire suite has been intruded into Archean metasedimentary rocks, granite and granodiorite plutons. No volcanic rocks of similar age or composition to the BLIS have been identified in the region, suggesting that either magma derived from the BLIS never reached the surface, or they have since been eroded away.

Paleoproterozoic tectonic reconstructions suggest that deformation along the southeastern margin of the Slave Craton was controlled by either: (1) largely transpressional forces along an oblique crustal scale boundary (Bleeker & Hall, 2007, Hanmer *et al.*, 1992, Hoffman, 1987), (2) a failed rift margin (Bowring *et al.*, 1984, Hoffman, 1973, Hoffman *et al.*, 1974). Both scenarios invoke crustal thinning mechanisms that could initiate decompression melting and deep structures to act as conduits for deep crustal or mantle derived melts.

The mafic rocks of the BLIS were first mapped in the 1930s by Stockwell (1932), Jolliffe (1936), and Henderson (1938), as part of regional mapping programs. Buckham (1936) studied the petrology of what he referred to as the Francois River gabbro, now known as the Caribou Lake gabbro and leucoferrodiorite units of the BLIS. However, until Davidson (1972) studied granites in the southern Slave province it was not considered that this mafic suite may be related to the adjacent granitoid rocks. Davidson (1978) created a regional scale map of the intrusive complex, and described the

Figure 2.1 - Geological map of the eastern lobe of the Blatchford Lake intrusive suite (BLIS). The dashed oval roughly indicates the extent of the Nechalacho layered suite known through drilling. Location: (A) zone of abundant rounded syenitic inclusions, (B) position of vertical drill hole intersecting olivine syenite, (Traverse) sampling profile across the rim syenite. For legend see Figure 2.2.

Figure 2.2 - Geology legend for Figure 2.1

field relations, mineralogy, and geochemistry of the various phases.

Numerous intrusive phases in the BLIS document a succession from ultramafic to felsic plutonism. Davidson (1978) proposed the following chronology of the BLIS based on cross-cutting relations and geochemistry: (1) mafic rocks of the Caribou Lake gabbro, grading to leucoferrodiorite; (2) Whiteman Lake quartz syenite; (3) Hearne Channel granite; (4) Mad Lake granite; (5) Grace Lake granite; (6) Thor Lake syenite. Davidson (1981) noted that based on chemistry the entire intrusive suite can be divided into two groups, an older metaluminous group (units 1 – 4), and a younger peralkaline group (units 5 and 6). Based on their spatial distribution, these two groups will be respectively referred to herein as the western and eastern lobes, respectively (as in Birkett *et al.*, 1994). Since the mapping by Davidson (1972, 1978) there have been extensive exploration diamond drilling programs by Kodiak Exploration Ltd and Avalon Rare Metals Inc. within the BLIS. Drill core has revealed new lithological units and mineralogical variations not visible at surface; these revelations and their significance will be addressed in the field relations and petrography section of this study.

The peralkaline eastern lobe contains evolved silica-saturated and undersaturated rocks, some of which are exceptionally enriched in rare metals, e.g., rare earth elements (REE). Centrally located in the eastern lobe, the Thor Lake syenite and the unexposed underlying Nechalacho layered suite host the Thor Lake rare-metal deposits, a cluster of polymetallic mineralized zones. The various Thor Lake rare-metal deposits consist of the R-, S-, T-, Fluorite-, and Lake-zone and their descriptions and characteristics have been summarized in Trueman *et al.* (1988). In 2009, the Lake-zone was renamed the Nechalacho deposit by Avalon Rare Metals Inc. Many of the numerous smaller rare-metal bearing zones have not been examined in detail, with the majority of work at Thor

Lake focused on the T-zone (Taylor & Pollard, 1996), Lake-zone (Pinckston, 1989, Pinckston & Smith, 1995), or on mineralogical studies (Cerny & Trueman, 1985, De St. Jorre & Smith, 1988, Smith *et al.*, 1991). Together, the Thor Lake rare metal deposits represent one of the world's largest resources of zirconium, niobium, and heavy rare earth elements (HREE) (Sheard *et al.*, 2012). Previous work on the mineralization in the "T" and Lake zones indicates the influence of a late, moderately low-temperature hydrothermal event (Pinckston & Smith, 1995, Sheard *et al.*, 2012, Taylor & Pollard, 1996). This locally-constrained event appears to have disrupted the primary magmatic signature of the rocks and is thought to have been responsible for the remobilization of REE (Sheard *et al.*, 2012). It is believed that this hydrothermal event was related to crystallization of phases in the eastern lobe (i.e., Nechalacho layered suite) resulting in the exsolution of fluid phases and the subsequent autometasomatism of local rocks (Pinckston & Smith, 1995, Sheard *et al.*, 2012).

As this study is principally focused on magmatic evolution of the BLIS we will not attempt to describe the numerous (>60) complex REE-bearing minerals associated with the rare-metal deposits or their petrogenesis. For the mineralogy of the Thor Lake rare-metal deposits refer to Trueman *et al.* (1988) or Pinckston & Smith (1995). Using a detailed line gravity survey with 1-2 km station spacing, Birkett *et al.* (1994) modeled a gravity profile across the BLIS that suggested the thickness of the Eastern lobe was ~ 1 km.

2.3 Field relations, classification, and petrography of the eastern lobe

The aim of this study is to understand the petrogenesis of primary intrusive phases in the eastern lobe of the BLIS. Field relations between the succession of ultramafic to felsic plutons were described in detail by Davidson (1978), constraining the chronological order of emplacement. However, exploration diamond drilling in the BLIS has revealed new units not incorporated in this chronology. Field relations of these newly defined units based on our field observations are summarized below in the context of the succession defined by Davidson (1972, 1978).

2.3.1 *Grace Lake granite*

The Grace Lake granite unit has the largest surficial exposure in the BLIS, covering an area of approximately 160 km². The western contact of the Grace Lake granite cross-cuts all units of the western lobe as well as a granodiorite body of the Archean Defeat plutonic suite. The remainder of its contact is of an intrusive nature into the Archean Burwash Formation metasedimentary rocks (Fig. 2.1, 2.2). The outer contact is typically vertical, but locally dips inwards towards the intrusion centre. The northern contact between the Burwash Formation and the Grace Lake granite is locally defined by a 2 – 20 m wide zone containing abundant (30 – 70%) metasedimentary inclusions. Contacts with the western lobe are marked by quenching and by isolated dykes of the Grace Lake granite extending into units of the western lobe. The southwestern portion of the Grace Lake granite contains abundant rafts of Hearne Channel granite and leucoferrodiorite belonging to the Caribou Lake gabbro. Many of these rafts occur on hilltops and typically have sub-horizontal contacts.

The Grace Lake granite is a pink weathering, amphibole-bearing, alkali feldspar granite. It is typically hypidiomorphic, medium to coarse-grained, with euhedral to subhedral perthitic alkali feldspar and interstitial quartz, amphibole (fluor-magnesioarfvedsonite to calcian arfvedsonite) and aegirine; fluorite and zircon are common accessory phases. Locally the amphibole has been altered to magnetite, which in places forms complete pseudomorphs of the amphibole. Both quartz and magnetite are locally poikilitic, and both can vary up to 40 modal %; overall there is a general decrease in quartz content from the granite margin inwards. The Grace Lake granite contains abundant rafts of Burwash metasediment varying in size from <1 to $>100\text{ m}^2$, as well as thin sub-horizontal lenses of syenite. In one small portion of the Grace Lake granite (area is centered on point A in Figure 2.1, covering $<0.75\text{ km}^2$), numerous rounded inclusions of syenitic material were observed. Near the center of this zone, the inclusions account for $> 30\%$ of the area, gradually decreasing outwards. The diameter of inclusions ranges from 2 cm to $> 1\text{ m}$ (Fig. 2.3c). The porphyritic syenite inclusions contain abundant fragments of the Grace Lake granite and a high proportion of opaque mineral phases.

2.3.2 *Thor Lake syenite*

The Thor Lake syenite is an approximately oval body located centrally in the Grace Lake granite (Fig. 2.1, 2.2). The contact between the two igneous units is not intrusive, but rather an abrupt mineralogical change, marked by a decrease in quartz content; there is no grain size variation or dykes of one unit intruding the other. This contradicts Pinckston & Smith (1995) but is in agreement with the field relations described by Davidson (1978), Taylor & Pollard (1996), and with our observations.

The contact on the west side is gradational over one to tens of meters, whereas contacts in the north and east are typically razor sharp. Where the boundary is sharp, the orientation of the contact is variable, in the northeast the contact is typically undulose and sub-horizontal, varying to the southeast where the contact becomes steep and locally dips outward from the center of the Thor Lake syenite into the Grace Lake granite. Pegmatitic pods are noticeably more abundant within the Thor Lake syenite near the contacts with the Grace Lake granite along the shore of Great Slave Lake (Fig. 2.3a). The mineralized zones in the Thor Lake syenite are generally associated with a magnetic high centered to the southeast of Thor Lake (Fig. 2.4). As the main interest in this study is the primary magmatic evolution of the eastern lobe, sampling was restricted to unmineralized rock-types to avoid issues relating the remobilization of REE (Sheard *et al.*, 2012). For mineralogical and geochemical purposes we distinguish three sub-units: leucosyenite (to include units 6b – 6d of Davidson, 1978), rim syenite (unit 6a, Davidson, 1978), and an olivine syenite. Our sub-divisions simplify the six varieties described by Davidson (1978) by grouping rocks together that exhibit textural variations but retain similar chemical compositions (leucosyenite; units 6b – 6d of Davidson, 1978), and omitting rock types from mineralized zones (unit 6e, 7 of Davidson, 1978).

2.3.2.1 Leucosyenite

The medium- to coarse-grained Thor Lake syenite - leucosyenite is an alkali-feldspar syenite consisting predominantly of euhedral to anhedral alkali-feldspar, amphibole (calcian-magnesian arfvedsonite), aegirine, and anhedral poikilitic quartz (< 10%). Spatially distinct areas of the leucosyenite are characterized by large (up to 4 cm)

Figure 2.3 - Textural relations in the Blatchford Lake intrusive suite - eastern lobe: (a) pegmatitic pod in the Thor Lake syenite. Note the centrally hosted brown carbonate. (b) Contact between the Grace Lake granite (top) and the Thor Lake syenite (bottom). (c) Rounded inclusions in the Grace Lake granite. (d) Biotite cumulate in the Nechalacho layered suite. (e) Cumulate olivine syenite. (f) Repetitive sequence of cumulate layering in a biotite-rich aegirine syenite unit of the Nechalacho layered suite.

poikilitic grains of amphibole (Fig. 2.5a). Magnetite, fluorite, apatite, and zircon are common interstitial accessory phases in the leucosyenite.

2.3.2.2 Rim syenite

The rim syenite is a prominent ridge near the northern and eastern margin of the Thor Lake syenite; a narrow gradational band of leucosyenite separates it from the Grace Lake granite. The topographic profile of the rim syenite is asymmetric, forming a steep outer margin and a moderate inward slope. It is identified in the field by its rusty and rubbly weathering and variable abundance of oxides (15 – 40%). Due to the distinctly elevated magnetic signature, the width and extent of the rim syenite can easily be observed in the regional magnetic surveys (Fig. 2.4) that show a concentric relationship between the rim syenite and the Thor lake syenite.

The dark green to brown, rusty-weathering rim syenite is fine- to coarse-grained, locally displaying a decrease in grain size with elevation towards the top of the ridge. The rim syenite is composed of subhedral poikilitic perthitic alkali feldspar, poikilitic amphibole (calcian-magnesian arfvedsonite), apatite, magnetite, euhedral to subhedral aegirine, local interstitial quartz, with rare primary euhedral calcite and anhedral to rounded fayalite. Where present the fayalite is strongly altered to Fe-oxides and other fine-grained products. The resistive weathering of the rim syenite is interpreted to be related to the variation in mineralogy and the decreased grain size relative to the Grace Lake granite and the Thor Lake leucosyenite.

Figure 2.4 - Total magnetic intensity field of the Blatchford Lake intrusive suite area after Pilkington *et al.* (2012). Dark black dashed lines indicate contacts between major geological units (see Figure 2.1). The Thor Lake rim syenite coincides with the central ring magnetic anomaly, the anomaly in the western portion coincides with the Caribou Lake gabbro of the western lobe. The linear NW-trending anomaly corresponds with a Indin diabase dyke, whereas the ENE-trending linear features correspond to the Hearne diabase swarm. CLG, Caribou Lake gabbro; WGG, Whiteman granitic group; HGG, Hearne granitic group; GLG, Grace Lake granite; TLS, Thor Lake syenite.

2.3.2.3 Olivine Syenite

A sub-unit of the Thor Lake syenite, an olivine syenite, was discovered in 2010 during drilling at depth near the northern margin of the Thor Lake syenite (point B, Fig. 2.1). The unit was intersected at depth of approximately 300 m by multiple drill holes over a distance of 130 meters, but due to the spacing between holes, its lateral and vertical extent remains relatively unconstrained.

The olivine syenite consists of subhedral poikilitic perthitic alkali feldspar grains with inclusions of euhedral clinopyroxene (ferrian-sodian augite to ferrian sodian hedenbergite) and rounded fayalite grains ($\text{Fa}_{>98}$), with interstitial biotite, apatite, and Fe-Ti oxides. The progressive downhole increase in grain size (0.1 – 5 mm) and modal abundance (5 – 35%) of fayalite (Fig. 2.3e), and repetitive sequences with gradational tops and sharply defined bases indicate that the olivine syenite formed as a cumulate. The abundance and unaltered state of fayalite crystals (Fig. 2.5b), and their cumulate textures in the olivine syenite distinguish it from the rim syenite.

As there are no outcrops of this unit, the contact relations are only accessible in drill core, but the unit appears to be sub-horizontally interfingered (<3 m fingers) with Thor Lake leucosyenite.

2.3.2.4 Burwash Formation

Both the Thor Lake syenite and Grace Lake granite are hosts to numerous hornfelsed inclusions of Burwash Formation. The abundance and size of these rafts (some exceeding 100 m diameter) generally increases toward the center of the Thor Lake syenite. These metasedimentary rafts are partially recrystallized, but locally retain

Figure 2.5 - Photomicrographs of mineralogical and textural features of the Thor Lake syenite: (a) poikilitic grains of hornblende in Thor Lake leucosyenite, (b) fayalite and hedenbergite (cpx) in Thor Lake olivine syenite. Abbreviations are as follows: amp=amphibole, ap=apatite, cpx=clinopyroxene, ksp=alkali-feldspar, ol=olivine.

primary sedimentary features including bedding planes. It has been postulated that the Thor Lake syenite, due to its evolved nature and location at the core of the intrusive suite, may also represent one of the higher structural positions in the system (C. Pederson, pers. comm. 2010). In this case, the abundance and size of these inclusions could be explained by proximity to the upper bounding surface of the intrusion. However, due to the strongly deformed nature of the Burwash Formation, the structures outside the complex cannot be correlated with structures present within rafts. Without additional information we are not able to conclusively determine if the rafts have remained *in situ* and represent roof pendants.

2.3.3 *Nechalacho layered suite*

The Nechalacho layered suite consists of a wide array of alkaline intrusive rocks forming numerous layers that locally display cumulate textures, rhythmic banding (Fig. 2.3d and f), and sharp sub-horizontal internal contacts (Sheard *et al.*, 2012). These silica-undersaturated rocks in the eastern lobe were first described in drill core by Pinckston (1989), within the Lake zone of the Thor Lake rare-metals deposits. Due to intense hydrothermal alteration and mineralization, the contact relations between the Thor Lake syenite and the silica-undersaturated rocks are obscured (Pinckston, 1989, Pinckston & Smith, 1995). However, based on strong alteration of the rock in the contact zone, and the abrupt chemical and mineralogical change from silica-saturated to undersaturated, rocks of the Nechalacho layered suite have been interpreted as being a late intrusive event (Pinckston, 1989, Pinckston & Smith, 1995). Samples for characterization were selected from zones in the Nechalacho layered suite that exhibited minimal evidence of alteration.

Unaltered nepheline crystals are typically steely-grey, whereas clay and mica mineral replacement is indicated by powdery material that is pinkish, red, or green in colour.

Based on the IUGS classification, rocks of the Nechalacho layered suite range from sodalite syenite to ijolite, reflecting the small differences in modal percent abundances of a few primary minerals, (i.e., alkali-feldspar, nepheline, sodalite, aegirine, and biotite: (Möller & Williams-Jones, 2011, Sheard, 2010). Rocks of the Nechalacho layered suite are medium-grained to pegmatitic and typically porphyritic. In addition to the alkali-feldspar- and nepheline-bearing rocks, zircon and other mineral pseudomorphs after eudialyte crystals show evidence of cumulate textures, suggestive of primary magmatic eudialyte cumulate layers (Sheard, 2010, Sheard *et al.*, 2012). Drilling indicates that the Nechalacho layered suite exceeds 1 km in depth and that it has a diameter of >1.5 km.

2.3.4 *Compton intrusions*

Two small plutonic stocks located approximately 2 km east of Thor Lake (Fig. 2.1) were originally mapped by Davidson (1972) as rafts of an earlier plutonic unit embedded in the Grace lake granite. He later revised this and considered that they were discrete intrusions belonging to the Compton intrusive suite (Davidson, 1978). The two intrusions are fine to medium-grained porphyritic diorite to quartz monzonite. The subvertical contacts at the margins of these two intrusions are chilled against the Grace Lake granite. The age of Compton intrusive suite has been determined to be 1867 Ma (Bowring *et al.*, 1984).

2.3.5 Diabase dykes

The entire BLIS is cross-cut by the northeast trending diabase dyke swarm believed to be part of the 1901 Ma Hearne swarm (Buchan *et al.*, 2010). The strongly magnetic NW-trending dyke that occurs just north of Thor Lake (Fig. 2.4) had been assumed to be part of the 1267 Ma Mackenzie dyke swarm (Davidson, 1978, Gilgen, 2010), but based on dyke orientation and geochemistry it has been re-classified as a 2126-2108 Ma Indin diabase dyke (Mumford *et al.*, 2012a).

2.4 Analytical Methods

See section 1.6

2.5 Whole-rock chemistry

The chemical compositions of representative rock samples are presented in Appendix A.1. Given that many of the rock types in the eastern lobe exhibit evidence of varying degrees of cumulate processes, the whole-rock major and trace-element chemistry should be considered with caution since the sampled rocks are unlikely to represent liquid compositions. In addition, the Nechalacho layered suite is host to a large REE deposit, associated with an extensive alteration system and many of the rocks are likely to have been altered by late hydrothermal fluids. Particular caution has been used when interpreting the REE patterns of these rocks. Essential geochemical features are summarized in Figs. 2.6 – 2.11.

2.5.1 *Major-element chemistry*

Units of the eastern lobe are dominantly peralkaline [i.e., $\text{Al}_2\text{O}_3 < (\text{Na}_2\text{O} + \text{K}_2\text{O})$] with a subordinate number of samples that are weakly metaluminous (Fig. 2.6). Eastern lobe samples are enriched in Fe and depleted in MgO, all having $\text{FeO}_t/(\text{FeO}_t + \text{MgO})$ ratios of greater than 0.80 (Fig. 2.7a). The SiO_2 content in the Grace Lake granite ranges from 76.4 to 62.7 wt. %, gradually decreasing from the outer margin to the contact with the Thor Lake syenite. Silica contents of the Thor Lake syenite range from 55.6 to 63.0 wt % excluding olivine syenite samples (41.6 – 47.3 wt %), and samples of the Nechalacho layered suite range from 33.0 to 54.3 wt %. Using bivariate major element plots versus SiO_2 (Fig. 2.8), numerous trends are observable between and within Grace Lake granite, Thor Lake syenite, and Nechalacho layered suite phases. Intra-phase trends exhibit linear negative correlations (e.g., Al_2O_3 , CaO, K_2O , Na_2O , Fe_2O_3) as well as more complex arcuate trends of MgO and P_2O_5 . Within individual phases strong correlations are observed between major element whole-rock compositions and mineralogy (e.g., increasing MgO and FeO, and decreasing Al_2O_3 , with decreasing modal feldspar/amphibole ratios). We interpret that the linear trends within individual phases (i.e., Fig. 2.8, SiO_2 vs Al_2O_3) are an expression of the cumulate nature of the units, reflecting variations in modal abundances of select mineral phases.

2.5.2 *Trace-element chemistry*

The Grace Lake granite, Thor Lake syenite, and Nechalacho layered suite all exhibit similar incompatible element patterns on chondrite-normalized multi-element

Figure 2.6 - Shand's index (modified from Maniar & Piccoli, 1989), showing dominantly peralkaline eastern lobe rocks.

Figure 2.7 - Granite discrimination diagrams: (a) $\text{FeOt}/(\text{FeOt}+\text{MgO})$ vs SiO_2 (Frost *et al.*, 2001), (b) Nb vs Y (Pearce *et al.*, 1984), (c) Zr vs $10000 \cdot \text{Ga}/\text{Al}$ (Whalen *et al.*, 1987), (d) Y vs Nb vs Ce (Eby, 1992). Symbols as in Figure 5. WPG=within-plate granite, ORG=ocean-ridge granite, VAG=volcanic-arc granite, syn-COLG=syncollisional granite, A1=mantle differentiates of ocean-island, intraplate and riftzone magmas, A2=related to continental margin and island-arc basalt forming processes. Symbols as in Figure 2.6.

geochemical variation diagrams (Fig. 2.9). These patterns are defined by light rare-earth elements (LREE) with a weak convex-up pattern from La to Sm, whereas the heavy rare-earth element (HREE) pattern is concave-up from Gd to Lu; the inflection point is generally marked by a negative Eu anomaly. Grace Lake granite samples exhibit the largest negative Eu anomalies (Eu/Eu^*), ranging from 0.19 – 0.46 ($n=12$), compared to the Thor Lake syenite (0.42 – 1.42, $n=19$) and the Nechalacho layered suite (0.37 – 0.45, $n=8$). Of the 19 Thor Lake syenite samples, only three have positive Eu anomalies: two of these samples are from the rim syenite and one is from an altered syenite close to the mineralization halo. The Grace Lake granite, Thor Lake syenite, and Nechalacho layered suite have low concentrations of compatible elements, (e.g., Ni <5 ppm and Cr <250 ppm, although some of this is possibly attributable to the milling/grinding process). Overall the eastern lobe rocks are enriched in incompatible elements, (e.g., Rb >55 ppm, Zr >97 ppm). The Grace Lake granite is generally more enriched in incompatible elements than the Thor Lake syenite and Nechalacho layered suite (Fig. 2.9). The $(\text{La}/\text{Yb})_N$ ratios of phases in the eastern lobe all exhibit wide variations, Grace Lake granite (7 – 46), Thor Lake syenite (8 – 21), and Nechalacho layered suite (14 – 46). The Grace Lake granite and Thor Lake syenite both have low $(\text{Sm}/\text{Lu})_N$ ratios, (3.1 – 9.7 and 3.3 – 6.3 respectively), while the Nechalacho layered suite shows more variation (4.9 – 20.9). Uranium contents of the three units are generally low but locally variable; concentrations are highest in the Grace Lake granite (1.4 – 8.2 ppm) and are noticeably lower in both the Nechalacho layered suite (0.55 – 3.4 ppm) and Thor Lake syenite (0.83 – 5.2 ppm).

Figure 2.8 - Selected oxides vs silica for units of the eastern lobe. Arrows in SiO_2 vs Al_2O_3 indicate trends interpreted as variations in modal abundances of major mineral phases (see text for details).

Figure 2.9 - Chondrite-normalized multi-element patterns for units of the eastern lobe: (a) Grace Lake granite, (b) Thor Lake syenite, (c) Nechalacho layered suite. Chondrite normalization values are from McDonough and Sun (1995).

2.5.3 *Geochemical transect across rim syenite*

To examine the chemical variability between the Thor Lake rim syenite, Thor Lake leucosyenite, and Grace Lake granite, a diamond saw was used to collect samples at 40 metre intervals along a linear traverse perpendicular to the rim syenite near its northern margin (Fig. 2.1). The results are summarized in Fig. 2.10.

The most topographically elevated point of the rim syenite has numerous element enrichments (e.g., Fe_2O_3 , TiO_2 , Sr) and depletions (e.g., SiO_2 , Rb, U). Overall, SiO_2 , Rb, Th concentrations decrease across the profile (from Grace Lake granite to leucosyenite) whereas most other elements increase (Fe_2O_3 , Na_2O , P_2O_5) or have a constant concentration. The major and trace-element chemical differences between samples along the traverse are strongly influenced by variations in the mineralogy between the Grace Lake granite and the Thor Lake leucosyenite - rim syenite. Despite of the variability it is possible to discern larger scale trends from this information and make some inferences about magma evolution. The largest chemical differences between samples occur in samples close to the rim syenite. The majority of elements that exhibit large fluctuations (positive or negative) are generally considered to be mobile in aqueous solutions, (e.g., Ba, U, Rb, Sr: (Jenner, 1996).

2.5.4 *Nd isotopes*

The Nd isotope data on fourteen whole rock samples are presented in Table 2.1. $\epsilon_{\text{Nd}i}$ values increase from the Grace Lake granite ($\epsilon_{\text{Nd}i} = +1.0$ to $+1.7$) through the Thor Lake syenite leucosyenite ($\epsilon_{\text{Nd}i} = +1.7$ to $+2.4$) to the Nechalacho layered suite at depth

Type	Sample	Nd (ppm)	$^{143}\text{Nd}/^{144}\text{Nd}_m$	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_i$	ϵ_{Nd}^T
TLS-ls	1201A	169.67	0.511487	31.00	0.1105	0.509900	1.74
TLS-ls	1202A	83.22	0.511615	16.40	0.1191	0.509903	1.80
TLS-ls	1203A	75.48	0.511441	13.17	0.1055	0.509926	2.25
TLS-ls	1037A	108.91	0.511586	20.70	0.1149	0.509934	2.42
TLS-os	373C	100.01	0.511618	20.07	0.1213	0.509874	1.24
TLS-os	373D	71.80	0.511671	15.49	0.1222	0.509914	2.02
TLS-rs	373E	79.72	0.511607	16.10	0.1221	0.509853	0.82
GLG	1060C	115.21	0.511567	22.63	0.1187	0.509860	0.97
GLG	392B	206.21	0.511285	32.96	0.0966	0.509896	1.67
GLG	347A	127.99	0.511265	20.64	0.0975	0.509864	1.03
GLG	535A	115.23	0.511678	23.58	0.1237	0.509899	1.73
NLSS	600A	70.44	0.511805	15.30	0.1313	0.509917	2.08
NLSS	600E	66.92	0.511711	13.66	0.1234	0.509937	2.47
NLSS	1171A	77.97	0.511891	18.11	0.1404	0.509872	1.20
Morose	1139A	23.74	0.511737	5.68	0.1446	0.509270	-0.25

Note: Epsilon Nd values calculated assuming an age (T) of 2182 Ma for all samples except Morose granite sample 1139A, where an age of 2586 Ma is assumed. Sm and Nd concentrations by isotope dilution.

Table 2.1 – Nd isotope compositions of the eastern lobe rocks

($\epsilon_{\text{Ndi}} = +1.0$ to $+2.5$). Potential crustal (contamination sources) assimilants in the local area include Burwash metasediments ($\epsilon_{\text{Ndi}} = -3.18$ to -5.98 , this study and Yamashita & Creaser, 1999), Morose granite ($\epsilon_{\text{Nd-2182}} = -3.0$), Defeat granodiorite ($\epsilon_{\text{Nd, 2182}} = -2.9$ to -5.9 , Yamashita *et al.*, 1999), and pre-Yellowknife Supergroup rocks (Davis & Hegner, 1992).

In a plot of SiO_2 versus ϵ_{Ndi} there is a negative correlation between the three primary phases of the eastern lobe (Fig. 2.11). The volumetrically minor “olivine- and rim-syenite” phases of the Thor Lake syenite have a noticeable departure from this trend with low silica contents (as would be predicted by the presence of cumulate olivine in the olivine-syenite) and variable ϵ_{Ndi} values ($\epsilon_{\text{Ndi}} = +0.82$ to $+2.02$). The least radiogenic of the olivine- and rim-syenite samples are within analytical error of the Grace Lake granite samples. The Nechalacho mineral deposit may also influence the Nd isotopic composition of samples collected from within its hydrothermal overprint. Minor clay and mica mineral replacement of alkali-feldspar and nepheline in the least radiogenic Nechalacho layered suite sample ($\epsilon_{\text{Ndi}} = +1.05$) are suggestive of slight hydrothermal alteration. This Nechalacho sample was collected from drill core at a depth of ~ 200 m, and is the closest sample to the Nechalacho mineral deposit. While simple closed-system hydrothermal alteration has a negligible effect on Nd isotopic ratios, the REE mineralization mechanisms in the Lake zone appear to have both magmatic and hydrothermal components (Sheard *et al.*, 2012). The hydrothermal component is poorly constrained but recent work suggests local remobilization of REE (Sheard *et al.*, 2012). The Nechalacho layered suite sample collected close to the mineralized zones may have been more affected by the hydrothermal alteration than the samples collected at greater

Figure 2.11 - ϵ_{Ndi} vs SiO_2 , initial ratios calculated for an age of 2182 Ma. Error bar represents 2σ error of ϵ_{Ndi} (± 0.3).

depths, which may have altered its Nd isotopic composition.

2.6 Geochronology

To resolve outstanding issues regarding the chronology of the eastern lobe two methods were employed: thermal ionization mass spectrometry (TIMS), and *in situ* laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS). During the geochronologic investigation of samples from the Thor Lake syenite and Nechalacho layered suite, particular emphasis was placed on the detection of a late growth phase associated with REE mineralization. Prior to U-Pb analyses, zircons from the two samples were imaged using a scanning electron microscope in backscattered electron mode. Detailed backscattered electron and cathodoluminescence imaging (for the Nechalacho layered suite sample), as well as *in situ* U-Pb dating, indicates that zircons selected for the more complete analysis from these two samples did not show evidence of a growth event after crystallization.

2.6.1 Thor Lake syenite - TIMS

A coarse-grained sample of Thor Lake leucosyenite was collected from well outside (~2.5 km) the known mineralized zone of the Thor Lake rare-metal deposits to avoid intense metamictization of zircon typical of the deposit, (i.e., Smith *et al.*, (1991). The rock was crushed, and zircon fractions were separated using standard techniques (crushing, grinding, Wilfley™ table, heavy liquids) and sorted by magnetic susceptibility using a Frantz™ isodynamic separator.

Four single-grain fractions were analysed using TIMS to calculate an age for the Thor Lake syenite. Data from these analyses are located in Table 2.2 and Figure 2.12. These fractions yielded a concordant age of 2176.8 ± 1.6 Ma.

2.6.2 *Nechalacho layered suite - LA-ICP-MS*

A medium-grained sample of the Nechalacho layered suite was taken from a diamond drill hole at a depth of 775 m. The sample is from a portion of an aegirine syenite-biotite cumulate sequence layer (e.g., Fig. 2.2d). Standard 30 μ m polished thin-sections were used to identify and characterize zircons using backscattered-electron and cathodoluminescence imaging on a JEOL 6400 SEM equipped with a Gatan Chroma CL system at the University of New Brunswick. Individual zircon grains were analyzed *in situ* in a standard polished thin-section; data from these analyses are located in Table 2.3. Eleven concordant analyses were used to determine an age of 2164 ± 11 Ma (Fig. 2.13).

2.7 Discussion

2.7.1 *A-type granites and potential source*

The low concentrations of compatible elements (e.g., Ni, Cr), high concentrations of incompatible elements (e.g., Zr, Rb), and high (La/Yb)_N ratios all indicate that rocks of the eastern lobe are highly evolved. Their peralkaline composition (Fig. 2.6), high Fe₂O₃/(Fe₂O₃+MgO) ratios (Fig. 2.7a), enrichment in large ion lithophile elements (LILE) and high field strength elements (HFSE), and Fe-rich mineralogy, all indicate that the eastern lobe rocks can be classified as A-type granites (Bonin, 2007), consistent with

Figure 2.12 - Concordia diagram showing the results of U-Pb TIMS dating of zircon from the Thor Lake syenite: (a) mean weighted average, (b) examples of annealed and leached single fractions, (c) BSE photomicrograph of a zircon from the Thor Lake syenite (*example zircons, not analysed).

Fraction and Description		Weight	U	Pb	TC Pb	²⁰⁶ Pb/ ²⁰⁴ Pb	²⁰⁶ Pb/ ²³⁸ U	1σ error	²⁰⁷ Pb/ ²³⁵ U	1σ error	²⁰⁷ Pb/ ²⁰⁶ Pb	1σ error	Apparent Ages (Ma)						
		(mg)	(ppm)	(ppm)	(pg)								²⁰⁶ Pb/ ²³⁸ U	1σ error	2σ	²⁰⁷ Pb/ ²³⁸ U	1σ error	2σ	Disc %
Z1	Co,Clr,Ffr,An	7	26.28	12.3	4.5	1076.6	0.40141	0.00041	7.52221	0.01133	0.13591	0.00012	2175.5	3.7	2175.6	2.7	2175.7	3	0.01
Z2	Co,Clr,Ffr,An	8	34.77	18.58	26.4	274.6	0.40287	0.0014	7.58137	0.03004	0.13649	0.00039	2182.2	12.8	2182.7	7.1	2183.1	10	0.05
Z3	Co,Clr	6	25.28	13.61	3.5	1026.9	0.40059	0.00047	7.51686	0.01197	0.13609	0.00013	2171.8	4.3	2175	2.9	2178	3.2	0.34
Z4	Co,Alt,Sub	21	20.36	11.26	7.4	1422	0.39667	0.00039	7.43567	0.01045	0.13595	0.0001	2153.7	3.6	2165.3	2.5	2176.3	2.6	1.22

Co=Colourless, Alt=Altered, Clr=Clear, Ffr=Few Fractures, An=Anbedral, Sub=Subbedral

Co=Colourless, Alt=Altered, Clr=Clear, Ffr=Few Fractures, An=Anbedral, Sub=Subbedral

Table 2.2 - TIMS U-Pb data, Thor Lake leucosyenite. Corresponds with whole rock geochemistry sample 1201A, location: E420494, N6884494 - coordinates are for a UTM projection zone 12, NAD83.

Figure 2.13 - Concordia diagram showing the results of U-Pb LA-ICP-MS dating of zircon from the Nechalacho layered suite: (a) BSE photomicrograph highlighting textural relations between zircon (white) and feldspar (medium and dark greys), (b) example BSE photomicrograph of analyzed zircon, (c) example CL photomicrograph of an analyzed zircon.

Analysis	Duration (s)	%Pb ¹	U (ppm)	Th (ppm)	Pb (ppm)	U/Th	Error correlation								Apparent Ages (Ma)							
							²⁰⁷ Pb/ ²³⁸ U	2 σ error	²⁰⁶ Pb/ ²³⁸ U	2 σ error	²⁰⁶ Pb/ ²³⁸ U vs ²⁰⁷ Pb/ ²³⁸ U	2 σ error	2 σ error	2 σ error	²⁰⁷ Pb/ ²³⁸ U	2 σ error	²⁰⁶ Pb/ ²³⁸ U	2 σ error	²⁰⁷ Pb/ ²³⁸ U	2 σ error	Disc %	
BZr1b*	29.491	>99.9	8	447	476	0.018	7.380	0.260	0.3987	0.0099	0.17	0.1338	0.0051	2153	65	2161	45	2150	32	-0.4		
BZr1h*	19.229	>99.9	9	503	536	0.019	7.450	0.320	0.4020	0.0100	0.06	0.1347	0.0054	2172	96	2174	47	2162	38	-0.1		
BZr1j	25.062	99.2	15	1050	573	0.016	7.270	0.290	0.3830	0.0120	0.59	0.1393	0.0047	2220	57	2087	56	2140	35	6.0		
BZr1a*	28.519	>99.9	12	428	452	0.029	7.250	0.300	0.3996	0.0100	0.36	0.1330	0.0058	2128	74	2171	46	2137	37	-2.0		
BZr1f	19.229	97.1	42	4940	1439	0.009	3.850	0.130	0.2441	0.0066	0.59	0.1151	0.0025	1881	46	1407	34	1600	26	25.2		
BZr1g	23.333	93.7	55	5950	1344	0.009	2.924	0.081	0.1704	0.0039	0.37	0.1252	0.0032	2020	51	1014	21	1384	21	49.8		
BZr2a*	18.796	99.8	31	486	463	0.063	7.420	0.210	0.3990	0.0110	0.85	0.1349	0.0031	2164	42	2162	50	2157	26	0.1		
BZr2c	16.42	98.6	49	492	548	0.101	8.060	0.150	0.3997	0.0100	0.58	0.1456	0.0026	2290	37	2166	46	2237	16	5.4		
AZr1c	7.8345	>99.9	47	3130	1087	0.015	3.350	0.190	0.2777	0.0093	0.32	0.0878	0.0057	1420	120	1579	47	1489	45	-11.2		
AZr1d	14.337	99.9	54	1586	619	0.033	5.400	0.190	0.3392	0.0058	0.49	0.1156	0.0036	1881	56	1887	27	1881	30	-0.3		
AZr2b	15.199	>99.9	30	676	601	0.045	7.200	0.260	0.3935	0.0092	0.28	0.1338	0.0041	2140	53	2138	43	2132	33	0.1		
AZr1b*	23.974	99.6	17	48	56	0.332	7.540	0.230	0.4042	0.0076	0.35	0.1346	0.0045	2179	62	2187	35	2173	29	-0.4		
AZr2c*	18.176	99.0	46	532	505	0.086	6.860	0.160	0.3689	0.0065	0.56	0.1347	0.0028	2162	38	2024	31	2095	19	6.4		
AZr2e*	9.0881	98.8	45	1246	1110	0.036	6.640	0.200	0.3595	0.0088	0.68	0.1353	0.0027	2166	35	1979	42	2064	26	8.6		
AZr2h*	25.541	99.9	25	478	512	0.053	7.310	0.180	0.3981	0.0089	0.42	0.1354	0.0032	2161	42	2159	41	2153	22	0.1		
AZr5h*	6.5087	88.5	30	1560	69	0.020	0.431	0.073	0.0235	0.0019	0.05	0.1360	0.0250	2120	340	153	11	359	53	92.8		
AZr2a*	19.351	>99.9	43	1227	1074	0.035	7.710	0.180	0.4128	0.0064	0.29	0.1362	0.0032	2179	40	2228	29	2195	21	-2.2		
AZr2g*	29.615	>99.9	30	960	962	0.031	7.850	0.200	0.4150	0.0072	0.45	0.1363	0.0032	2187	40	2237	33	2212	22	-2.3		
AZr2f	15.591	>99.9	30	1152	939	0.026	7.900	0.260	0.4092	0.0099	0.45	0.1382	0.0045	2217	61	2210	45	2216	29	0.3		
AZr2i	22.093	>99.9	29	1266	1046	0.023	7.900	0.160	0.4111	0.0073	0.46	0.1391	0.0030	2216	37	2219	33	2221	18	-0.1		
AZr1c	22.485	98.8	16	51	54	0.315	7.530	0.190	0.3912	0.0074	0.17	0.1410	0.0037	2231	45	2128	34	2173	23	4.6		
AZr1f	18.568	97.0	17	43	48	0.410	7.000	0.340	0.3560	0.0110	0.67	0.1416	0.0052	2243	66	1963	53	2108	45	12.5		
AZr2d	19.195	>99.9	22	624	686	0.036	8.680	0.270	0.4305	0.0093	0.16	0.1457	0.0051	2313	55	2307	42	2306	27	0.3		
AZr2e-2	16.061	99.7	31	1075	1020	0.030	8.210	0.210	0.4116	0.0076	0.54	0.1458	0.0027	2294	32	2227	33	2256	22	2.9		
AZr1a	13.005	96.7	16	105	97	0.151	7.240	0.360	0.3590	0.0150	0.72	0.1501	0.0045	2355	56	1976	73	2155	44	16.1		
AZr2j	27.578	>99.9	52	4450	1985	0.012	10.080	0.220	0.4612	0.0088	0.58	0.1587	0.0029	2441	32	2448	38	2442	20	-0.3		
AZr4a	17.549	99.13	15	1849	2178	0.008	10.210	0.370	0.4396	0.0097	0.35	0.1672	0.0053	2541	57	2348	43	2454	35	7.6		

¹ Anderson (2002) common lead correction. * analyses used in concordia plot

Table 2.3 - LA-ICP-MS U-Pb data, Nechalacho layered suite. Corresponds with whole rock geochemistry sample 600A, taken from Avalon Rare Metal Inc. drill hole L10-194 at a depth of 775.2 m. Drill hole location: E416724, N6886118 - coordinates are for a UTM projection zone 12, NAD83.

other granite discrimination diagrams, (e.g., Zr vs Ga/Al; Fig. 2.7c). Tectonic-discrimination diagrams (Fig. 2.7b and 2.7d) indicate that the rocks likely formed in an intraplate setting from a mantle-derived melt (Eby, 1992, Pearce *et al.*, 1984).

While most of the rocks discussed in this paper are too evolved to provide reliable information about their potential source(s), we can make a few inferences based on the Nd isotopic ratios. The calculated initial Nd ratios of rocks from the eastern lobe indicate that the parental melt was derived from a source that had a time-integrated enrichment in Sm relative to Nd, and there is evidence for systematic isotopic contamination from an enriched (crustal?) component. Thus we address one of the major questions regarding the BLIS: are these mantle derived melt, or could they have been produced by melting lower crustal rocks? Figures 2.14a and 2.14b show the Nd isotopic evolution of samples from the eastern lobe, depleted mantle melts from regional 2.7 Ga lower crustal mafic rocks, and potential local crustal contaminants. The evolutionary trends displayed in Figure 2.14b indicate that, combined with relatively small degrees of crustal contamination, both depleted mantle and lower crustal sources could account for the initial Nd isotopic ratios of eastern lobe rocks. The distribution of trace-elements, however, can help to differentiate between mantle and lower crustal sources. The stability of garnet in the lower crust, as well as its affinity for HREE is well documented. Therefore, mafic melts originating from the lower crust are generally assumed to form in the presence of residual garnet, and have low HREE abundances and a steep HREE trend. The concave-up HREE pattern and low $(\text{Sm/Lu})_N$ of the Grace Lake granite, Thor Lake syenite, and in part the Nechalacho layered suite, suggest that the parental magma did not form in equilibrium with garnet. While melting lower crustal rocks, such as underplated equivalents of the 2.7

Ga mafic Kam group (Cousens, 2000), could produce the Nd isotopic ratios observed in the eastern lobe rocks, the trace-element signatures do not support a lower crustal source, but rather point towards a mantle derived source. Fractionation of a LREE-rich phase (e.g., allanite or apatite) in late stage magmas could potentially mask an originally steep HREE slope. This possibility was tested by plotting various fractionation indicators related to such minerals, (e.g., P_2O_5 versus Tb/Lu). No correlation was observed in these plots, suggesting that significant fractionation of a REE-rich phase did not occur in the late stage magmas.

Isotopic compositions of local metasediments, granitoids, and basement rocks suggest that any could have been a possible contaminant, individually or as part of a mixture (Fig. 2.14a). The cumulate nature of the most isotopically primitive rocks (i.e., Nechalacho layered suite) prevents us from defining a parental liquid composition. Without being able to identify a starting point, it is unfeasible to accurately model the degree of assimilation or discriminate between possible contaminants.

2.7.2 *Constraints on emplacement*

Estimating emplacement conditions of the eastern lobe is a critical factor for evaluating various REE mineralization models. The depth of intrusion influences numerous factors governing the evolution of a plutonic system, such as the nature of exsolved magmatic volatile phases (i.e., single versus two-phase), reduced access to the surface for volatiles and/or a volcanic eruption, and the presence of meteoric water. Temperature is also important in assessing the thermodynamic controls on mineralizing assemblages, and combined with other factors influences the longevity of the post-magmatic hydrothermal

Figure 2.14 - Plot of ϵ_{Ndi} vs time of crystallization of eastern lobe rocks additional to the eastern lobe rocks, the evolution of the depleted mantle¹ (Goldstein *et al.*, 1984): (A) Burwash Formation (Yamashita & Creaser, 1999), plutonic rocks of the Morose (this study) and Defeat suites (Yamashita *et al.*, 1999), and pre-Yellowknife super group (YKSG) rocks (Davis & Hegner, 1992), and (B) Archean Kam group rocks (Cousens, 2000).

system. However, there is a distinct deficiency of appropriate/calibrated thermometers and barometers for direct use on plutonic peralkaline rocks (Anderson *et al.*, 2008). During this study, efforts were made to assess the viability of various thermometers, including the Ti-in-zircon thermometer (Ferry & Watson, 2007, Watson & Harrison, 1983, Watson *et al.*, 2006), Zr saturation thermometer (Hanchar & Watson, 2003, Watson & Harrison, 1983), and hornblende-plagioclase thermometer (Blundy & Holland, 1990, Holland & Blundy, 1994). Results from these thermometers have an extremely wide range and/or geologically unrealistic values. Most barometers used in granite studies are calibrated only for metaluminous rocks, (e.g., Al-in-hornblende (Anderson & Smith, 1995, Schmidt, 1992), and therefore are unsuitable for peralkaline phases of the eastern lobe (Anderson *et al.*, 2008).

A possible solution for the estimation of emplacement depth involves using rocks from the western lobe of the BLIS. The syenitic to granite rocks of the western lobe have cross-cutting relations with those in the eastern lobe, similar sill morphologies and grain sizes, and estimates of their age of emplacement are generally within analytical error to those in the eastern lobe (Table 2.4). This suggests that the two groups of granitic rocks were emplaced roughly within the same period of time (1-5 Ma), and consequently crystallized at a similar depth. Western lobe granites and syenites are metaluminous and therefore may work with the Al-in-hornblende thermometer. Having no constraint on temperature of the crystallizing melt restricts the use of the Al-in-hornblende barometer to a calibration that does not take temperature into account, (i.e., Schmidt(1992), thereby limiting its precision (Anderson & Smith, 1995).

Mumford et al. (Chapter 4) tested the Al-in-hornblende geobarometer and the hornblende-plagioclase thermobarometer on granitic units of the western lobe, and determined that all intrusions crystallized at a depth of approximately 4 – 4.5 kbar. Using a pressure gradient of 0.26 kbar/km (continental crust of average granitic density), this corresponds to a depth of ~ 16 km. Given the coeval nature of the two lobes we suggest that this also represents the depth of emplacement of phases in the eastern lobe of the BLIS.

2.7.3 *Geochronology of the BLIS*

The chronology of the BLIS has long been a subject of contention and confusion (Table 2.4). Regarding the eastern lobe, the confusion stems from a U-Pb zircon date of 2094 Ma determined by Bowring *et al.* (1984) for a sample from the mineralized zone of the Thor Lake syenite, and the poorly understood nature of the contact between the Grace Lake granite and Thor Lake syenite. This date has been assumed to suggest either: (1) that the Thor Lake syenite was a separate intrusion *c.* 90 Ma younger than the rest of the BLIS, or (2) that the date represents the age of mineralization, which postdates the BLIS.

Taylor & Pollard (1996) suggested that zircons with a 2094 Ma age represent the hydrothermal event related to the formation of the Thor Lake REE deposits. Studies by MacWilliam & Williams-Jones (2011) and Pinckston & Smith (1995) indicate that the metasomatic event linked to the REE mineralization is related to the emplacement of the Nechalacho layered suite. Consequently, MacWilliam & Williams-Jones (2011) proposed that the 2094 Ma date represented the crystallization age of the Nechalacho layered suite.

Unit	Age (Ma)	Mineral	Method	Reference
Thor Lake syenite	2064 +/- 46	Biotite	K-Ar of hornfelsed metasediment inclusions	Wanless et al. (1979)
Thor Lake syenite	2150 +/- 58	Whole-rock	K-Ar of hornfelsed metasediment inclusions	Wanless et al. (1979)
Thor Lake syenite*	2094 +/- 10	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Thor Lake syenite*	2118 +/- 16	Polyolithionite	Ar-Ar	Taylor and Pollard (1996)
Thor Lake syenite	2176 +/- 1.6	Zircon	Single-grain U-Pb TIMS	This study
Dyke in Thor Lake syenite	2190.7 +/- 6.9	Zircon	In situ LA-MC-ICP-MS	Walsh (2010)
Nechalacho layered suite*	2068 +/- 57	Whole-rock	Sm-Nd isochron	Gilgen (2010)
Nechalacho layered suite	2164 +/- 11	Zircon	In situ LA-MC-ICP-MS	This study
Grace Lake granite	2057 +/- 56	Riebeckite	K-Ar	Wanless et al. (1979)
Grace Lake granite	2133 +/- 112	Hornblende	K-Ar	Wanless et al. (1979)
Grace Lake granite	2176.2 +/- 1.3	Zircon and Monazite	Multi-grain U-Pb TIMS	Sinclair et al. (1994)
Hearne Channel granite	2175 +/- 5	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Mad Lake Granite	2166 +/- 47	Biotite	K-Ar	Wanless et al. (1979)
Whiteman Lake quartz syenite	2127 +/- 79	Hornblende	K-Ar	Wanless et al. (1979)
Whiteman Lake quartz syenite	2185 +/- 5	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Caribou Lake gabbro	2184 +/- 2	Zircon	Multi-grain U-Pb TIMS	Mumford et al. (2012)

*Samples from mineralized zones

Table 2.4 - Summary of radiometric ages determined for the Blatchford Lake intrusive suite.

Sheard *et al.* (2012) also concluded that the age represented the crystallization of the Nechalacho Layered suite and/or the rare metal mineralization.

Work by Smith *et al.* (1991) showed that zircons in the T- and Lake-zone are zonally metamictized, likely due to high-localized concentrations of thorium in these zones. The metamictization process can severely compromise the crystal structure of the mineral, which can then lead to radiogenic lead loss. Therefore, the upper discordia intercept age reported by Bowring *et al.* (1984) may simply reflect unsystematic radiogenic lead loss and not represent the age of crystallization or mineralization.

Results from the *in situ* (LA-ICP-MS) and TIMS dating presented in this paper show that: (1) the Grace Lake granite and Thor Lake syenite crystallized simultaneously within analytical error at ca. 2176 Ma, (2) the younger Nechalacho layered suite at 2164 ± 11 Ma also crystallized, just within analytical uncertainty of the age of the Thor Lake syenite and the Grace Lake Granite, (3) there is no evidence for a magmatic zircon growth phase at 2094 Ma. The cogenetic relationship between the plutonic phases is comparable with many multiphase alkaline complexes worldwide (Downes *et al.*, 2005, Marks *et al.*, 2008, Steenfelt, 1991), including other intrusive suites where there is a transition from silica-oversaturated to undersaturated magmas, (e.g., Kangerlussuaq Intrusion, Greenland: (Riishuus *et al.*, 2008); and Messum Igneous Complex, Namibia: (Harris *et al.*, 1999).

2.7.4 *Origin of the rim syenite*

Based on the observed field relations, the contact between the Grace Lake granite and the Thor Lake syenite is not intrusive, but is a gradual mineralogical change

dominated by decreasing quartz content (Fig. 2.3b). The observed relationship is consistent with geochronologic data presented above that indicates that the two units were emplaced at ca. 2176 Ma within analytical uncertainty. However, the nature of the contact between the leucosyenite and the rim syenite (and olivine syenite) is more enigmatic. To determine the origin of the rim syenite and its relation to the leucosyenite we first review the key differences between the two units.

The rubbly weathering of the rim syenite obscures the subtle mineralogical differences between it and the Thor Lake leucosyenite. An additional distinction is that the rim syenite is not a continuous feature, being virtually absent at the southwestern contact between the Grace Lake granite and Thor Lake syenite. In drill core, the contacts between the Thor Lake rim syenite and Thor Lake olivine syenite are gradational (marked by the increasing abundance of olivine), but the contacts between the cumulate olivine syenite and the leucosyenite are abrupt. In addition, the lower $\epsilon_{\text{Nd}i}$ values of the rim and olivine syenite relative to the leucosyenite indicate that the units are not simply related by fractional crystallization but may have had interaction with the Grace Lake granite or other possible radiogenic contaminants (Fig. 2.11). The gradational contacts and the lower $\epsilon_{\text{Nd}i}$ values suggest that the rim and olivine syenites form a mineralogical continuum related to but distinct from the leucosyenite. The lack of chill margins or brecciation is consistent with a coeval relationship between the two magmas/crystal mushes.

An explanation that can account for the observed elements is that the rim syenite represents the basal remnants of an eroded ring dyke formed by central caldera collapse, and that the Grace Lake granite and Thor Lake syenite represent the source chamber (Fig.

Figure 2.15 - Structural levels of A-type magmatism (modified from Bonin, 2007). The depth values are approximate and the relative sizes of chambers are not to scale. Partial melting zones are located in deeper portions of the upper mantle.

Figure 2.16 - Cross-sectional schematic model describing the formation of the Thor Lake rim and olivine syenites: (a) semi-rigid crystal mush along the upper margin of chamber is intersected by ring faults from caldera collapse , (b) over-pressured volatile saturated magma (compositional akin to the Thor Lake syenite) escapes along structural weaknesses, cools quickly against country rocks ± crystal mush, (c) localized area of decreased fO_2 causes olivine to crystallize and density contrasts allow for crystal setting and formation of the cumulitic olivine syenite, (d) present day erosional surface. Fault geometry after Mueller et al. (2008).

2.15). Caldera collapse, while the outer margins of the Grace Lake granite and Thor Lake syenite were partially solidified crystal mushes, may have caused melts from the interior of the cooling pluton to be forced up through the ring structure (Fig. 2.16) along radial faults associated with caldera collapse. The emplacement of magma into higher stratigraphic levels would act as a conduit for fluid flow, thereby allowing for depressurization of the residual system. Based on other ring-dyke complexes the model would require a source depth between 14 and 20 km (e.g., Bonin, (2007), which is consistent with the estimated depth of emplacement of the eastern lobe based on the western lobe.

Characteristics of A-type granites (such as the Grace Lake granite and Thor Lake syenite) include low H₂O contents and oxygen fugacities (Loiselle & Wones, 1979). These hypersolvus single feldspar granites also generally reflect more reducing conditions and lower water pressures relative to subsolvus granites (Bonin & Giret, 1985b). If the volatile compounds exsolved and liberated during depressurization consisted of largely anionic species (i.e., CO₂⁻, OH⁻, F⁻), as are typical of evolved A-type systems, then a degassing magma would become progressively more reduced. This would result in a decrease in the relative oxygen fugacity (Sato, 1978). Oxygen fugacity has been demonstrated to have a strong control on the crystallizing mineral assemblage, particularly Fe³⁺ - Fe²⁺ mineral phases (Sack *et al.*, 1980), and low fO_2 conditions are generally required for the formation of fayalite at the expense of magnetite, arfvedsonite, hematite, and aegirine, which require moderate to high fO_2 conditions (Marks *et al.*, 2011). An abrupt drop in vapor pressure would account for low fO_2 conditions required for the rapid crystallization of fayalite.

Figure 2.17 - Qualitative $\mu\text{Na}_2\text{O}$ vs μO_2 diagram of relative stabilities of the different two-phase assemblages for the system Fa—Mag—Hem—Arf—Aeg. The dashed line indicates the qualitative effect of increasing α_{SiO_2} (modified from Marks *et al.*, 2011).

In addition to the crystallization of fayalite, the mineralogical transition between the Thor Lake leucosyenite (and Grace Lake granite) to the Thor Lake olivine syenite is also evident by the change in pyroxene composition from aegirine to a more hedenbergitic end-member, reflecting decrease of Na activity in the system. The absence of amphibole (or appreciable amounts of any other hydrous phase – only trace biotite) in the olivine syenite, supported by positive loss on ignition values, suggests that this magma was less H_2O saturated relative to the surrounding melts. Marks *et al.* (2011), using Schreinemaker's analysis of the system Na-Fe-Si-O-H, created qualitative diagrams

to describe the crystallizing two-phase mineral assemblages in $\mu\text{Na}_2\text{O}$ and μO_2 (μ =activity) space (Fig. 2.17). While their calculations do not predict the formation of hedenbergitic pyroxenes in the olivine syenite (due to the absence of Ca in the system) they do predict the stable aegirine-arfvedsonite assemblage in the Thor Lake leucosyenite and Grace Lake granite, as well as the coexisting fayalite and magnetite at reduced $f\text{O}_2$ in the olivine syenite. The discrete nature of the fluid flow and consequent pressure loss localized along a ring structure could explain the limited spatial distribution of fayalite and its restriction to the proximity of the rim syenite in the eastern lobe. The emplacement of such a narrow ring would quickly cool and crystallize, sealing the system and allowing the underlying system to re-equilibrate and vapor pressure to build, effectively stopping the formation of fayalite. The closure of the system would allow it to restore the pressure and thus become cyclical with repeated failures as is suggested by the multiple cumulate horizons seen in the core. Emplacement of Thor Lake syenitic melt along a ring dyke system would also facilitate mixing/assimilation with the Grace Lake granite and the metasedimentary host rocks. Given the lower ϵ_{Nd} of the Grace Lake granite and Burwash Formation, this interaction could explain the variation of ϵ_{Nd} between the Thor Lake rim and olivine syenites relative to the leucosyenite.

The ring dyke model also offers two plausible mechanisms to account for the fine-grained nature of the rim syenite relative to the leucosyenite: (1) the expelled magma from the central portion of the chamber was cooled against the lower temperature crystal mush of the partially solidified margin or country rocks (Fig. 2.16), or (2) the pressure drop promoted rapid crystallization. The rubbly weathering of the rim syenite could be attributed to a localized area of intense fluid flow. The geochemical profile across the rim

syenite highlights strong elemental variations in contrast to the much more consistent values analysed elsewhere on the profile (Fig. 2.10). Relative depletion in easily hydrothermally transported elements (e.g., SiO₂, U, Rb) from the Grace Lake granite through the rim syenite versus the relatively constant behavior of generally hydrothermally immobile elements (e.g., REE, Th) is consistent with a localized fluid conduit.

The arcuate and discontinuous character of ring dykes (e.g. Woolley, 2001) may also account for the absence of the rim syenite at the southwestern contact between the Grace Lake granite and Thor Lake syenite (Fig. 2.1). The abrupt emplacement nature of a ring dyke, the subsequent crystallization and gradual re-equilibration of the crystallizing melt could also account for the asymmetric profile of the rim syenite (Fig. 2.10) with a steep outer margin and a moderate inward slope. The co-location of the Indin dyke and the T-Zone suggest that there may have been a localized pre-existing structural weakness north of Thor Lake. This weakness could account for the western termination of the northern portion of the rim syenite. As there are no observed contact relations between the rim syenite and the Nechalacho layered suite, it should be noted that this model for the formation of the rim syenite is independent of the Nechalacho layered suite.

Worldwide, intrusive complexes that expose the basal portions of ring dyke systems are particularly rare, likely a function of a low preservation potential due to their restricted vertical extent. The closest equivalent to the stratigraphic position of the Thor Lake rim syenite may be the El Pinal tonalite in Baja, California (Duffield, 1968).

2.7.5 *Extent of the Nechalacho layered suite*

The two-line gravity survey of Birkett *et al.* (1994) estimated that the current total depth of the eastern lobe was no more than 1 km. Since then, drilling has confirmed its presence to a depth of >1100 m, with no indication of a bottom-bounding surface. The discrepancy between modeling of the line gravity survey and the observed thickness of the Blatchford Lake intrusive suite may be a consequence of the limited density contrast between the Grace Lake granite, Thor Lake syenite, and Burwash metasedimentary rocks (Pilkington *et al.*, 2012). Additionally, the average density of the unmineralized Nechalacho layered suite has yet to be determined, further complicating gravity models.

The Compton intrusions that intrude the Grace Lake granite west of Thor Lake are xenolith rich, containing blocks of magnetite-bearing carbonaceous sedimentary rocks, Grace Lake granite and autolithic magmatically layered rafts. No xenoliths of the Nechalacho layered suite were observed during detailed mapping of the Compton intrusions, indicating that they: (1) were emplaced prior to the Nechalacho layered suite, or (2) did not intrude through the Nechalacho layered suite, and therefore were beyond the limit of its possible western extent. This indication of the western limits of the Nechalacho layered suite is consistent with the size and position of the magnetic high where it has been confirmed by drill holes to be associated with the mineralized Nechalacho layered suite (Fig. 2.4).

2.7.6 *Evolution of the eastern lobe*

Riishuus *et al.* (2008) provides a summary of previous work and characteristics of major alkaline syenite complexes that transition from silica-oversaturated to

undersaturated, similar to the transition displayed in the eastern lobe of the BLIS. While the mechanisms and timing vary between individual models, the general consensus is that the transition to silica-oversaturated rocks is related to the crustal contamination of a silica-undersaturated parental magma (Foland *et al.*, 1993, Harris *et al.*, 1999, Marks *et al.*, 2004b, Riishuus *et al.*, 2008).

In order to assess the evolution of the eastern lobe it is first important to confirm that all units in the eastern lobe are genetically related. Presented geochemical, isotopic results demonstrate that all peralkaline units of the eastern lobe are genetically linked, and geochronologic analyses suggest a coeval relationship.

Given the high LILE abundances and isotopic evidence for a large component of depleted mantle, we propose that the parental melt was derived by melting a time-integrated mantle source enriched in Sm relative the Nd, that was metasomatized just prior to melting, as in the process described by (Pilet *et al.*, 2011, Pilet *et al.*, 2008). The absence of negative Nb anomalies in eastern rocks suggests that they were derived from a source relatively unaffected by subduction zone processes, thus favoring an asthenospheric or young lithospheric source. HREE patterns (Fig. 2.9) suggest that if melts were derived from an asthenospheric source a thinned lithosphere would be required such that melting was above the garnet stability field. In this model, low degree partial melting of a metasomatized source produced melts with a nephelinite composition that rose, coalesced and underplated the crust. Fractional crystallization of this magma combined with assimilation of country rock (AFC) created an evolved residual melt (nephelinite?) that, driven by density contrasts and using pre-existing structural weaknesses, rose to form a lopolithic chamber in the mid-crust (Fig. 2.15). Figure 2.17

illustrates the formation of the three primary phases in the eastern lobe. Crustal assimilation into the magma was focused at the margins of the lopolith and thus formed another density driven residual melt with a bulk composition approaching the composition of the Nechalacho layered suite. The ascent of this melt through the crust results in the assimilation of local silica-rich country rocks. On a plot of petrogeny's residua system (Bowen, 1937), this enrichment of silica causes the position of the bulk composition to cross the feldspar join into the silica-saturated field. Any additional AFC of the melt causes the bulk composition of initial pulses to trend towards the granite minimum (emplacement of the Grace Lake granite, Fig. 2.18a). Repeated pulses of nephelinitic magma from the mid-crustal lopolith utilize the same plumbing system to inject the upper chamber; however, subsequent pulses are more and more protected from interaction with country rocks due to armouring of the melt pathway by preceding pulses (e.g. Harris *et al.*, 1999). This allows the crystallization of magmas with progressively less contamination from crustal rocks (transition from Grace Lake granite to Thor Lake syenite, Fig. 2.18b). With increasing armoring, the ascending magma is no longer able to assimilate enough siliceous material until a critical point is reached where the magma composition does not cross over the feldspar join and thus fractionates towards the nepheline syenite minimum (emplacement formation of the Nechalacho layered suite, Fig. 2.18c). The 2164 ± 11 Ma age calculated for the Nechalacho layered suite suggests that while it is cogenetic with the Grace Lake granite and Thor Lake syenite there may have been an appreciable delay in its emplacement.

The circular surficial exposure and concentric zonation of the eastern lobe often conjures up mental images of a voluminous spherical magma chamber which has been

Figure 2.18 - Schematic model describing the petrogenesis of major units in the eastern lobe: (a) crustal contamination and emplacement of the Grace Lake granite from a nephelinitic parental melt, (b) progressive armouring of the magmatic pathways and emplacement of the Thor Lake syenite, (c) emplacement of the Nechalacho layered suite – influx of magma from parental source (?). The lower magma chamber in corresponds to the lopolith in Figure 2.15.

deeply eroded to display its inner workings. However, based on gravity modeling of the eastern lobe, and modern granite emplacement models, it seems more probable that the eastern lobe was emplaced as a series of downward stacking, rapidly emplaced, thin, flat-lying sheets (i.e. Farina *et al.*, 2010, Paterson & Vernon, 1995) and that we are now just looking at the uppermost layers. This is supported by the sub-horizontal nature of many syenite lenses within the Grace Lake granite.

Based on the geochemistry and field relations and the petrogenetic evolution of the eastern lobe presented above, we define an inward and downward evolving system. The current erosional level of the Blatchford Lake intrusive suite precludes us from determining whether the Grace Lake granite encapsulated the core of the eastern lobe and thereby represents the uppermost/outermost layer. However, given that the composition of the Grace Lake granite at the margins approaches the granitic eutectic minimum, and the distribution of phases in the eastern lobe and the gross geochemical trends observed, we suggest that (barring the existence of an unrecognized or now eroded and magmatically distinct phase) the Grace Lake granite forms the uppermost layer in the system. The concentric central zonation pattern of the Grace Lake granite and Thor Lake syenite could be an expression of centralized doming related to the emplacement of the Nechalacho layered suite.

The over-saturated magmas could have been produced by contamination at various stages of evolution of a parental nepheline-normative alkali basaltic magma. However, similar to the rationale used by Foland (1993), we suggest that the formation of silica-oversaturated magmas in the BLIS was a late-stage event rather than an early event in the magmatic evolution of the eastern lobe. Lines of evidence include: (1) the near

continuous major and trace element trends from silica over to under-saturated rocks, (2) the major and trace element compositions of the over-saturated rocks suggest larger degrees of fractionation, (3) the subtle ϵ_{Nd} isotopic trends are more easily explained by contaminating a melt enriched in Nd, and (4) the relative lack of intermediate silica over-saturated rocks all suggest that contamination occurred to a relatively evolved felsic silica-undersaturated magma.

While the Kangerlussaq Intrusion of East Greenland represents one of the closest analogs to the BLIS, our model differs slightly from that proposed by Riishuus *et al.* (2008) largely due to geophysical evidence that suggests the absence of a large package of silica-oversaturated rocks and their ‘hidden’ cumulates in the BLIS. This distinction between the two models eliminates the need for significant magma mixing between silica over and undersaturated melts in the upper crust (a potential rheologic issue) as well as invoking a ballooning magma chamber model – the mechanics of which have been shown to be problematic (Paterson & Vernon, 1995).

2.8 Conclusions

The Grace Lake granite, Thor Lake syenite, and Nechalacho layered suite are cogenetic magma intrusions. The Grace Lake granite and Thor lake syenite are coeval intrusions, whereas the emplacement of the Nechalacho layered suite may have been delayed by as much as 10 Ma. The parental magma for all three units was nephelinitic, derived from the low-degree melting of a metsomatized source with a large depleted mantle component. The silica over-saturated transition from the Grace Lake granite to the

silica under-saturated Nechalacho layered suite records the progressive armouring of magmatic pathways from silica-rich country rocks.

The Thor Lake rim syenite and olivine syenite form a mineralogical continuum and represent the basal remnants of an eroded ring dyke, with the BLIS forming the source chamber for the ring dyke. The presence of fayalite is a consequence of an abrupt drop in vapor pressure resulting from the emplacement of the ring dyke.

The cogenetic relationship between units of the eastern lobe further substantiates the mineralization model proposed by previous workers (Davidson, 1982, Pinckston & Smith, 1995) of a residual mineralizing fluid derived from late stage crystallization of the youngest peralkaline melts, (i.e., units of the Nechalacho layered suite). However, numerous questions remain including: (1) the low LREE/HREE of the mineralized zones (Sheard, 2010), (2) the timing of the emplacement of the Nechalacho layered suite relative to formation of the rim syenite, and (3) the significance of the silica-rich T-zone.

Future studies may be aided by the use of the Lu-Hf isotope system to further substantiate the trends revealed using the Sm-Nd isotope system for the eastern lobe. In addition to mirroring the behavior of Sm-Nd, the Lu-Hf system would further test the absence of a garnet-bearing source. Precision U-Pb TIMS dating of the Nechalacho layered suite may further elucidate the gap in timing between its emplacement and the rest of the eastern lobe. A high-resolution airborne gravity and magnetic survey of the BLIS was conducted in 2011 (Pilkington *et al.*, 2012), however no gravity modeling has been done to date to estimate the depth of the intrusions.

3 Chapter: Origin of two monzonite-diorite intrusive stocks hosted in the Blatchford Lake intrusive suite and their relations to local diabase dyke swarms

3.1 Introduction

Two small intrusive stocks situated approximately two kilometers west of the Nechalacho rare-earth element (REE) deposit (Figs. 3.1, 3.2), are hosted within the 2176 Ma Grace Lake granite unit of the Blatchford Lake intrusive suite. The stocks were first described by Davidson (1972) as a single giant inclusion from an earlier plutonic body, but later (Davidson, 1978) described them as separate diorite to monzonite intrusions that are texturally and compositionally indistinguishable from the 1865 Ma (Table 3.1) Compton intrusive suite (CIS), and suggested the stocks were genetically linked to it. The CIS consists of a series of intrusive suite throughout the East Arm of Great Slave Lake, hosted within rocks of the Great Slave Supergroup. The CIS rocks typically range from dioritic to monzonitic in composition (Roscoe *et al.*, 1987), and generally occur as thick sills (>50 m) that form lopoliths on many of the southern islands in the East Arm, (e.g., Blanchet Island, Figs. 3.1, 3.2). The nature of these two stocks and their relationship to the CIS is further complicated by the cross-cutting diabase dyke swarms.

Detailed mapping of the two intrusive stocks identified previously undocumented field relations, including cross-cutting diabase dykes, and exceptional examples of modal layering and magmatic flow structures. The observed relations call into question the temporal (and therefore the genetic) association between the CIS sills located in the East Arm and the two intrusive stocks hosted in the Blatchford Lake intrusive suite. If the

Figure 3.1 - Location of the Blatchford Lake intrusive suite and other select intrusions throughout the East Arm of Great Slave Lake.

Figure 3.2 - Geological map of the south stock (SS) and north stock (NS). The upper left-hand inset shows the location of the SS and NS within the Blatchford Lake intrusive suite.

Unit	Age (Ma)	Mineral	Method	Reference
Compton intrusive suite	1861 +/- 17	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Compton intrusive suite	1872 +/- 8	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Compton intrusive suite	1867 +/- 22	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Compton intrusive suite	1865 +/- 15	Best estimate from above analyses		Bowring et al. (1984)
NS	1892 +/- 4	Zircon	In situ LA-ICP-MS	This study
Butte Island intrusive suite	1895 +/- 5	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Hearne diabase	1901 +/- 4	Baddeleyite	U-Pb TIMS	Buchan et al. (2010)
Indin diabase	2126 +/- 3	Baddeleyite	U-Pb TIMS	Buchan et al. (2010)
Indin diabase	2118 +/- 1	Baddeleyite	U-Pb TIMS	Buchan et al. (2010)
Indin diabase	2108 +/- 2	Baddeleyite	U-Pb TIMS	Davis and Bleeker (2007)

Table 3.1 - Summary of radiometric ages determined for select Paleoproterozoic mafic intrusions in the region of the East Arm, Great Slave Lake, NT.

Blatchford stocks are related to the Compton intrusive suite, they are the only CIS occurrences north of the Hearne Channel in the Archean Slave craton and have important implications regarding timing of local mafic dyke swarms.

To unravel the mafic intrusive history in the area we investigate the geochemistry, geochronology and field relations of the plutonic stocks and diabase dykes in the region. With the renewed interest in diabase dyke swarms and their relation to large igneous provinces (LIPs Ernst & Bleeker, 2010) this study has regional implications with respect to mafic magmatism during the Paleoproterozoic.

3.2 Field Relations

Based on their relative geographic distribution the two plutonic stocks are referred to as the north stock (NS) and south stock (SS). Both contain enclaves of Grace Lake granite and have sharp quenched sub-vertical contacts with the Grace Lake granite, indicating that they are intrusive with respect to the Grace Lake granite. Davidson (1978) stated that the two intrusions “both cut cleanly across east-northeast-trending diabase dykes in the surrounding granite”. In the geological map produced by Davidson (1978), he denotes a diabase dyke in the southeastern portion of the NS that is truncated by the NS. However, our mapping shows that the diabase is not truncated, but extends along the southern margin of the NS intrusion. Sharp sub-vertical contacts were observed between the ENE-trending diabase and the NS unit, and careful examination reveals that the diabase is both quenched against the NS and contains small fragments of the NS (Fig. 3.3a), indicating that the diabase dyke post-dates the NS. Locally, the width of this diabase exceeds 10 m, and the crystal size coarsens inwards to a medium-grain size.

Figure 3.3 - Textural features and inclusions within the NS: (a) contact between NS (top) and the Nechalacho diabase dyke (bottom), (b) magmatic dropstone disrupting micro-rhythmic layering in layered raft, (c) cross-bedding within layered raft, (d) magnetitite inclusion, (e) transition between massive mg-porphyritic diorite and curvilinear layered sequences, (f) small inclusion of micro-rhythmic layered sequence in fine-grained porphyritic diorite, (g) conformable transition from linear layering to medium grained-porphyritic diorite, (h) contact between calc-silicate xenolith and fine-grained porphyritic diorite.

Figure 3.4 - Field relations in the SS and Blatchford Lake intrusive suite: (a) breccia hosted within fine-grained SS adjacent to crosscutting Nechalacho diabase dyke, (b) rounded autoliths (?) hosted in fine-grained SS monzonite, (c) felsic dykelets cross-cutting Nechalacho diabase, (d) quench margin between Nechalacho diabase and Grace Lake granite, (e) rhythmic layering in the Caribou Lake gabbro.

Relations between the diabase dykes and the SS unit are more complex. In the southeastern portion of the SS a diabase dyke occurs adjacent to a localized area of brecciated angular blocks within the SS (Fig. 3.4a). This area coincides with a southerly extension of the diabase dyke that cross-cuts the NS (Fig. 2). In the northeastern portion of the SS a NE-trending, sub-vertical diabase dyke cross-cuts and is quenched against the SS. The width of the central portion of this diabase exceeds 5 m, and pinches out in its western and eastern extents (Fig. 3.2). The diabase itself is crosscut by thin aphanitic felsic dyke/dyketes (Fig. 3.4c) that range in width from <1 cm to >40 cm. These intrusions are generally orientated perpendicular to the strike of the diabase. Contact relations suggest that these dyke/dyketes originated from the SS. The contact between the diabase and the Grace Lake granite also displays quenching as well as a small localized occurrence of partial melting (Fig. 3.4d).

Both the NS and the SS contain numerous xenolithic/autolithic inclusions and rafts, varying in size from <1 cm to >10 m. Lithologies include quartz syenite (Grace Lake granite), quartz monzonite, layered metasedimentary calc-silicate rocks, magnetite, anorthosite, and rhythmically layered gabbroic sequences (Figs. 3.3, 3.5), with the latter being the largest and most abundant. No inclusions of nepheline syenite or any other rock type resembling those of the Nechalacho layered suite (Sheard *et al.*, 2012) were observed. Gravity modeling by Birkett *et al.* (1994) indicated that both the SS and NS “are thin tabular bodies without great vertical extent” and that no root zones were detected. However, Birkett *et al.* acknowledged that their model was not a unique solution and that it was in conflict with observed field relations in the SS and NS.

Figure 3.5 - Composite figure depicting the variation and distribution of magmatic features in an outcrop of the layered raft sequences hosted by the NS.

3.3 Lithology and Mineralogy

3.3.1 *North stock - Porphyritic diorite and layered rafts*

The NS is a massive, fine to medium-grained porphyritic monzodiorite to diorite comprised of a plagioclase (An_{36-54}) and diopside matrix with phenocrystic biotite and alkali-feldspar. Common interstitial accessory phases include apatite and opaque phases, with rare enstatite and zircon.

The porphyritic diorite unit described above is host to numerous large layered gabbroic rafts. The majority of rafts are hosted in medium-grained porphyritic diorite but are not restricted to it, as occurrences of rafts in the fine-grained porphyritic diorite are noted. These rafts typically consist of modally graded layers interspersed with massive gabbro/diorite layers. The modally graded layers comprise microrhythmic sequences that are both planar and curvilinear. The planar laminated sequences typically have uniform, well defined layering and consistent lamellae thicknesses within individual rafts but can vary between rafts. Lamellae range from 2 – 3 mm to > 3 cm in width (Fig. 3.3, 3.5). The curvilinear sequences are much more variable, ranging from weak to well-defined layering, and commonly displaying sedimentary-like features such as cross-bedding, truncation, flow-banding, and dropstones (Fig. 3.5). Locally the curvilinear and linear sequences conformably transition to and from massive medium-grained porphyritic diorite (Fig. 3.3e, 3.3g). The intra-raft lamellae thicknesses in curvilinear sequences tend to be more consistent than in the linear sequences, typically in the range of 2 – 5 mm. In both the planar laminated sequences and the curvilinear sequences, individual lamellae consist of cumulate diopside, biotite, and rare enstatite grading into cumulate plagioclase (An_{52-83}).

The unconformable contacts between the layered units and the porphyritic host are knife sharp, with no reduction in grain size towards the contact in either unit (Fig. 3.4f). The size (<5 cm – >10 m) and distribution of these layered units, as well as the orientation of lamellae, are sporadic throughout the intrusion (Fig. 3.2).

3.3.2 *South stock*

The majority of the SS comprises massive fine to medium-grained subporphyritic monzonite to quartz monzonite with accessory amphibole (silicic edenite – tremolite) and biotite, with rare interstitial diopside, apatite and zircon. Locally diopside alters to amphibole.

One locality in the SS hosts an abundance of cobble size, rounded to subrounded, medium grained plutonic inclusions of granitic – monzonitic mineralogy (Fig. 3.4b). Based on field based textural and mineralogical similarities, these inclusions are believed to be autolithic in nature.

3.3.3 *Diabase Dykes*

In addition to the diabase dykes in direct contact with the NS and SS (field relations described above) there are two other diabase dyke swarms that transect the Blatchford Lake intrusive suite. Previous workers identified two diabase dyke swarms in the area, the Hearne and the Indin swarm (Davidson, 1978, Mumford *et al.*, 2012a). The Hearne dykes are the most abundant and Indin dykes are rare. The Hearne diabase dykes in the region are typically sub-vertical, aphanitic dark grey to black and commonly have a greenish tinge, and generally vary in width from 30 cm – 2 m, but examples exceeding 6

m wide have been observed. They consist of moderate to strongly altered plagioclase laths, amphibole, opaques, with rare clinopyroxene.

Indin dykes are readily identified by their NW-trend and strong magnetic signature on aeromagnetic surveys (e.g. Pilkington *et al.*, 2012). They are sub-vertical fine-grained to aphanitic, dark grey, and at surface have widths on the order of 80 cm.

In general, all diabase dykes trending $\sim 060^\circ$ in the region have been assumed to be part of a single swarm, collectively referred to as the Hearne swarm (Davidson, 1978). Currently the literature contains no representative chemistry for *bona fide* Hearne dykes. However, a cursory geochemical inspection of the “Hearne” dykes around the Blatchford Lake intrusive suite by Perovic (2011) revealed multiple dyke populations with significant geochemical variations within individual populations, suggesting that all of these dykes may not be Hearne dykes. This study expands on Perovic’s work with new comparative analyses and field relations. One of the dyke subsets identified by Perovic (2011) was the diabase dykes described above that cross-cut the SS and NS. For the purpose of this paper these are called the camp road diabase dykes, given their proximity to the road that accesses the Nechalacho REE exploration camp. These dykes are morphologically distinct from the Hearne diabase dykes in that they are significantly wider, longer, more coarse-grained, and are not innately planar but adapted their shape to follow the margins of the SS and NS. Mineralogically these fine to medium-grained dykes consist of moderately altered plagioclase laths, clinopyroxene, amphibole, and biotite. Both clinopyroxene and amphibole also occur as rare phenocrystic phases; phenocrystic amphiboles are typically oikocrystic with inclusions of plagioclase.

3.4 Analytical Methods

3.4.1 Sampling

Samples were collected from outcrop and diamond drill core during the 2009-2010 field seasons, drill core was made available by Kodiak Exploration Ltd. Representative samples of the CIS were collected from Blanchet Island (Fig. 3.1).

3.4.2 Methodology

See section 1.6

3.5 Geochronology

A fine-grained sample of the NS was selected from outcrop, corresponding to geochemical sample 534A. Standard 30 μ m polished thin sections were used to identify and characterize zircons using backscattered-electron and cathodoluminescence imaging on a JEOL 6400 SEM equipped with a Gatan Chroma CL system at the University of New Brunswick. Individual zircon grains were analyzed *in situ* in a standard polished thin-section; data from these analyses are located in Table 3.2. Six concordant analyses were used to determine an age of 1892 ± 4 Ma (Fig. 3.6) by LA-ICP-MS.

3.6 Whole-rock chemistry

The chemical composition of representative rock samples are given in Appendix A.2. Samples taken from the layered rafts of the NS are clearly cumulate in nature and do not represent magma compositions. Essential geochemical features are summarized in Figs. 3.7-3.12. Nd isotope data on 16 whole rock samples are presented in Table 3.3. Epsilon Nd ($\epsilon_{Nd(T)}$) values were calculated using an average age (T) of 1885 Ma for all

Figure 3.6 - Concordia diagram showing the results of U-Pb LA-ICP-MS dating of zircon from the NS: (a) BSE photomicrograph highlighting textural relations between cluster of zircons (white) and feldspar (dark grey) and clinopyroxene (medium grey), (b) example BSE photomicrograph of analyzed zircon, (c) example BSE photomicrograph of an analyzed zircon.

Analysis	Duration (s)	U (ppm)	Th (ppm)	Pb (ppm)	U/Th	Error correlation				Apparent Ages (Ma)				Disc %					
						²⁰⁶ Pb/ ²³⁸ U	± error	²⁰⁶ Pb/ ²³⁸ U	± error	²⁰⁶ Pb/ ²³⁸ U vs ²⁰⁷ Pb/ ²³⁵ U	²⁰⁷ Pb/ ²³⁵ U	± error	²⁰⁷ Pb/ ²³⁵ U		± error	²⁰⁷ Pb/ ²³⁵ U	± error		
534A3Zr1a	29.491	2400	1982	1594	1.207	4.38	0.13	0.2888	0.0072	0.91	0.1098	0.0011	1797	19	1634	36	1706	24	9.1
534A3Zr1b	9.6346	2680	1870	1450	1.42	3.98	0.1	0.2611	0.0054	0.80	0.1102	0.0013	1801	34	1495	29	1628	24	17.0
534A3Zr1c	10.34	1880	1240	960	1.488	4.91	0.17	0.3106	0.0095	0.61	0.1148	0.0014	1884	48	1743	47	1802	32	7.5
534A3Zr1d	25.731	4050	4520	3010	0.933	3.281	0.064	0.2301	0.0042	0.74	0.1042	0.0012	1701	22	1335	22	1475	15	21.5
534A3Zr1e	29.374	3150	2730	1995	1.168	3.753	0.054	0.2584	0.0042	0.79	0.1056	0.0011	1723	19	1484	20	1582	11	13.9
534A3Zr2a	23.617	2813	1981	1550	1.437	3.89	0.12	0.2514	0.0094	0.51	0.11323	0.00095	1851	15	1445.5	45	1611.2	21	21.9
534A3Zr3a	19.739	1260	940	815	1.397	4.4	0.12	0.2882	0.009	0.95	0.11193	0.00089	1830	15	1631	45	1709	26	10.9
534A3Zr3b	16.449	3890	2260	1477	1.81	2.795	0.06	0.2035	0.0038	0.78	0.1157	0.0011	1628	20	1194	20	1353	17	26.7
534A3Zr3c	15.392	2910	2170	1279	1.382	2.84	0.053	0.2046	0.0037	0.62	0.1012	0.0013	1644	23	1200	20	1368	14	27.0
534A3Zr3d	12.69	1890	1320	835	1.596	3.356	0.56	0.2341	0.016	0.85	0.1056	0.0067	1724	29	1355	79	1493	79	21.4
534A3Zr4a	17.768	1530	690	1530	2.161	7.96	0.55	0.2766	0.0079	0.94	0.207	0.01	2894	95	1573	40	2220	72	45.6
534A3Zr4b	11.985	829	419	650	2.06	7.22	0.39	0.33	0.012	0.81	0.1588	0.0041	2440	37	1838	63	2135	61	24.7
534A3Zr4c	13.512	2610	2700	1727	0.996	3.946	0.074	0.267	0.0046	0.75	0.1071	0.0013	1749	31	1525	23	1622	15	12.8
534A3Zr4e	29.609	2093	1372	1015	1.66	3.825	0.077	0.2503	0.0051	0.87	0.11085	0.00099	1812	16	1439	26	1596	16	20.6
534A3Zr5a	10.457	857	603	503	1.438	5.2	0.14	0.3318	0.0078	0.27	0.1153	0.0013	1881	44	1847	39	1852	25	1.8
534A3Zr5aa	23.734	1520	1150	970	1.52	4.59	0.28	0.2704	0.0086	0.96	0.1226	0.0039	1995	27	1547	43	1747	43	22.5
534A3Zr5ab	22.677	2544	1891	1224	1.362	2.677	0.072	0.2008	0.0048	0.92	0.09691	0.0009	1565	14	1179	26	1321	19	24.7
534A3Zr5b*	26.789	544	355	323.8	1.542	5.439	0.057	0.3406	0.0052	0.31	0.1151	0.0015	1885	24	1889	25	1890.4	9	-0.2
534A3Zr5c	9.0471	1075	824	633	1.336	5.25	0.097	0.3349	0.0056	0.63	0.1151	0.0015	1865	37	1861	27	1860	15	0.4
534A3Zr5d	13.159	2636	2023	1219	1.326	3.029	0.21	0.2152	0.0051	0.48	0.1019	0.0044	1659	20	1256	27	1414.8	42	24.3
534A3Zr5e*	18.799	978	728	642	1.379	5.413	0.058	0.3406	0.005	0.47	0.1144	0.0011	1869	24	1889	24	1886	9.2	-1.1
534A3Zr5f	11.867	964	690	581	1.425	5.358	0.061	0.3391	0.005	0.30	0.1151	0.0012	1880	29	1882	24	1878	9.6	-0.1
534A3Zr5g	27.494	765	553	523	1.395	5.564	0.065	0.3506	0.0049	0.78	0.11441	0.00096	1872	16	1937	24	1910	10	-3.5
534A3Zr5h*	16.449	960	748	631	1.305	5.469	0.052	0.3412	0.0049	0.58	0.1001	0.00086	1889	27	1892	24	1895	8.1	-0.2
534A3Zr5h	29.491	1404	778	691	1.88	4.92	0.1	0.3132	0.006	0.84	0.1142	0.0011	1865	17	1755	30	1804	17	5.9
534A3Zr5i	20.797	2140	1550	1130	1.348	3.84	0.33	0.2533	0.0098	0.85	0.1098	0.0044	1792	32	1455	49	1598	56	18.8
534A3Zr5j	27.846	2411	1820	1357	1.345	4.021	0.056	0.2643	0.0042	0.87	0.1097	0.00092	1795	15	1511	22	1637	11	15.8
534A3Zr5k*	16.919	1183	892	762	1.328	5.439	0.058	0.3409	0.0052	0.68	0.1152	0.001	1882	24	1891	25	1893	8.9	-0.5
534A3Zr5l	15.039	855	389	383	2.215	5.06	0.19	0.313	0.0097	0.89	0.1173	0.002	1913	25	1752	48	1825	29	8.4
534A3Zr5m	28.786	1008	517	494	1.954	5.563	0.077	0.3453	0.0048	0.68	0.1173	0.0011	1915	17	1912	23	1911	12	0.2
534A3Zr5n*	12.572	1085	629	646	1.753	5.442	0.048	0.3409	0.0047	0.69	0.1152	0.00086	1881	19	1891	23	1891	7.7	-0.5
534A3Zr5o	20.092	1530	1167	883	1.345	4.167	0.28	0.2709	0.0083	0.45	0.1119	0.0047	1829	24	1548	41	1667	32	15.4
534A3Zr5p	18.682	3800	4060	2420	0.948	2.816	0.099	0.1951	0.0044	0.70	0.1049	0.002	1711	24	1149	23	1362	25	32.8
534A3Zr5q	21.972	700	315	397	2.212	6.23	0.34	0.3325	0.0074	0.40	0.1395	0.0058	2220	41	1814	35	2006	40	18.3
534A3Zr5r	12.337	1074	653	521	1.681	5.03	0.058	0.3117	0.0045	0.67	0.1168	0.001	1906	30	1749	22	1824	9.7	8.2
534A3Zr5s	16.919	1040	704	938	1.537	7.33	0.54	0.3131	0.0081	0.66	0.1681	0.0087	2508	99	1755	39	2145	57	30.0
534A3Zr5v	6.4622	1780	786	599	2.284	5.01	0.09	0.314	0.006	0.78	0.1147	0.0017	1886	46	1760	29	1819	15	6.7
534A3Zr5w	8.8122	743	415	434	1.812	5.14	0.12	0.322	0.0059	0.92	0.1167	0.0015	1906	20	1799	29	1842	18	5.6
534A3Zr5x*	19.152	646	283	312	3.12	5.45	0.067	0.3424	0.007	0.78	0.1154	0.0014	1888	22	1897	33	1892	10	-0.5
534A3Zr5y	28.316	1944	1553	1434	1.252	4.968	0.065	0.3054	0.0049	0.86	0.11704	0.00085	1911	13	1718	24	1814	11	10.1
534A3Zr5z	16.567	937	614	605	1.542	5.123	0.084	0.3121	0.0052	0.81	0.11856	0.0012	1934	14	1751	25	1841	14	9.5
534A3Zr6a	8.8122	3961	1794	1365	2.204	2.432	0.078	0.1679	0.0043	0.87	0.1036	0.0017	1689	20	1000	23	1252	22	40.8
534A3Zr7a	18.212	870	565	487	1.514	5.68	0.055	0.3487	0.0049	0.53	0.1181	0.001	1926	20	1928	22	1930	8.5	-0.1
534A3Zr7b	9.0471	376	168.6	184	2.19	5.24	0.068	0.3335	0.0061	0.65	0.1153	0.0011	1884	22	1861	30	1859	11	1.2
* analyses used in concordia plot																			

* analyses used in concordia plot

Table 3.2 - LA-ICP-MS U-Pb data, fine-grained diorite of the NS. Corresponds with whole rock geochemistry sample 534A, location: E414228, N6887717 - coordinates are for a UTM projection zone 12, NAD83.

samples.

3.6.1 *Compton intrusive suite and related rocks*

The Compton intrusive suite, SS, NS, and layered rafts within the NS are all generally metaluminous, with high Na_2O (1.5 – 6.6 wt. %) and low SiO_2 (46.9 – 63.5 wt. %), and follow a calc-alkaline trend (Fig. 3.7). Using the classification of Frost *et al.* (Frost *et al.*, 2001), these rocks are magnesian granitoids and range from alkali-calcic to alkalic (Fig. 3.8). Rocks from these intrusions generally plot in the monzo-gabbro to quartz-monzonite fields in $\text{Na}_2\text{O} + \text{K}_2\text{O}$ versus SiO_2 diagrams (Fig. 3.7c). All intrusions display large negative Nb anomalies and moderate REE slopes with $(\text{La/Lu})_N$ ranging from 7 to 29. Normalized to chondritic abundances (McDonough & Sun, 1995), the heavy rare earth elements (HREE) of all intrusions display a concave-up shape (Fig. 3.9). Zirconium anomalies are variable between units; Compton intrusive suite samples have both small positive and negative anomalies, NS and SS have negligible to small positive anomalies, and the layered rafts have moderate negative anomalies (Fig. 3.9). Pb (1.5 – 50.3 ppm) and Th (0.5 – 14.1 ppm) contents are variable but generally elevated. Large ion lithophile elements (LILE) are typically elevated, (e.g., 210 – 1350 ppm Ba, 25 – 152 ppm Rb). All intrusions plot mainly within “volcanic arc granite” or “active continental margin” fields of geotectonic discrimination diagrams (Fig. 3.10). Initial Nd isotopic ratios range from $\epsilon_{\text{Nd}(1885)} = -2.1$ to -2.6 for the Compton intrusive suite compared to $\epsilon_{\text{Nd}(1885)} = -1.1$ to -1.6 for the NS and SS, and $\epsilon_{\text{Nd}(1885)} = -1.8$ to -2.0 for the layered rafts hosted in the NS.

Figure 3.8 - Granitoid classification schemes from Frost *et al.* (2001): (a) $\text{FeO}/(\text{FeO} + \text{MgO})$ vs SiO_2 showing the boundary between ferroan plutons and magnesian plutons, (b) $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ vs SiO_2 showing the ranges of alkali, alkali-calcic, calc-alkalic, and calcic rock series. Symbols as in Figure 3.7.

Type	Sample	Nd (ppm)	$^{143}\text{Nd}/^{144}\text{Nd}_m$	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_i$	ϵ_{Nd}^T
SS	1053A	24.69	0.511479	4.49	0.1099	0.510116	-1.60
SS	1055A	27.08	0.511394	4.56	0.1018	0.510132	-1.30
NS	534A	24.00	0.511689	4.95	0.1247	0.510142	-1.10
CIS	1064A	23.59	0.511513	4.55	0.1167	0.510066	-2.59
CIS	1067A	18.22	0.511675	3.85	0.1277	0.510091	-2.11
CIS	550A	15.11	0.511651	3.20	0.1280	0.510063	-2.65
Hearne	338A	21.49	0.512067	5.59	0.1574	0.510115	-1.63
Hearne	1197A	31.86	0.511800	7.37	0.1398	0.510066	-2.58
Hearne	373A	29.10	0.511936	7.31	0.1518	0.510053	-2.85
Hearne	417A	23.41	0.512020	6.04	0.1560	0.510085	-2.21
Camp-DB	1021B	20.44	0.512102	5.31	0.1570	0.510155	-0.85
Camp-DB	374A	16.76	0.512064	4.32	0.1558	0.510131	-1.31
Camp-DB	542A	20.50	0.512080	5.36	0.1581	0.510119	-1.55
Camp-DB	537A	18.05	0.512114	4.80	0.1606	0.510122	-1.49
NS-LR	1022A	11.22	0.511860	2.63	0.1415	0.510105	-1.82
NS-LR	1058B	14.18	0.511820	3.26	0.1389	0.510097	-1.97

Note: Epsilon Nd values calculated assuming an age (T) of 1885 Ma for all samples. Sm and Nd concentrations by isotope dilution. north stock (NS) and south stock (SS); CIS, Compton intrusive suite; Hearne, Hearne diabase; Camp-DB, Camp road diabase; LR, layered raft.

Table 3.3 - Nd isotope compositions of the CIS and related rocks

3.6.2 Hearne and Camp road diabase dykes

Compositionally the Hearne and Camp road diabase dykes are very similar. Both are tholeiitic, metaluminous, and have Mg#’s ranging from 29 to 52. They have slightly sloping REE patterns, $(La/Lu)_N$ ranging from 1.7 – 4.9, and pronounced negative Nb anomalies (Fig. 3.9). On average the Hearne dykes have marginally higher REE abundances and steeper REE profiles. The Hearne dykes exhibit small positive Zr anomalies, whereas the Camp road diabase dykes have both small negative and positive Zr anomalies. Compared to the Compton suite intrusions, the Hearne and Camp road diabase dykes have much flatter REE profiles (Fig. 3.9). The majority of initial Nd isotopic ratios from the Camp road dykes ($\epsilon_{Nd(1885)} = -0.8$ to -1.6) fall within analytical uncertainty of Hearne dykes hosted within the Blatchford Lake intrusive suite ($\epsilon_{Nd(1885)} = -1.6$ to -2.8).

3.7 Mineral Chemistry

Biotite and clinopyroxene are the only ubiquitous mafic phases in the SS, NS, layered rafts, and the CIS intrusive suite. The compositions of these ferromagnesian phases are dependent on the nature of the magma from which they crystallize (Abdel-Rahman, 1994, Dal Negro *et al.*, 1982). As such they can retain information about their parent magma and may be used as tools to correlate between units or to compare with local intrusions, i.e., the Blatchford Lake intrusive suite. Figure 3.11a displays the variation in MgO and Al₂O₃ observed in biotite crystals. With the exception of samples from the layered rafts, there is a distinct compositional separation of rocks from the Compton intrusive suite and related rocks when compared to samples from the Blatchford

Figure 3.9 - Chondrite-normalized multi-element patterns for rock related to the NS and SS: (a) NS, (b) layered rafts hosted in the NS, (c) SS, (d) Compton intrusive suite, (e) Camp road diabase, (f) Hearne diabase. Chondrite normalization values are from McDonough and Sun (1995).

Figure 3.10 - Geotectonic and granitoid discrimination diagrams: (a) Th/Yb vs Ta/Yb (Schandl & Gorton, 2002), (b) Rb vs Y+Nb (Pearce *et al.*, 1984). Symbols as in Figure 3.7. ACM=active continental margin, WPVZ=within-plate volcanic zone, WPB=within-plate boundary, MORB=mid-ocean ridge basalt, WPG=within-plate granite, ORG=ocean-ridge granite, VAG=volcanic-arc granite, syn-COLG=syncollisional granite. Symbols as in Figure 3.7.

Figure 3.11 - Biotite chemistry of the SS, NS, and related rocks, Al₂O₃ vs MgO (modified from Abdel-Rahman, 1994). P – peraluminous; C – calc-alkaline, A – alkaline, arrow illustrates the trend between rocks of the NS, SS, and the Compton intrusive suite.

Figure 3.12 - Clinopyroxene chemistry of the SS, NS, and related rocks: (a) composition of clinopyroxenes based on Morimoto (1989) classification scheme, (b) Al vs Mg#. Symbols as in Figure 3.11. Arrow illustrates the trend between rocks of the NS, SS, and the Compton intrusive suite.

Lake intrusive suite.

Analysed clinopyroxene crystals from the SS, NS, layered rafts and Compton intrusive suite are typically diopside (Fig. 3.12a). Using Mg# versus Al, Figure 12b illustrates chemical variations between units. There is a broad compositional overlap between the analyses from Compton intrusive suite and the NS and SS with crystals from mafic phases of the Blatchford Lake intrusive suite.

In both of these diagrams, two distinct trends can be discerned, one for rocks related to the Compton intrusive suite and SS and NS, and one for rocks of the Blatchford Lake intrusive suite (Figs. 3.11, 3.12b). In general both biotite and clinopyroxene display consistent compositional trends between the Compton intrusive suite, SS, NS, and layered rafts. For example, in both phases there is a systematic decrease in alumina incorporated into the phases, starting with layered rafts followed in order by the Compton intrusive suite, NS, and SS.

3.8 Discussion

3.8.1 Compton intrusive suite and their relation to the NS and SS

Davidson (1978) first postulated that the SS and NS were directly related to the Compton intrusive suite present along on the opposite shore of the Hearne Channel. New data presented in this paper substantiate this claim but disagree with previous age determinations (Table 3.1).

3.8.1.1 Age relations

Davidson (1978) proposed that the NS and SS were part of the CIS (1865 ± 15 Ma, Bowring *et al.*, 1984). However, field relations show that the NS and SS are cross-

cut by local diabase dykes thought to be part of the Hearne diabase swarm (1901 ± 4 Ma, Buchan *et al.*, 2010).

Substantial improvements in both mass spectrometry and laboratory protocols over the past two decades have significantly improved analytical precision in U-Pb zircon studies. Therefore we suggest that the ages determined by Bowring *et al.* (1984) be considered with caution when compared to the new U-Pb data presented in this study.

The concordant age of 1892 ± 4 Ma of the NS determined by in this study occurs outside analytical error of the previous best estimate for the age of Compton intrusive suite (1865 ± 15 Ma), but within error of the individual dates used to calculate the best estimate (Bowring *et al.*, 1984). In their geologic description of the East Arm, Hoffman *et al.* (1977) note that compositionally the CIS can be subdivided into two distinct sets, separated to the west and east of longitude $111^{\circ}30'$. The eastern intrusive suite are dominated by porphyritic monzonites, and the western intrusive suite generally comprise hornblende-biotite diorites. The two samples of Compton intrusive suite (Stark Lake and Christie Bay laccoliths; Fig. 3.1) dated by Bowring *et al.* (1984) are situated east of the divide. To date, no radiometric dating has been done on the western phases of the Compton intrusive suite. Geochemical analyses of Compton intrusive suite presented in this paper are all from intrusive phases west of the divide, primarily from Blanchet Island, the largest of the Compton intrusions in the East Arm. Given the compositional division of the Compton intrusions, it seems plausible that the two groups may not be coeval. Additional geochronology of the western Compton intrusive suite is required before the discrepancy between ages can be validated.

The age determined for the NS is in excellent agreement with the 1895 ± 5 Ma age from a biotite-bearing monzogranite-granodiorite sample of the Butte Island intrusive suite (Bowring *et al.*, 1984). Descriptions of the Butte Island intrusive suite are limited, and there is currently no available compositional data. The geochronology and geochemical characterization of this intrusive suite is beyond the scope of our study, but would be useful to confirm our findings. While slightly younger, the Ghost dyke swarm described by Buchan and Ernst (Ernst & Buchan, 2010) should also be evaluated for potential links with the CIS.

3.8.1.2 Geochemical relations

The whole-rock geochemistry, Sm-Nd isotopic data, and mineral chemistry of biotite and clinopyroxene presented above suggest that the SS, NS, and Compton intrusive suite originated from a similar source and evolved in a comparable manner. Based on available data, and notwithstanding the uncertainty of age relations between the Compton intrusive suite and the NS, we will now consider the NS and SS as belonging to the CIS.

The major element, trace element, and mineral chemistry data all show a consistent systematic trend of progressive differentiation in the order of: layered rafts – Compton intrusive suite > NS > SS (e.g., Figs. 3.7, 3.9, 3.11, 3.12). The observed chemical trends (i.e., increasing silica and REE contents with decreasing Mg#, and systematic variation in mafic phase compositions) suggest that crystal fractionation was a major factor in magma evolution. Figure 3.13a depicts the departure between the initial Nd ratios of the CIS ($\epsilon_{\text{Nd}(1885)} = -1.1$ to -2.6) and depleted mantle ($\epsilon_{\text{Nd}(1885)} = +5.4$). This significant gap, combined with the calc-alkaline trend, decoupling of LILE/HFSE, high

Pb contents, and Nb troughs of the CIS is indicative of a strong crustal component. The origin of this crustal component could be related to either contamination of a mantle derived melt or the melting of mafic lower crustal rocks.

Incompatible element ratio geotectonic discrimination diagrams support a continental arc setting (Fig. 3.10), suggesting the melting of the mantle wedge. The negative Nb anomalies in CIS, SS, and NS samples indicate the presence of a significant component with a subduction-related signature. Additionally, the positive trend of between Th/Yb and SiO₂ (Fig. 3.13b) suggests that differentiation of the CIS—with the exception of some rocks of the SS—involved moderate crustal input. Modeled curves for various local crustal contaminants in Figure 3.13a indicate that the degree of crustal assimilation for a depleted mantle source would be on the order of 10-20%. Although not a definitive solution, based on this evidence we favor a genetic model involving the contamination of mantle derived melt.

3.8.2 *Nature and origin of layered rafts*

Using gravity modeling, Birkett *et al.* (1994) postulated that the strongly magnetic Caribou Lake gabbro body of the Blatchford Lake intrusive suite could extend eastward beneath the eastern lobe, up to halfway across the entire complex. If this statement were correct, then at its maximum extent the Caribou Lake gabbro would extend beneath the SS and NS, thereby raising two questions: (1) do the NS or SS provide any evidence of the Caribou Lake gabbro extending that far eastward, and (2) are the layered rafts within the NS xenoliths derived from the Caribou Lake gabbro?

Although the Caribou Lake gabbro contains phases that exhibit layering textures superficially comparable to those observed in the layered rafts hosted in the NS (e.g., Figs. 3.3, 3.4e, 3.5), whole-rock, Sm-Nd isotopic, and mineral chemistry data indicate that no genetic link exists between the units. Compositional data imply instead an autolithic relationship between the layered rafts and the NS.

The observed cross-bedding and dropstone features are assumed to have formed in a similar manner to those in sedimentary systems and as seen in other layered plutonic systems, (e.g., Duke Island: (Irvine, 1965) Skaergaard: (Irvine *et al.*, 1998); and the Stillwater Complex: (McCallum *et al.*, 1980). One fundamental difference between layering in sedimentary sequences and in igneous systems is that due to sidewall and roof crystallization the principle of original horizontality does not always hold up. However, the presence of gravity driven magmatic dropstones allows us to predict “way up” in individual rafts, (i.e., towards the roof of the magma chamber) using these structures. The orientations of these are plotted in Figure 3.2. The arcuate inward-facing direction of the “way up” indicators suggests a cone/pipe like body, implying that the layered bodies formed *in situ*. However, given the limited number of directional indicators, abrupt raft margins, variability in size and distribution of the rafts, we believe these gabbroic blocks formed *ex situ*, and their current distribution is a function of random positioning.

The variability of layering within individual sequences, (e.g., Figure 3.5) suggests that these rafts formed from either (1) an extremely complex and cyclic turbulent history alternating between periods of crystallization and deposition versus erosion, or (2) that some slumping or other plastic deformation has occurred, or (3) a combination of both.

Figure 3.13 - SS, NS and Compton intrusive suite: (A) ϵ_{Ndi} vs Th/Yb, Curves are labeled with their respective end-members and demonstrate mixing (symbols along curves in 10% increments). (B) SiO_2 vs Th/Yb. Values for modeled mixing curves: depleted mantle, $\epsilon_{\text{Ndi}} = 4.8$ (Goldstein *et al.*, 1984), Th/Yb = 0.0341 (Salters & Stracke, 2004); Morose granite, $\epsilon_{\text{Ndi}} = -3$, Th/Yb = 37.29 (Mumford *et al.*, 2010); Defeat granodiorite, $\epsilon_{\text{Ndi}} = -2.9$, Th/Yb = 9.47 (Mumford *et al.*, 2010); Burwash Formation, $\epsilon_{\text{Ndi}} = -5$, Th/Yb = 4.22 (Yamashita & Creaser, 1999).

While the NS and SS are both similar in size, age and morphology, and share the same geographic area, the abundance, size and lithologic variance of xenolithic and autolithic inclusions in the NS is significantly higher than in the SS intrusion. This could be a function of emplacement mechanism (single or multiple pulses, ballooning or sheet-stacking), velocity, viscosity, or distance from the source. We have shown that the layered rafts are genetically linked to the NS, but little is known regarding the provenance of the calc-silicate and magnetite inclusions. Knowing the relative stratigraphic origin of these units could be used to assess whether xenolithic/autolithic material is moving up or down in the system and 'where' the layered rafts formed, (i.e., have they fallen into the pipe, or were they brought up during emplacement). The common presence of mantle and lower-crustal xenoliths in many volcanic rocks highlight the outstanding potential for upward vertical movement of xenolithic material during emplacement/eruption; however, in pipe systems the downward movement of material has also been shown to occur at scales greater than 1.5 km (Osborne & Grimes-Graeme, 1936). The chemistry of the biotite and clinopyroxene crystals in the layered raft are much more primitive than those in the NS, SS or the Compton intrusive suite in the East Arm, suggesting that the layered rafts are cumulate products that formed prior to the emplacement of the NS and thus have been brought "up" the pipe. However this raises questions about the capability of a magma pulse to move large (presumably denser) rafts vertically and, if possible, the extent to which this process could operate at. No root zone was detected in the gravity modeling by Birkett *et al.* (1994), so if the movement was vertical, then the magnitude of movement exceeded the downward resolution of the gravity survey, suggesting transport of >1 km?

3.8.3 *Relationship between the Hearne and Camp road diabase dykes*

From their current level of exposure, the distribution of the Camp road diabase dykes (Fig. 3.2) and their overall orientation of $\sim 060^\circ$, it is easy to conceive that the three known occurrences of the Camp road diabase dykes represent a single dyke connected at depth, whose sinuous shape was influenced by the presence of the SS and NS. Henceforth, the dykes will be considered as a single entity. Cross-cutting relations show that the Camp road diabase dyke is older than both the NS and SS. While the Camp road dyke is clearly quenched against the SS, the felsic dykelets originating from the SS that cross-cut the Camp road diabase dyke could suggest that the two intrusions were nearly coeval. Two plausible theories are offered for the origin of the dykelets. (1) During emplacement of the Camp road diabase dyke the SS was not completely crystalline. The rapid cooling and contraction of the Camp road diabase created structural weaknesses through which over-pressured residual intercrystalline melts from the SS were injected as dykelets. (2) The heat flux generated from the cooling Camp road dyke was enough to cause localized partial melting of the SS which was only marginally sub-solidus. The absence of melt injections along the contact between the Camp road and the NS could then imply that either the NS had cooled significantly further than the camp road diabase dyke (i.e., longer time delay), or that due to its less evolved nature its solidus temperature was too high for the residual heat to permit localized melting.

Compositionally the Hearne and Camp road dykes are almost identical; the range of compositions of the Hearne dykes almost entirely encompasses that of the Camp road dykes. While the initial Nd isotopic ratios of the Camp road diabase dykes are slightly more positive, when analytical error is taken into account the isotopic range of the two

swarms largely overlap with each other, and have similar evolutionary pathways (Fig. 3.14). These similarities suggest that the two dyke swarms share a common source/parental magma.

The analytical uncertainty of the 1901 ± 4 crystallization age for the Hearne diabase swarm and the 1892 ± 4 Ma crystallization age of the NS indicate that the intrusions were emplaced within a restricted period. The near coeval relationship between the SS and Camp road diabase, and the shared orientation of the Hearne and Camp road swarms (suggesting similar tectonic stress regimes during emplacement) indicate that the emplacement of the Camp road diabase likely occurred within a few million years of the NS. We speculate that emplacement of the Camp road diabase is directly linked to the presence of the NS and SS. After the emplacement of the Hearne dykes, when the conduit system that fed the swarm ceased to be kinematically favourable, remnants of its parental magma system likely still existed at depth if the time between emplacement of the Hearne and Camp road diabase dykes was short. The emplacement of the NS and SS created an easily exploitable pathway through the upper crust, which could then be utilized by the same source/parental magma system as the Hearne dykes to form the Camp road diabase dyke. The slightly higher Nd isotopic ratios of the Camp road diabase dyke relative to the Hearne diabase dykes suggest less crustal contamination. If the two systems utilized the same plumbing systems this may be related to the armouring of magmatic conduits. In summary, the two major differences between the Hearne and Camp road dykes are (1) the morphology of the dykes, and (2) the absolute/relative timing of emplacement. The difference in morphology observed might only be a local effect due to the presence of the CIS. Therefore, while these variations between the dyke swarms are significant, they may

Figure 3.14 - Plot of ϵ_{Ndi} vs time for depleted mantle¹ (Goldstein *et al.*, 1984) and crystallization of rocks from the: (a) NS, SS, and Compton intrusive suite, (b) Camp road and Hearne diabase dykes.

not be useful for characterization of dykes in the region without the aid of cross-cutting field relations or precision radiometric dating. Therefore it is suggested that the Camp road dykes should be considered as a localized subset of the Hearne swarm.

3.8.4 *Potential melting mechanisms*

The timing of the CIS suggests that it is a product of the 2.0 - 1.8 Ma Trans-Hudson orogeny, and the collision of the Slave and Rae-Hearne plates during the assembly of the Columbia supercontinent. The regional transpressional environment produced during the oblique docking of the Slave and Rae-Hearne provinces (Whitmayer & Karlstrom, 2007) could have caused localized extension along the suture, initiating decompression melting of underlying depleted mantle components. If the source of the CIS is related to the melting of lower crustal rocks (see Geochemical relations section above), another possible mechanism for melting is lithospheric delamination along the south eastern margin of the Slave Craton. In their classification scheme, Frost *et al.* (2001) indicate a link between plutons that exhibit unusual magnesian/alkali-calcic to alkalic chemistry such as in the CIS (Fig. 3.8) and delamination related melting of lower crustal rocks. Both of these potential melting mechanisms (decompression and delamination) could account for the formation of the CIS and are largely consistent with the known tectonic and geologic setting of the East Arm during this period (Bleeker & Hall, 2007, Davis & Bleeker, 2007, Whitmayer & Karlstrom, 2007). However, studies by Davis *et al.* (2003b) and Thompson *et al.* (1996) suggest that a thick lithosphere has stabilized by 1.8 Ma. The buoyancy of a young, relatively hot lithosphere would not

favor models involving delamination as it requires the gravity driven separation of the lithosphere.

3.9 Conclusions

- (1) Chemically the NS and SS represent the northwestern continuation of the CIS into the Slave province.
- (2) The multiple diabase dykes that intrude along the margins of the SS and NS are likely interconnected, and together form a single intrusion, termed the Camp road diabase dyke. The Camp road diabase and the Hearne diabase swarm share a common source/parental magma but are separated by a modest, but geologically significant time gap.
- (3) The age of the NS has been determined to be 1892 ± 4 Ma. The NS, SS, and the Camp road diabase dyke represent three distinct temporal events, with relative timing being $NS > SS \geq$ Camp road dyke. The cogenetic relationship between the NS and SS implies that they are linked by the same magmatic system, indicating that the delay between intrusions is restricted to the lifespan of the parental system, and was likely quite short.
- (4) The layered rafts hosted in the NS are autolithic in nature, and have likely been brought up from a deeper portion of the system during the emplacement of the NS.
- (5) There is no evidence of either the NS or SS intruding through the Camp road layered syenite series, thereby suggesting a limit to its westerly extent.

(6) Currently there are no comparative geochemical data available for the possibly coeval Butte Island intrusive suite. Geochemical characterization of these intrusions combined with improved geochronology may enhance our understanding of Paleoproterozoic intrusions in the East Arm.

4 Chapter: Petrology of the western lobe of the Blatchford Lake intrusive suite

4.1 Introduction

Individual phases in multiphase igneous systems record discrete, punctuated events from an evolving system, volcanic or plutonic, whereby each new phase represents a derivative from a common precursor. Variations between phases are controlled by the degree of differentiation of the parental melt prior to segregation, as well as external factors affecting the derivative melt post-segregation, (e.g., Tuolumne Intrusive Suite in the Sierra Nevada (Bateman & Chappell, 1979, Coleman *et al.*, 2004).

Large multiphase igneous systems that span wide compositional ranges offer an excellent opportunity to track melt development, and gain insight into their genesis and interaction with the lithosphere. The more numerous and compositionally diverse the phases, the more information we can garner about the evolutionary pathway of the differentiating system. While the ability to use geochemistry to directly model plutonic systems is often obscured by the cumultic nature of many large slow cooling bodies, we can still use large-scale compositional changes to track a progression. A substantial departure from typical assimilation and fractional crystallization (AFC) controlled differentiation trends often signifies the presence of a distinct mechanism or factor, (e.g., the transition from silica oversaturated to undersaturated (Foland *et al.*, 1993, Riishuus *et al.*, 2008). These departures offer us a glimpse at individual processes occurring throughout the crust and into the upper mantle.

It is under this pretext that we examine the Blatchford Lake intrusive suite of the Northwest Territories, Canada. Covering an area of $> 230 \text{ km}^2$, the Blatchford Lake intrusive suite is the largest body in a series of Paleoproterozoic intrusions in the southern Archean Slave Province, collectively referred to as the 2175-2185 Ma southwestern Slave magmatic province (Bleeker & Hall, 2007). Davidson (1972, 1978), the first to describe the Blatchford Lake intrusive suite as a single entity, sub-divided it into an older sub-alkaline portion (western lobe), and a younger cross-cutting peralkaline portion (eastern lobe, chapter two). This unusual transition from ultramafic sub-alkaline to highly evolved peralkaline rocks is one of numerous distinct features of the Blatchford Lake intrusive suite.

The western lobe contains the least differentiated and least contaminated phases in the Blatchford Lake intrusive suite based on studies by Davidson (1972, 1978, 1981, 1982) and its mafic character, making it ideal to investigate the nature of the source and the early evolution of the intrusive suite. Understanding the petrology of the western lobe will also allow us to carefully evaluate fundamental questions regarding the Blatchford Lake intrusive suite, such as: (1) do the western and eastern lobes share a petrogenetic relation, (2) what factors or mechanisms might be responsible for the transition from sub-alkaline to peralkaline between the lobes, (3) under what conditions was the western lobe emplaced (pressure-temperature). Understanding the early evolution of this intrusive suite is not without economic significance either, as the Blatchford Lake intrusive suite hosts the world class Thor Lake rare metal deposits (Pinckston & Smith, 1995, Sheard *et al.*, 2012, Trueman *et al.*, 1988), and has strong Cu-Ni-PGE potential in the mafic/ultramafic units (Marmont, 2006, Marmont, 2007). Source characterization of the Blatchford Lake

intrusive suite also provides insight into the overall development of the Paleoproterozoic southwestern Slave magmatic province.

4.2 Geological setting and previous work

Located approximately 100 km southeast of Yellowknife, the Blatchford Lake intrusive suite occurs along the north shore of the Hearne Channel of Great Slave Lake (Fig. 2.1, 2.2). The entire Blatchford Lake intrusive suite is hosted in Archean metasediments, granite and granodiorite plutons. With the exception of a weak localized foliation (sub-vertical, NW-trending), and rare Proterozoic north-south trending sub-vertical faults of low displacement, the Blatchford Lake intrusive suite is undeformed.

Rocks from the western lobe of the Blatchford Lake intrusive suite were first mapped in the 1930's by Stockwell (1932), Jolliffe (1936), and Henderson (1938), as part of a regional government mapping program. Buckham (1936) studied the petrology of what he referred to as the Francois River gabbro, now known as the Caribou Lake gabbro and leucoferrodiorite units of the Blatchford Lake intrusive suite (Davidson, 1978). Davidson (1978) later emphasized a relationship between the syenitic and granitic rocks of the eastern lobe and rocks from the western lobe based largely on their alkaline character and field relationships. The eastern lobe consists of peralkaline alkali-feldspar granite that is zoned inwards to a syenite core. Underlying the syenite core is a silica-undersaturated sequence collectively known as the Nechalacho layered suite. The central portions of the eastern lobe host the world class Thor Lake rare metal deposits (Pinckston & Smith, 1995, Sheard *et al.*, 2012, Trueman *et al.*, 1988). For a complete description of the eastern lobe of the Blatchford Lake intrusive suite refer to Mumford *et al.* (Chapter 2)

and Davidson (1978). From 2004 to 2007 Kodiak Exploration Ltd. actively explored the Caribou Lake gabbro for Cu-Ni-PGE mineralization. Exploration models were focused on sulfide banding near the basal contact or higher in the intrusions associated with magnetite-rich reefs (Marmont, 2007). Drilling programs during 2006-2007 resulted in over 16,000 m of drill core. Limited success was achieved during the 2006 drilling, where an 8 m thick massive sulfide lens was intersected (Marmont, 2006).

4.3 Field relations and petrography

Field relations between the various rock units of the western lobe were first described by Davidson (1972, 1978, 1982). However, fieldwork completed during this study has shown that the distinction between rock types in the field is not as obvious as indicated on the geological maps of Davidson (1972, 1978, 1982). For example, according to Davidson (1972, 1978, 1982) the Whiteman Lake quartz syenite, Mad Lake granite, and Hearne Channel granite occur as three distinct phases in the western portion of the complex. However, the ratio between plagioclase, quartz, and alkali feldspar is highly variable within single rock units, as is the presence of characterizing features such as xenocrysts of 'dark plagioclase' (Hearne Channel granite), green pyroxene and fayalite (Whiteman Lake quartz syenite), and the 'salt-and-pepper' texture of biotite, hornblende, and subporphyritic feldspar phenocrysts (Mad Lake granite, Davidson, 1978). Where present, these defining textural and mineralogical variations occur only a small scale, and clear intrusive contacts are only rarely visible in the field. If present, these are in many cases gradual and lacking sharp contacts, and therefore provide evidence for only at a short time gap between the emplacement of the various rock units. Davidson (1972, 1978,

1982) noted a systematic variation in mineralogy and texture in the Whiteman Lake quartz syenite and concluded that it is in fact a multi-phase composite intrusion. We believe, based on the observed contacts and variations within and between the western granitic intrusions, that they all represent coeval multi-phase composite intrusions with localized variations in mineralogy and texture. However, we do recognize a large-scale systematic variation from north to south. Therefore we treat the Whiteman Lake quartz syenite, Mad Lake granite, and Hearne Channel granite as two transitional groups; namely, the Whiteman granitic group (to include the Whiteman Lake quartz syenite and the northern portion of the Mad Lake granite) and the Hearne granitic group (to include the Hearne Channel granite and the southern portion of the Mad Lake granite; Fig. 2.1). In light of this distinction, we describe the observed field relations and petrography of phases in the western lobe. All dates listed are U-Pb zircon dates, and are summarized in Table 4.1.

4.3.1 Western Lobe

4.3.1.1 Caribou Lake gabbro and leucoferrodiorite

The oldest phase in the Blatchford Lake intrusive suite is the Caribou Lake gabbro, which is in contact with all three Archean country rock units: Morose granite, Defeat suite granodiorite, and Burwash Formation metasediments of the Yellowknife Supergroup (Davidson, 1982). The Caribou Lake gabbro is generally recessive, and contacts are often obscured or hidden beneath lakes or vegetation. Where observed, the contacts between the Caribou Lake gabbro and the Archean country rocks dip steeply (70 – 85°) away from the centre of the BLIS. The Caribou Lake gabbro is the most

Unit	Age (Ma)	Mineral	Method	Reference
Caribou Lake gabbro	2184 +/- 2	Zircon	Multi-grain U-Pb TIMS	Mumford et al. (2012)
Whiteman Lake quartz syenite	2185 +/- 5	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Whiteman Lake quartz syenite	2127 +/- 79	Hornblende	K-Ar	Wanless et al. (1979)
Mad Lake Granite	2166 +/- 47	Biotite	K-Ar	Wanless et al. (1979)
Hearne Channel granite	2175 +/- 5	Zircon	Multi-grain U-Pb TIMS	Bowring et al. (1984)
Thor Lake syenite	2176 +/- 1.6	Zircon	Single-grain U-Pb TIMS	Mumford et al. (2013)
Grace Lake granite	2176.2 +/- 1.3	Zircon and Monazite	Multi-grain U-Pb TIMS	Sinclair et al. (1994)
Nechalacho layered suite	2164 +/- 11	Zircon	In situ LA-MC-ICP-MS	Mumford et al. (2013)

Table 4.1 - Summary of relevant radiometric ages for the Blatchford Lake intrusive suite.

Figure 4.1 - Select field relations in the western lobe: (a) flat-lying Whiteman granitic group sill overlain by leucoferrodiorite, (b) Whiteman granitic group dykes intruding Caribou Lake gabbro, (c) modal layering in the Caribou Lake gabbro, (d) pegmatitic zone of Caribou Lake gabbro, (e) Burwash Formation inclusions within the Whiteman granitic group.

compositionally (peridotite to anorthosite) and texturally diverse unit in the Blatchford Lake intrusive suite. As noted by Davidson (1978) the Caribou Lake gabbro has a progressive change eastwards, starting with the chill margin against the Morose granite (Fig. 2.1). Towards the center of the complex, the gabbro transitions between: (1) zones of abundant pegmatitic patches (Fig. 4.1d) along the north and western shores of Caribou and Whiteman Lake, (2) massive to locally, weakly rhythmically-layered gabbro, layering defined by variation in modal abundance of plagioclase (Fig. 4.1c), variably dipping ($65 - 80^\circ$) to the south, (3) to coarse, uniform, massive leucoferrodiorite and anorthosite in the eastern exposures of the intrusion.

The recessive weathering of the Caribou Lake gabbro prevents the surficial mapping of individual rock types; therefore, field characterization is limited to two sub-units (1) leucoferrodiorite – anorthosite, and (2) Caribou Lake gabbro, a combination of all remaining units.

In addition to the large-scale west-east variations identified by Davidson (1978), diamond drilling by Kodiak Exploration Ltd. has revealed numerous new phases of the Caribou Lake gabbro and highlights the complexity of the system. Gravity and magnetic surveys of the Blatchford Lake intrusive suite indicate that the Caribou Lake Gabbro extends beneath the Whiteman Lake Granitic group and has a great vertical extent (Birkett *et al.*, 1994). This is corroborated by Kodiak's drilling, which has shown that the Caribou Lake gabbro extends to at least 950 m depth.

In drill core, contacts between phases are commonly gradational, reflecting variations in modal mineralogy, however, sharp intrusive contacts are observed, and typically dip from $50^\circ - 67^\circ$. Foliations are also common, generally defined by the

arrangement of plagioclase laths, dips range from 40° – 60°. Grain size is highly variable ranging from massive fine-grained units to discrete pegmatitic lenses.

Rock types observed include gabbro, leucoferrodiorite, peridotite, pyroxenite, anorthosite, and magnetite. These rock types largely represent modal variations of normal major constituent minerals in mafic systems (i.e., orthopyroxene, olivine, clinopyroxene, plagioclase, magnetite), with the latter four rock types representing cumulate end members. Thus textural features observed in outcrop and drill core all suggest the Caribou Lake gabbro was dominated by cumulate processes. The vertical arrangement of rock types within the Caribou Lake gabbro, as documented from drill core, is complex and relatively unsystematic. Basal cumulate units (i.e., peridotite and clinopyroxenite) are interspersed between leucoferrodiorite and gabbro bodies. Thickness and frequency of units are both highly variable; individual cumulate units ranging in thickness from <0.5 m to 20 m. Units are commonly cross-cut by granitic dykes and sills (Whiteman granitic group?).

In addition to the major minerals described above, accessory phases include amphibole (silicic edenite to edenite hornblende), biotite, sulfides, alkali-feldspar, apatite, and rare baddeleyite. Sulfide phases (pyrrhotite, pyrite, chalcopyrite, and rare sphalerite) are generally disseminated, locally forming discrete bands that are typically foliation parallel. In fine to medium-grained rocks relations between clinopyroxene and plagioclase range from ophitic to subophitic (Fig. 4.2a), in coarser grained rocks orthocumulate textures dominant. Clinopyroxene (diopside) crystals typically display numerous fine exsolution lamellae, and locally display rim overgrowths that lack exsolution lamellae (Fig. 4.2b). Serpentinization of olivine is common, but is particularly

Figure 4.2 - Photomicrographs of mineralogical and textural features of the western lobe: (a) subophitic textures in the Caribou Lake gabbro, (b) lamellae-rich clinopyroxene crystals with late overgrowth rims, (c) large xenocrystic feldspars in Whiteman granitic group. Abbreviations are as follows: CPX=clinopyroxene, KSP=alkali-feldspar, OL=olivine, PL=plagioclase, QTZ= quartz. All microphotographs taken under crossed-polarized light.

intense in peridotite layers. The Caribou Lake gabbro has been dated at 2184 ± 2 Ma (Mumford *et al.*, 2012b), although the data used was of relatively poor quality as it is based on a single concordant analysis.

In the southwest portion of the western lobe of the Blatchford Lake intrusive suite, Davidson (1972, 1978, 1981, 1982) mapped a >5 km long and up to 300 m wide dyke-like extension, which he considered to be part of the Caribou Lake Gabbro based on cross-cutting diabase dykes and field relations. The fine to medium-grained gabbroic extension cuts clearly across the Archean Morose granite at an orientation of $\sim 060^\circ$, and has been dubbed by other authors as the “feeder” dyke (Marmont, 2007), postulating that it may have been a major conduit for the formation of the Caribou Lake gabbro. The contact between the feeder dyke and the Caribou Lake gabbro is obscured by recessive weathering and vegetation. The gabbroic dyke is cross-cut by multiple smaller (<2 m wide), northeast-trending aphanitic diabase dykes from an unknown swarm. Other workers have questioned the petrogenetic relationship between the feeder dyke and the Caribou Lake gabbro (e.g. Marmont, 2007).

4.3.1.2 Whiteman granitic group

The Whiteman granitic group intrudes the Caribou Lake gabbro, its contact at the northern margin near Whiteman Lake is near vertical and quenched. However, in the southern portions around Mad Lake, the contact is sub-horizontal (Fig. 4.1a). Diamond drilling by Kodiak Exploration Ltd. near the center of the granitic body, shows that the granite is comprised of numerous thin (< 50 m) sub-horizontal sills interfingered with phases of the Caribou Lake gabbro. The central portion of the Whiteman granitic group is

full of xenoliths, ranging in size from < 5 cm to > 100 m, and locally constituting up to ~60% of the rock. These xenoliths consist of Burwash Formation (Fig. 4.1e), Defeat granodiorite, and various phases of the Caribou Lake gabbro. Davidson (1978) noted that the distribution of phases of gabbro hosted in the Whiteman granitic group are consistent with the zonation found in the gabbro body to the southwest, suggesting that they are proximal to their original locality. Southwest of the main body, dykes from the Whiteman granitic group are abundant within the Caribou Lake gabbro (Fig. 4.1b). The multiphase Whiteman granitic group is a heterogeneous body, compositionally ranging from quartz syenite to granite. In the western portion of the Whiteman granitic group the transition is systematic, trending from quartz syenite in the northwest to syenite compositions in the south. The eastern portion ranges from quartz syenite to granite with no apparent systematic trend. Contacts between phases vary locally from gradational boundaries to sharp intrusive margins. Individual phases are typically massive, fine to medium-grained, and range in color from pinkish grey to rusty pink, locally exhibiting a greenish tinge. The predominant phase is a hornblende-perthite quartz syenite, with interstitial biotite, clinopyroxene, altered fayalite, zircon and rare apatite. Feldspars generally display moderate sericitation, and larger feldspars are occasionally zoned from antiperthitic cores to perthite rims, or consist of alternating bands. The Whiteman granitic group has been dated at 2185 ± 5 Ma (Bowring *et al.*, 1984).

4.3.1.3 Hearne granitic group

The Hearne granitic group intrudes the Caribou Lake gabbro, Burwash Formation, and Morose granite. Western contacts with Burwash Formation and Morose granite are steep, but the northern contact is sub-horizontal, lying beneath the Caribou Lake

leucoferrodiorite. Davidson (1978) noted that the large mass of leucoferrodiorite in the center of the Hearne granitic group has gently to moderately dipping inward contacts. Remnants of a chill margin are observed along the top and bottom contacts of the Hearne granitic group.

The Hearne granitic group largely comprises massive rusty-pink colored, fine to medium-grained, sub-porphyritic granite. The granite is dominated by perthitic feldspars that are locally poikilitic, with rounded to sub-angular quartz inclusions. Larger feldspars are more common in the Hearne granitic group, and are zoned in a manner similar those found in the Whiteman granitic group (Fig. 4.2c). Xenoliths of Burwash Formation are common within the Hearne granitic group. The presence of xenocrystic plagioclase as noted by Davidson (1978) is sporadic, generally localized, and should not be used as a distinguishing feature. Prime examples for this texture were observed along the shoreline of Great Slave Lake. Moderate sericitization is typical in all feldspars. Amphibole and biotite characterize the mafic mineralogy, with rare interstitial zircon; amphibole often occurs as poikilitic crystals with inclusions of quartz. The Hearne granitic group has been dated at 2185 ± 5 Ma (Bowring *et al.*, 1984).

4.3.2 *Eastern lobe*

The field relations, geochemistry, geochronology, and petrology of the eastern lobe are described in Mumford *et al.* (chapter two) and references therein. The 2176 Ma (Mumford *et al.*, 2012b, Sinclair *et al.*, 1994) peralkaline eastern lobe is largely composed of coarse-grained alkali feldspar granite (Grace Lake granite), towards the center the Grace Lake granite grades into an alkali feldspar syenite (Thor Lake syenite).

Underlying the Thor Lake syenite, unexposed at the surface is a silica-undersaturated layered intrusion; known as the Nechalacho layered suite (chapter two). The Nechalacho rare-metal deposit is hosted within Thor Lake syenite and Nechalacho layered suite.

Contacts between the west and eastern lobes are marked by quenching and rare dykes of the Grace Lake granite extending into the Hearne granitic group and the leucoferrodiorite units of the western lobe. The southwestern portion of the Grace Lake granite contains abundant rafts of Hearne granitic group and leucoferrodiorite belonging to the Caribou Lake gabbro. Many of these rafts occur on hilltops and typically have sub-horizontal contacts.

4.3.3 *Diabase Dykes*

The entire Blatchford Lake intrusive suite is cross-cut by a northeast trending diabase dyke swarm believed to be part of the 1901 Ma Hearne diabase swarm (Buchan *et al.*, 2010). These dykes are typically sub-vertical, dark grey or black often imparting a greenish tinge, aphanitic, and vary in width from 30 cm – 1.5 m. A number of these diabase dykes occur along the western margin of the Caribou Lake gabbro, particularly along the shoreline of Caribou Lake, complicating contact relations with the Morose granite.

4.4 Analytical methods

4.4.1 Sampling

Samples of the western lobe and diabase dykes were collected from outcrop and diamond drill core during the 2009-2010 field seasons, diamond drill core was made available by Kodiak Exploration Ltd.

4.4.2 Methodology

See section 1.6

4.5 Whole-rock chemistry

The chemical compositions of representative rock samples are given in Appendix A.3. The obvious cumulate nature of phases in the Caribou Lake gabbro indicates that samples do not represent liquid compositions and should be viewed with caution. Sample 403A was collected from the chill margin of the Caribou Lake gabbro against the Archean Morose granite. Essential geochemical features are summarized in Figures 4.3-4.6.

4.5.1 Western lobe

Rocks of the Caribou Lake gabbro, Whiteman granitic group, and Hearne granitic group are sub-alkaline to mildly alkaline, and follow a tholeiitic trend (Fig. 4.3). Using the classification scheme of Frost *et al.* (2001) the leucoferrodiorite, Whiteman granitic group, and Hearne granitic group are metaluminous alkali-calcic to alkali, ferroan-type granitoids (Fig. 4.4), and are analogous to A-type granites (e.g. Bonin, 2007). The Mg#

of Caribou Lake gabbro samples ranges from 18-77, leucoferrodiorite from 9-28, and the chill margin sample has a value of 35 (Fig. 4.5). Systematic major element variation between rock units of the western lobe is apparent in major and trace Harker diagrams (Fig. 4.5), and illustrates near continuous trends from the Caribou Lake gabbro to Hearne granitic group. In these diagrams, SiO_2 has a negative correlation with Fe_2O_3 , Mg#, CaO, and TiO_2 , and a positive correlation with K_2O , Rb, Zr, and La. High loss on ignition (LOI) values in Caribou Lake gabbro samples generally reflect the intense serpentinization of olivine.

Chondrite-normalized multi-element patterns of the Caribou Lake gabbro and leucoferrodiorite samples are generally parallel, moderately elevated in light rare-earth elements (REE), and slightly depleted in Th (Fig. 4.6). The Caribou Lake gabbro has variable Nb anomalies and typically negative Eu anomalies, whereas leucoferrodiorite samples generally exhibit small positive Nb anomalies and variable Eu anomalies; both likely are related to the plagioclase effect. In the most evolved leucoferrodiorite samples there is a slight concave shape to the heavy rare-earth elements (HREE). The chondrite-normalized multi-element pattern for the chill margin sample displays neither a Nb or Eu anomaly and is situated approximately at the divide between the Caribou Lake gabbro and the leucoferrodiorite. Ni and Cr contents in the chill margin sample of the Caribou Lake gabbro are low, 27 and 58 ppm respectively.

The Whiteman granitic group and Hearne granitic group have similar chondrite-normalized multi-element patterns (Fig. 4.6), but have slight variations. Relative to Whiteman granitic group the Hearne granitic group has elevated Th and larger negative Nb and Eu anomalies. Rocks of the Whiteman granitic group generally exhibit small Zr

Figure 4.3 - Major element discrimination diagrams for rocks of the western lobe: (a) AFM diagram (modified from Irvine & Barager, 1971), (b) $\text{Na}_2\text{O} + \text{K}_2\text{O}$ vs SiO_2 (TAS) diagram (modified from Cox *et al.*, 1979), (c) Shand's index (modified from Maniar & Piccoli, 1989).

Figure 4.4 - Granitoid classification schemes from Frost *et al.* (2001): (a) $\text{FeO}/(\text{FeO} + \text{MgO})$ vs SiO_2 showing the boundary between ferroan plutons and magnesian plutons, (b) $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ vs SiO_2 showing the ranges of alkali, alkali-calcic, calc-alkalic, and calcic rock series. Symbols as in Figure 4.3.

Figure 4.5 - Selected oxides vs SiO_2 for units of the western lobe.

Figure 4.6 - Chondrite-normalized multi-element patterns for units of the western lobe: (a) Caribou Lake gabbro (CLG) and leucoferrodiorite (LFD), (b) Whiteman granitic group (WGG), (c) Hearne granitic group (HGG). Chondrite normalization values are from McDonough and Sun (1995).

anomalies and have a slight concave up HREE pattern. On average the absolute concentration of REE is higher in the Hearne granitic group than the Whiteman granitic group.

4.5.2 “Feeder” dyke

Figure 4.7, a chondrite-normalized multi-element geochemical variation diagram, compares the feeder dyke to other local mafic units, (i.e., Hearne diabase dykes and the aphanitic diabase dykes that crosscut the feeder dyke). Patterns of the feeder dyke has flatter HREE patterns than samples of the Caribou Lake gabbro (Fig. 4.6), and more closely resembles those of the Hearne diabase swarm (Fig. 4.7). Patterns of the crosscutting aphanitic diabase dykes are distinct from the Hearne diabase swarm, feeder dyke, and Caribou Lake gabbro, exhibiting a steeper middle to heavy REE patterns (Fig. 4.7).

4.5.3 Nd isotopes

The Nd isotope data on 19 whole rock samples is presented in Table 4.2. Epsilon Nd (ϵ_{Nd}) values calculated using an average initial age (i) of 2182 Ma for all samples of the Blatchford Lake intrusive suite. ϵ_{Ndi} values for samples of Caribou Lake gabbro range from +1.6 to +3.4, from +0.5 to +2.37 in the leucoferrodiorite, and chill margin sample 403A has an ϵ_{Ndi} of +0.6. Samples of the Whiteman granitic group range from +0.83 to -2.97, and the Hearne granitic group ranges from -0.18 to -1.65. There a strong negative trend in the plot of SiO_2 versus ϵ_{Ndi} , systematically decreasing from the Caribou Lake gabbro, leucoferrodiorite, Whiteman granitic group, to the Hearne granitic group (Fig.

Figure 4.7 - Chondrite-normalized multi-element patterns of the Hearne diabase swarm, feeder dyke and cross-cutting diabase dykes. Chondrite normalization values are from McDonough and Sun (1995).

Rock type	Sample	Nd (ppm)	$^{143}\text{Nd}/^{144}\text{Nd}_{\text{meas}}$	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_i$	ϵ_{Nd}^T
CLG - chill margin	403A	22.25	0.511879	5.16	0.1416	0.511879	0.65
CLG - leucoferrodiorite	1077B	47.98	0.511714	10.38	0.1308	0.509834	0.46
CLG - fg to mg gabbro	1075C	5.59	0.512292	1.54	0.1670	0.509892	1.58
CLG - leucoferrodiorite	1078B	47.24	0.511681	10.03	0.1284	0.509836	0.49
CLG - leucoferrodiorite	420A	34.10	0.511801	7.34	0.1301	0.509932	2.37
CLG - ol-rich gabbro	1079B	12.00	0.512063	2.93	0.1476	0.509942	2.56
CLG - peridotite	1076A	4.47	0.512043	1.06	0.1433	0.509984	3.39
CLG - pyroxenite	1076B	8.79	0.512005	2.06	0.1414	0.509973	3.17
HGG	1172A	107.45	0.511523	21.28	0.1197	0.509802	-0.18
HGG	449A	59.82	0.511784	13.68	0.1382	0.509797	-0.27
HGG	483A	62.37	0.511431	12.23	0.1186	0.509727	-1.65
WGG	1076C	77.89	0.511517	14.91	0.1157	0.509853	0.83
WGG	1102A	67.92	0.511453	12.88	0.1146	0.509806	-0.10
WGG	1080A	67.05	0.511358	12.07	0.1088	0.509794	-0.33
WGG	1113A	38.09	0.511284	7.12	0.1130	0.509660	-2.97
WGG	369A	57.15	0.511359	10.63	0.1125	0.509742	-1.34
WGG	404A	69.89	0.511590	14.09	0.1218	0.509839	0.55
WGG	429A	65.55	0.511527	13.06	0.1205	0.509796	-0.30
WGG	1128A	69.83	0.511452	12.91	0.1117	0.509846	0.69
Feeder dyke	1197A	31.86	0.512287	7.37	0.1398	0.511800	-0.39

Note: Epsilon Nd values calculated assuming an age (T) of 2182 Ma for all samples. Sm and Nd concentrations by isotope dilution. CLG, Caribou Lake gabbro; HGG, Hearne granitic group; WGG, Whiteman granitic group.

Table 4.2 - Nd isotope compositions of rocks of the western lobe.

4.8). Three samples—two from the Whiteman granitic group (369A and 1113A) and one from the Hearne granitic group (483A)—have markedly lower ϵ_{Nd} than the remainder of their group, and deviate from the above described SiO_2 versus ϵ_{Nd} trend. The feeder dyke has an ϵ_{Nd} of -0.4.

4.6 Mineral Compositions and thermobarometry

While useful for characterizing petrogenetic and mineralization processes, to date there has been no attempt to constrain the depth of emplacement of units in either the eastern or western lobes of the Blatchford Lake intrusive suite. This is partially attributed to the distinct dearth of barometers applicable to peralkaline rocks, such as those that comprise the eastern lobe where most investigations of the Blatchford Lake intrusive suite have focused.

Chilled margins on the top and bottom of the Hearne granitic group, fine-medium grained sub-porphyritic textures and sill morphologies of the phases in the Whiteman granitic group and Hearne granitic group suggest a shallow emplacement. To test this qualitative evidence we employ the Al-in-hornblende barometer on the metaluminous granitic rocks of the western lobe. Results of the Al-in-hornblende barometer using the Schmidt (1992) calibration are listed in Table 4.3. Plagioclase-hornblende thermometry was also applied to the same rocks. Results from calibrations using the equilibria of edenite + albite = richerite + anorthite (Anderson & Smith, 1995, Holland & Blundy, 1994) are reported in Table 4.3.

Amphibole rim compositions from Whiteman granitic group rocks yielded pressure estimates of 3.8 – 4.5 kbar (average 4.1 ± 0.2 kbar) according to the Schmidt

Figure 4.8 - ϵ_{Ndi} vs SiO_2 , initial ratios calculated for an age of 2182 Ma. Error bar represents 2σ error of ϵ_{Ndi} (± 0.3). Symbols as in Figure 4.4.

(1992) calibration. The temperature-corrected calibration of Anderson & Smith (1995) using the second temperature calibration of Holland and Blundy (1994; compare Anderson, 1996) yielded pressure estimates from 3.5 to 4.4 kbar (average 3.9 ± 0.3 kbar) at temperatures from 670 to 723°C (average 689 ± 19 °C).

Hearne granitic group rocks yielded pressure estimates of 4.3 – 4.9 kbar (average 4.5 ± 0.2 kbar) according to the Schmidt (1992) calibration. The temperature-corrected calibration of Anderson and Smith (1995) yielded pressure estimates from 3.8 to 4.9 kbar, (average 4.4 ± 0.4 kbar) at temperatures from 645 to 719°C (average 686 ± 26 °C). Uncertainty in pressure and temperature is reported as 1σ precision error as in Anderson and Smith (1995).

4.7 Discussion

4.7.1 Feeder dyke

In his argument for the feeder dyke belonging to the Caribou Lake gabbro, Davidson (1978) assumed that the NE-trending aphanitic diabase dykes that crosscut the feeder dyke are part of the Hearne diabase swarm. However, work by Mumford *et al.* (chapter three) indicates that multiple generations of diabase dykes exist in the Blatchford Lake region that trend at $\sim 060^\circ$. In this study we have shown that the aphanitic diabase dykes that cross-cut the feeder dyke are chemically distinct from the Hearne diabase dykes (Fig. 4.9), thus contradicting Davidson's argument regarding the cross-cutting diabase dykes.

ϵ_{Nd} values of the Caribou Lake gabbro range from +1.6 to +3.4, whereas the feeder dyke has a value of -0.4 (Table 4.2), consistent with values for the Hearne diabase

(calculated at 2182 Ma) swarm which range from -0.1 to -1.1 (chapter three). Mapping done during this study, and work done by Davidson (1972, 1978) indicate that there is an overall decrease in abundance of Hearne diabase dykes around the feeder dyke. This observation could be explained by the presence of a pre-existing structural weakness at the time of emplacement that concentrated the melt from the Hearne diabase swarm into a single dyke. This could explain the localized absence of Hearne diabase dykes around the feeder dyke, and account for its increased width. While originally considered to be an extension of the Caribou Lake gabbro, the geochemical signatures, northeast-trend of the dyke, and the absence of Hearne diabase dykes in the immediate vicinity, suggest that the feeder dyke is not related to the Blatchford Lake intrusive suite, but rather is part of the Hearne diabase swarm. The steeper patterns middle to heavy REE patterns in the feeder dyke could indicate the presence of garnet in the source, suggesting that the feeder dyke represents deeper melting than the rest of the Hearne diabase swarm.

4.7.2 Western lobe geochemical relations

Before discussing the source and petrogenesis of the western lobe phases it is important to ensure that all phases are in fact cogenetic. The field relations, continuous trends in geochemical variation diagrams, systematic trends in Nd isotopic ratios, and consistent U-Pb radiometric ages, suggest that the Hearne granitic group, Whiteman granitic group, and Caribou Lake gabbro are cogenetic.

The chill margin sample of the Caribou Lake gabbro (sample 403A) has been considered to be the closest representation of the bulk liquid composition of the Caribou Lake gabbro. In geochemical variation diagrams, the major and trace element

Sample	429A	429A	429A	429A	429A	429A	429A	444A	444A	444A	444A	444A	444A	444A	444A
Unit	1-amp1	1-amp2	2-amp1	3-amp1	3-amp2	4-amp1	4-amp2	1-amp1	1-amp2	2-amp1	2-amp2	3-amp1	3-amp2	4-amp1	5-amp1
	WGG	WGG	WGG	WGG	WGG	WGG	WGG	HGG	HGG	HGG	HGG	HGG	HGG	HGG	HGG
SiO ₂	40.08	39.80	39.86	40.60	40.52	39.79	40.44	39.61	39.44	39.81	39.35	39.58	39.68	39.77	38.68
TiO ₂	1.55	0.97	1.63	1.38	1.14	2.04	1.90	1.36	1.40	1.37	1.67	1.19	1.18	1.34	1.31
Al ₂ O ₃	7.39	8.11	7.78	7.71	7.83	7.66	7.73	8.10	8.32	7.90	8.07	8.34	7.91	8.00	8.44
FeO	29.87	30.10	29.86	28.89	29.28	30.06	30.41	31.44	31.24	30.92	30.58	30.62	30.88	30.97	30.64
MgO	2.61	2.22	2.26	2.99	3.03	2.17	2.31	1.52	1.55	1.46	1.54	1.69	1.80	1.54	1.50
MnO	0.77	0.75	0.71	0.69	0.69	0.74	0.77	0.70	0.65	0.72	0.73	0.61	0.68	0.66	0.64
CaO	10.09	10.38	10.74	10.37	10.40	10.14	10.15	10.15	10.30	10.08	10.24	10.35	10.12	10.11	9.98
Na ₂ O	2.18	1.89	2.21	1.87	1.95	2.27	2.26	1.97	2.04	2.08	2.03	2.06	2.04	2.10	2.12
K ₂ O	1.21	1.47	1.27	1.33	1.28	1.31	1.29	1.46	1.46	1.46	1.64	1.49	1.37	1.39	1.53
F	0.53	0.51	0.53	0.52	0.62	0.48	0.60	0.35	0.49	0.52	0.51	0.40	0.59	0.36	0.40
Cl	0.40	0.65	0.49	0.46	0.28	0.51	0.53	1.04	0.92	0.89	0.75	1.03	0.90	0.85	1.06
Total	96.70	96.85	97.37	96.80	97.03	97.16	98.38	97.72	97.80	97.23	97.12	97.37	97.16	97.08	96.30
<i>Mole fraction of corresponding plagioclase</i>															
XAb	90	89	87	90	87	87	93	88	92	94	92	88	87	85	92
XAn	9	10	12	9	9	11	6	10	6	5	7	11	12	13	6
Ref.	<i>Pressure estimates (kbar)</i>														
1	3.82	4.47	4.16	4.04	4.13	4.07	4.04	4.47	4.66	4.31	4.48	4.70	4.32	4.39	4.90
2	3.73	4.43	3.77	4.00	4.04	3.49	4.08	4.11	4.76	4.54	4.45	4.49	3.86	3.84	4.93
	<i>Temperature estimates (°C)</i>														
3	684.9	679.4	708.7	679.0	684.5	722.3	670.3	705.4	664.2	645.3	677.7	694.1	713.3	719.2	672.3
References: 1, hornblende barometer (Schmidt, 1992); 2, hornblende barometer (Anderson & Smith, 1995); 3, edenite-albite-richertite-anorthite thermometer (Holland & Blundy, 1994)															

Table 4.3 - Crystallization conditions based on hornblende and plagioclase compositions.

composition of the chilled margin sample is transitional between samples of the Caribou Lake gabbro and some of the leucoferrodiorite, consistent with crystal fractionation and the formation of basal cumulates. However, the Nd isotopic composition of the chilled margin sample ($\epsilon_{\text{Nd}} = +0.6$) is significantly lower than the units of the Caribou Lake gabbro that clearly represent basal cumulates, (i.e., pyroxenite and peridotite with $\epsilon_{\text{Nd}} = +3.2$ to $+3.4$, respectively). In general, ϵ_{Nd} values are higher in Caribou Lake gabbro samples that have high modal concentrations of pyroxene and/or olivine (i.e., cumulitic phases) relative to uniform, fine- to medium-grained gabbroic phases. The distribution of cumulate layers sandwiched between units of massive gabbro indicates that the Caribou Lake gabbro did not differentiate in situ, but rather is a composite intrusion derived from multiple pulses of melt. The distinct rim formed on clinopyroxene crystals of the Caribou Lake gabbro indicates a chemical disequilibrium (Fig. 4.2b), likely reflecting a change in the bulk composition of melt that it crystallized from. We suggest that the cumulate layers are formed from upwelling phenocryst-rich magmas that interacted with country rocks during ascent. Upon emplacement, gravity induced settling of dense mafic phenocrysts formed cumulate layers. Due to the strong contrast between the rates of diffusion of Nd in mineral phases relative to the speed of ascent of magma, any phenocrysts in the ascending magma would retain the Nd isotopic signature of the parental chamber during their transport. However, the magma transporting them would be susceptible to crustal contamination during ascent and emplacement. This mechanism could account for the systematic variation of ϵ_{Nd} between basal cumulate layers and rocks of the Caribou Lake gabbro that crystallized *in situ*. This also suggests that chill margin samples from the Caribou Lake gabbro are not necessarily representative of the

parental melt from which the Caribou Lake gabbro crystallized, but may have been influenced by crustal input during transport.

Based on the lack of evidence for *in situ* differentiation, Davidson (1982) suggested that phases of the western lobe represent separate intrusions derived from fractionation at depth. The 4 – 4.5 kbar estimates for the crystallization of the western lobe granites indicate a mid-crustal depth of emplacement. The isotopic and mineralogical evidence presented above, in addition to the compositionally discrete nature of phases within the western lobe, supports the existence of a deeper, less crustally contaminated parental system. Based on this evidence, the existence of a mid-crustal parental system is presumed. The depth of this mid-crustal chamber is relatively unconstrained, but the presence of significant Eu anomalies in western lobe rocks suggests that plagioclase was a stable crystallizing phase, indicating a maximum depth of ~0.8 GPa (Borghini *et al.*, 2010).

Phases of the Caribou lake gabbro clearly represent the least differentiated rocks in the Blatchford Lake intrusive suite, however several geochemical features suggest they are already significantly evolved relative to a primary/primitive melt, including: enrichment in iron relative to magnesium (Davidson, 1982), moderate to low concentrations of compatible elements (e.g., Ni, Cr), and moderate silica-contents of chill margin and fine to medium-grained gabbroic rocks. While it is evident that due to its evolved nature, rocks of the Caribou Lake gabbro do not represent the parental melt composition, Nd isotopes and general geochemical signatures can be used to infer limited information regarding the source. Based on the presented geochemistry, we suggest that source rocks of the western lobe were enriched in LILE and HFSE, and had a time-

integrated source that was depleted of Nd relative to Sm (i.e., positive ϵ_{Nd}). The degree of LILE-HFSE enrichment and positive ϵ_{Nd} isotopic ratios parallels rocks in the eastern lobe (chapter two). In their study of the petrogenesis of the eastern lobe Mumford *et al.* (chapter two) demonstrated that rocks in this particular geologic setting, exhibiting these same geochemical signatures are likely mantle derived melts. The depleted isotopic signature (relative to chondrite uniform reservoir) and strong enrichment in LILE and HFSE could be attributed to a process involving the metasomatism of a previously depleted mantle source prior to melting, such as the process described in Hawkesworth *et al.*, (1984), Pilet *et al.*, (2011), and Pilet *et al.*, (2008). Based on the degree of silica saturation and enrichment in alkalis and incompatible elements of the most primitive rock exposed in the western lobe, we propose that the parental melt resembled an alkali olivine basalt to tholeiitic basalt, and was derived by melting a mantle source that had a time-integrated enrichment in Sm relative to Nd that was metasomatized shortly before melting.

Field relations combined with major and trace element geochemistry indicate that the western lobe rocks show a differentiation trend, evolving from Caribou Lake gabbro, to leucoferrodiorite, to Whiteman granitic group, to the Hearne granitic group. The strong negative correlation between ϵ_{Nd} values and SiO_2 (Fig. 4.8) in the western lobe samples indicates that differentiation was influenced by crustal assimilation in addition to fractional crystallization. The three high silica samples of the Whiteman granitic group and Hearne granitic group that exhibit ϵ_{Nd} values < -1 deviate from the negative trend formed by the other samples, and also exhibit lower REE, Ga, Zr, Nb and higher Pb concentrations. We interpret this as evidence of localized crustal contamination. While

every attempt was made to retrieve inclusion free representative samples during field work, it is possible that these samples contained small xenolithic inclusions.

A common technique used to investigate igneous systems involves numerically modeling chemical differentiation in order to constrain various aspects of an evolving melt, such as: degree of crustal assimilation, identifying potential assimilants, degree of crystal fractionation, fractionating mineral assemblages. However, modeling of this nature is particularly problematic in systems such as the Blatchford Lake intrusive suite, where large compositional changes make modeling calculations ineffective due to large errors associated with selecting appropriate partition coefficients and crystallizing mineral assemblages. Modeling of the western lobe rocks is further hampered by the fact that many of the rocks do not represent liquid compositions. One potential method of constraining the differentiation of western lobe rocks involves modeling changes in the Nd isotopic composition. Nd isotopes are largely unaffected by igneous processes, including crystal fractionation and the formation of cumulates, yet are strongly influenced by crustal addition. Thus they can be used to estimate the degree of crustal contamination. In order to model the extent of crustal input it is first necessary to estimate compositions of both the parental magma and potential crustal assimilants. As we have established above, the exact composition of the parental melt is unknown, but we do hypothesize that it is an isotopically depleted, mantle derived melt, and therefore we will use a depleted mantle composition as an approximation. Potential local crustal contaminants include Archean granitoids (Morose and Defeat suite) and Burwash Formation metasediments. Given that the parental magmatic system likely resided at mid- to lower crustal depths, we will estimate the influence of lower crustal rocks using the

Figure 4.9 - (A) Plot of ϵ_{Nd} vs time of crystallization of western lobe rocks, the evolution of the depleted mantle¹ (Goldstein *et al.*, 1984), Burwash Formation (Yamashita & Creaser, 1999), plutonic rocks of the Morose (Mumford *et al.* 2013) and Defeat suite granodiorite (Yamashita *et al.*, 1999), and Archean Kam group rocks (Cousens, 2000). (B) ϵ_{Nd} vs Th/Yb, Curves are labeled with their respective end-members and demonstrate bulk mixing trends (symbols along curves in 10% increments). End-member values are summarized in Table 4.4. Symbols as in Figure 4.3.

Variable	Depleted mantle	Kam group*	Burwash formation*	Morose granite	Defeat granodiorite*
Yb (ppm)	0.401	2.762	1.66	0.441	0.569
Th (ppm)	0.0137	1.06	7.00	16.445	5.39
Nd (ppm)	0.713	10.18	22.79	24.89	12.55
$\epsilon\text{Nd}_{(21\&2)}$	4.8**	0.7	-5	-3	-2.9
Reference	Salter & Strack (2004)	Cousens (2000)	Yamashita & Creaser (1999)	Mumford et al. (2013)	Mumford et al. (2010)
* signifies average					
** Goldstein et al. (1984)					

Table 4.4 - Variables used to model mixing curves in Figure 4.9.

composition of Kam group volcanic rocks (Cousens, 2000). Figure 4.9a describes the variation of ϵ_{Ndi} with time for rocks of the western lobe relative to these potential crustal contaminants. However, in order to effectively discriminate between contaminants we must model ϵ_{Ndi} against another variable. Figure 4.9b describes the bulk mixing trends between depleted mantle and crustal rocks, using ϵ_{Ndi} versus Th/Yb as a proxy for crustal contamination. Similar partition coefficients between Th and Yb cause the ratio to have a low sensitivity to fractional crystallization, but the strong affinity of Th to upper crustal rocks makes it very responsive to crustal input. While we cannot directly model AFC curves, it should be noted that the effect of fractional crystallization would shift these bulk mixing curves to slightly higher Th/Yb ratios. Based on these features we suggest that Kam group rocks are a potential contaminant early in the evolution of the western lobe, but that local Archean granitoids (dominated by Morose granite) are the most probable source of crustal input in evolved phases. While mixing curves offer only a crude estimate, the degree of crustal input appears to be on the order of 5-30 %.

4.7.3 Petrogenetic link with the eastern lobe

We have presented evidence for a cogenetic relationship between phases of the western lobe; however, its relationship to the eastern lobe remains tenuous. A link between the two lobes was first proposed by Davidson (1978). He later noted a discontinuity in compositional trends between the western and eastern lobes and postulated separate origins (Davidson, 1982). While Davidson (1982) suggested that traditional AFC processes governed variation between phases within individual lobes, he

did not suggest a mechanism that could account for a petrogenetic link between the two lobes.

In order to provide a basis for a petrogenetic link between the two lobes it must be shown that the two lobes share a similar source and a process that can account for the formation of separate silica-saturated and undersaturated parental melts from this source.

The following indicate a petrogenetic link between the two lobes:

- (1) concentrated geographic distribution;
- (2) U-Pb radiometric ages that indicate the two lobes are roughly coeval (chapter two);
- (3) Similar range and composition of Nd isotopic ratios;
- (4) major and trace element compositional similarities (i.e., A-type granites, similar chondrite-normalized multi-element patterns).

As described above, chemical compositions of rocks from the western lobe form a punctuated, yet near continuous differentiation sequence from sub-alkaline/alkaline ultramafic cumulates to metaluminous granites. The chemical progression and overall silica-saturated nature of the Caribou Lake gabbro, leucoferrodiorite, Whiteman granitic group and Hearne granitic group indicate a liquid line of descent approaching the silica-oversaturated granite minimum. Mumford *et al.* (chapter two) have shown that the parental magma for the eastern lobe was strongly silica-undersaturated. Liquidus phase relations in Petrogeny's residua system (Ne-Ks-Q-H₂O) imply that melts either differentiate towards the granite minimum (forming silica-saturated rocks) or the nepheline syenite minimum (forming silica-undersaturated rocks), with the two minima separated by a thermal barrier (Bowen, 1937). The transition from silica-saturated to

undersaturated rocks, although relatively rare, has been documented in other systems (Foland *et al.*, 1993, Harris *et al.*, 1999, Marks *et al.*, 2004a, Riishuus *et al.*, 2008), and also occurs at a much smaller scale in the eastern lobe (chapter two). Generally the petrogenetic basis for explaining the transition is dependent on a silica-undersaturated parental melt that is subsequently contaminated by silica-rich country rocks (for a complete description of these processes see Riishuus *et al.*, 2008). However, in most systems where this model is employed the transition is generally from granites to nepheline syenites. In these cases, as well as in the eastern lobe (chapter two), a silica-undersaturated parental melt is often identified based on a negative correlation between differentiation index (e.g., SiO_2) and indicators of crustal contamination (e.g., Nd, Sr, Hf isotopes). The differentiation trends presented in this paper (i.e., Figs 4.5, 4.6, 4.8, 4.9) do not support a model of this kind. Thus the thermal barrier of Petrogeny's Residua System rules out the possibility that the peralkaline eastern lobe granite/syenite bodies represent final fractionates from the system that generated the western lobe granites.

While the nature of the relationship between the two lobes is unresolved, it is clear that at some point during differentiation the western and eastern lobes evolved via separate evolutionary pathways. The possible relationships between the two lobes can be sub-divided into two groups: (1) they formed from distinct and separate sources and have no petrogenetic relationship, or (2) they are derived from the mechanical splitting of a single primary/primitive melt, and individual fractions evolved discretely due to external factors. As proposed above, the western lobe rocks likely formed from parental alkali olivine basalt to tholeiitic basalt, whereas the eastern lobe is postulated to have formed from a nephelinitic to basanitic composition (chapter 2). While the chemical division

between the two estimated parental compositions of the eastern and western lobes is significant, it does not preclude the possibility that the two lobes are petrogenetically related. With this premise, we propose three mechanisms with the potential to create derivative peralkaline silica undersaturated and tholeiitic silica saturated melts from a single source, and evaluate them.

These three suggested mechanisms consist of: (1) partial melting the same source to different degrees, or (2) at different depths (Kushiro, 1968), or (3) the reaction between host peridotite and silica undersaturated melts formed by melting metasomatic veins in metasomatized lithospheric mantle (Foley, 1992, Pilet *et al.*, 2011, Pilet *et al.*, 2008).

The degree of partial melting has a significant effect on the major and trace element composition in mantle derived melts. Low-degree partial melts are typically silica-undersaturated and have elevated concentrations of incompatible elements, (e.g., REE). Increasing degrees of partial melting causes the ensuing melt to shift from silica-undersaturated to oversaturated, and this transition is accompanied by a general decrease of incompatible element abundances, (i.e., flat REE patterns of MORB-type magmas). While the degree of silica saturation is variable in rocks from both the eastern and western lobes their incompatible element patterns are parallel to sub-parallel (chapter two), indicating that their parental melts are not simply related by different degrees of partial melting.

The effect of pressure on eutectic melt compositions operates in response to changes in the stability of major mineral phases and their propensity to melt at various pressures (i.e., albite to jadeite + quartz). Kushiro (1968) described the changing position of the eutectic minimum in a volatile free Ne-Fo-Q system, in response to increasing

pressure from 1 atm to 3 GPa (Fig. 4.10). Results from this simplified system indicate that the eutectic moves with increasing pressure from tholeiitic silica-saturated compositions to nepheline-bearing alkaline compositions. Whereas this mechanism is capable of producing both the parental compositions, the actual application presents some difficulties. While oversimplified, we will use Kushiro's (1968) experiments on compositions of eutectic melts with pressure to illustrate this. In order to create separate tholeiitic silica-saturated nepheline-bearing alkaline melts using the system illustrated in Figure 4.10, the minimum pressure variance is on the order of 1 GPa (~40 km). The coeval nature of the Blatchford Lake intrusive suite suggests that both lobes formed at roughly the same time, and that their parental systems also coexisted. The essentially simultaneous melting of two distinct regions, separated by 40 km in a relatively vertical column poses significant geometric and thermodynamic problems, and is assumed to be geologically unrealistic and overly complex relative to other potential mechanisms. A more practical possibility would be the adiabatic melting of source rocks entrained in an upwelling plume, permitting the melting of source rocks at two distinct depths. Vertical velocities estimated for mantle plumes indicate speeds of 100 km/Myr in the upper mantle (Steinberger & Antretter, 2006) and could fit into the known time constraints of the two lobes. One issue using this model of adiabatic melting of material within a mantle plume relates to the depleted Nd isotopic signature of the western lobe. As previously demonstrated, the source for the western and eastern lobe is likely metasomatized depleted mantle. While recycled metasomatized lithospheric mantle is assumed to be injected into the convecting mantle by subduction or delamination and brought up in plumes, the degree of isotopic depletion in the western lobe permits only a short interval

Figure 4.10 - Phase diagram illustrating the change in eutectic composition with increasing pressure (modified from Kushiro, 1968). All but the low ends of cotectic curves have been removed for clarity. E_c = eutectic melt composition.

(10's of Ma) between metasomatism and melting. However, the fastest estimates for the recycling of crustal material are on the order of 500 Ma (Sobolev, 2011). The juxtaposition of these two different time scales suggest that melting of entrained metasomatized lithospheric mantle within a plume is highly improbable.

Recent work by Pilet *et al.* (2011, 2008) as well as work by previous authors (Foley, 1992, Francis, 1976, Francis & Ludden, 1990) suggests that the melting of hydrous amphibole-bearing metasomatic veins, common in lithospheric mantle xenoliths, can reproduce the range of major, trace element, and isotopic compositions found in alkaline rocks. These metasomatic veins are interpreted to be cumulate products formed during fractionation crystallization of low-degree, volatile-rich partial melts from H₂O+CO₂-bearing mantle peridotite (Pilet *et al.*, 2011). The ascent of these low degree partial melts and their subsequent reaction, cooling, and fractional crystallization within the cooler lithospheric mantle form veins with a continuum of phase assemblages. The assemblages in these veins range from anhydrous (dominated by clinopyroxene + garnet ± olivine ± orthopyroxene) to anhydrous (dominated by amphibole + clinopyroxene ± phlogopite ± orthopyroxene) (Pilet *et al.*, 2011). The formation of these veins also influences the composition of surrounding peridotite, (i.e., metasomatic halo around veins; Bodinier *et al.*, 1990; Francis, 1976; Nielson & Noller, 1987). The generation of these metasomatic veins (and/or their subsequent melting) can be driven by either lithospheric extension causing upwelling asthenosphere (Thompson *et al.*, 2005, Wass & Rogers, 1980) or by small intraplate plumes (Granet *et al.*, 1995, Hoernle *et al.*, 1995). In both cases the metasomatic veins are derived from an asthenospheric source and carry the isotopic signature of their source rocks. Others have proposed that melts from

metasomatic veins can react with host peridotite (lithospheric mantle) to create a range of compositions (Foley, 1992, Lundstrom *et al.*, 2000). Pilet (2008) experimentally demonstrated that this reaction is likely to occur and can produce a continuum of melts from nephelinite to alkali olivine basalt and tholeiites. Francis & Ludden (1990) first proposed this model to describe the development of a Fort Selkirk volcanic complex in the Yukon, Canada. Thus we suggest that this represents a geologically feasible mechanism to form a petrogenetic link between the western and eastern lobes of the Blatchford Lake intrusive suite. Small variations in the speed of ascent and crustal residency times of the two parental melts (and their resulting magmatic systems) could explain the observed field relations of the two lobes, i.e., western lobe crosscut by the eastern lobe.

In summary, field relations and U-Pb radiometric dating of the eastern and western lobes indicate that the two lobes of the Blatchford Lake intrusive suite are roughly coeval. While chemically distinct, strong major, trace element and isotopic compositional similarities exist between the two lobes. This evidence coupled with the proposed mechanism for the generation of separate peralkaline silica undersaturated and tholeiitic silica saturated melts (described above), substantiate Davidson's (1978) hypothesis that the two lobes are genetically linked.

4.8 Conclusions

Results from our study indicate that the phases in the western lobe of the Blatchford Lake intrusive suite represent discrete punctuated pulses from an unexposed deep-seated parental system. Depth of emplacement is estimated at 4 – 4.5 kbar.

Differentiation within the western lobe was largely controlled by fractional crystallization and crustal assimilation; probable contaminants include Kam group source rocks and Archean granitoids. Trace-element and radiogenic isotopic signatures suggest a depleted mantle source (lithosphere), that was metasomatized shortly prior to melting by an enriched source (asthenosphere). Reaction between the melts of metasomatic vein material and host depleted peridotite is proposed as a possible mechanism to account for the wide spectrum of magma types observed in the Blatchford Lake intrusive suite. This process combined with observed field relations, geochronology, and major, trace and radiogenic isotope geochemistry, demonstrates a genetic link between the two lobes.

5 Chapter: Implications for the formation of the Southwest Slave magmatic province

5.1 Introduction

The Blatchford Lake intrusive suite is the largest in a group of alkaline/subalkaline intrusions in the southern Slave craton emplaced at *ca.* 2180 Ma (Fig. 1.1, Table 1.1). These intrusions are collectively referred to as the Southwest Slave magmatic province (SWSMP, Bleeker & Hall, 2007, Buchan *et al.*, 2010) and include the Big Spruce Lake alkaline intrusion, Blatchford Lake intrusive suite, Dogrib diabase dykes, Duck Lake sill, and the Squalus Lake intrusion. While recent radiometric dating suggests that it is significantly older (2217 ± 4 Ma Mumford *et al.*, 2012b), a relationship between the 31 km long Simpson Island dyke of the East Arm of Great Slave Lake (Fig. 1.1) and the SWSMP has also been proposed based on substantial geochemical similarities (Badham, 1979, Mumford *et al.*, 2012a, Mumford *et al.*, 2012b).

Data and interpretations presented in chapters two and four describe the petrogenesis of the Blatchford Lake intrusive suite and provide constraints on the composition of its mantle source and parental magma types. These petrogenetic considerations and constraints can be used to gain insight into the regional geology of the southern Slave Craton, in particular, early Paleoproterozoic magmatism. This chapter will compare the geology and geochemistry of other intrusions in the SWSMP and the Simpson Island dyke to the Blatchford Lake intrusive suite. This comparison will allow us to further our understanding of fundamental questions regarding whether the processes responsible for the formation of the Blatchford Lake intrusive suite can also explain the

geographic distribution, range of magma compositions, and punctuated timing of the SWSMP.

5.2 Geology and geochemistry of the Southwest Slave Magmatic Province

Brief field visits were made by the author to all intrusions of the SWSMP (and the Simpson Island Dyke) during the 2009-2011 field seasons. During these visits key field relations were confirmed, and representative samples of major rock types were collected. Samples described in this chapter, unless otherwise stated, were collected by the author and analysed according to the methodology described in section 1.6. While temporally distinct, the Simpson Island dyke will be reviewed and evaluated with the intrusions of the SWSMP for evidence of a potential link. Brief geological descriptions of the intrusions are summarized below. Major and trace-element data are presented in Appendix A.4, and Nd isotopic data are presented in Table 5.1.

5.2.1 *Big Spruce Lake alkaline intrusion*

The Big Spruce Lake alkaline intrusion, located approximately 150 km northwest of Yellowknife, is the second largest multi-phase intrusion in the SWSMP. Rock types consist of silica-saturated to oversaturated gabbros, diorites and syenites, as well as silica-undersaturated varieties such as nepheline syenites and carbonatites. The Big Spruce Lake alkaline intrusion was the subject of two Ph.D. theses; work by Martineau (1970) focused on the petrology of the intrusion, and Cavell (1986) concentrated on the petrogenesis and geochronology (Cavell & Baadsgaard, 1986) of the intrusion.

5.2.2 *Dogrib diabase dykes*

The ENE-trending Dogrib diabase dykes occur around Yellowknife bay, and extend to the northeast for more than 180 km. They are typically dark grey, fine-grained, and have widths on the order of 75 m.

5.2.3 *Duck Lake sill*

The Duck Lake sill (also known as the Duck Lake intrusive sheet) is a mafic to ultramafic body located 3 to 4 km east of Yellowknife, and is exposed over a strike length of 12 km, and outcrop widths locally reach 500 m. It comprises an upper quartz gabbro and a lower peridotite; these two phases are present in roughly equal proportions and separated by a narrow transitional zone. A more detailed description of the Duck Lake sill is offered by Gibbins (1987).

5.2.4 *Squalus Lake intrusion*

The Squalus Lake intrusion is located approximately 105 km NNE of Yellowknife. Discovered in 1991 during regional mapping, the multiphase intrusion was later the focus of an undergraduate thesis (Cairns, 1993). The intrusion largely consists of leucocratic to melanocratic alkali feldspar syenite, although crosscutting carbonatite dykes have been noted (Mumford *et al.*, 2012a).

5.2.5 *Simpson Island dyke*

The Simpson Island dyke (also known as the Easter Island dyke) occurs in the islands of the East Arm of Great Slave Lake. It outcrops over a length of 31 km and a

maximum exposed width of approximately 125 m. The near vertical dyke gradually changes eastward along strike from an olivine gabbro to an albite syenite. Additional detailed descriptions of the dyke are available from Badham (1979), Burwash (1978), and Mumford *et al.* (2012b).

5.2.6 *Geochemistry of the SWSMP and the Simpson Island dyke*

Many of the units of the SWSMP are composite intrusions that often exhibit wide mineralogical and compositional ranges, (e.g., Blatchford Lake intrusive suite). With the exception of the Dogrib diabase dykes all intrusions are assumed to exhibit *in situ* differentiation to some degree, and likely do not represent true liquid compositions. The carbonatite samples from Big Spruce Lake alkaline intrusion and Squalus Lake intrusions exhibit strong compositional differences from the rest of their respective intrusions, including strong Sr, Ba, and REE enrichment.

All of the examined intrusions in the SWSMP are alkaline in character with the exception of the western lobe of the Blatchford Lake intrusive suite and the Dogrib diabase dykes, which are subalkaline (Fig. 5.1). Using the classification scheme of Frost *et al.* (2001) granitoids in the SWSMP are dominantly ferroan type, alkali to alkali-calcic rocks that are largely metaluminous with subordinate number that are peralkaline (Fig. 5.2). Extended chondrite-normalized trace and REE plots were used to compare incompatible element distributions between intrusions (Fig. 5.3). The eastern lobe of the Blatchford Lake intrusive suite is the only intrusion with a pronounced negative Eu anomaly; other intrusions have either no Eu anomaly, or do not have a consistent behaviour between samples.

Figure 5.1 - Total alkalis vs silica diagram (modified from Cox *et al.*, 1979). Includes Dogrib diabase data from B. Cousens (unpublished data, 2012) and Ernst and Buchan (Ernst & Buchan, 2010).

Blatchford Lake intrusive suite – western (BLIS-W) and eastern (BLIS-E) lobes, Big Spruce Lake alkaline intrusion (BSLC), Squalus Lake intrusion (SLI), Duck Lake sill (DLS), Dogrib diabase dykes (DG), and Simpson Island dyke (SID).

Figure 5.2 - Granitoid classification schemes from Frost *et al.* (2001): (a) $\text{FeO}/(\text{FeO} + \text{MgO})$ vs SiO_2 showing the boundary between ferroan plutons and magnesian plutons, (b) $\text{Na}_2\text{O} + \text{K}_2\text{O} - \text{CaO}$ vs SiO_2 showing the ranges of alkali, alkali-calcic, calc-alkalic, and calcic rock series. (c) Alumina saturation index (ASI) vs A/NK, where $\text{A/NK} = \text{Al}_2\text{O}_3/(\text{Na}_2\text{O} + \text{K}_2\text{O})$, and $\text{ASI} = \text{molecular ratio of Al}/(\text{Ca} - 1.67\text{P} + \text{Na} + \text{K})$. Symbols as in Figure 5.1.

With the exception of the relatively flat patterns of the Dogrib dykes, the intrusions all display moderate to strongly elevated REE contents, and a strong LREE enrichment. Nb is variable between intrusions, the Squalus Lake intrusion and Dogrib diabase dykes have minor negative Nb anomalies and the Blatchford Lake intrusive suite and Big Spruce Lake alkaline intrusion have both minor positive and negative anomalies, whereas the Simpson Island dyke and Duck Lake Sill have negligible Nb trends. As a whole the incompatible element patterns are very similar between intrusions within the SWSMP.

The convex LREE-enriched patterns of Pr, Nd, and Sm that occur in the most evolved samples in the Big Spruce Lake alkaline and Squalus Lake intrusions correspond to carbonatite samples (Fig. 5.3). These samples also exhibit strong negative Zr anomalies. The remaining intrusive suites have quite variable Zr concentrations, displaying no consistent patterns with the exception of the Simpson Island dyke and the Duck Lake Sill which have small positive anomalies. Plotting Nb/Ta versus Zr/Hf yields a tight cluster for the bulk of analyses with $Nb/Ta \approx 18$ and $Zr/Hf \approx 40$ (Fig. 5.4), comparable to primitive mantle ($Nb/Ta = 17-18$, $Zr/Hf = 37-41$). The outlier analyses generally consist of highly evolved silica-undersaturated rocks and carbonatites.

Figure 5.5 displays the range of Nd isotopic values for all intrusions in the SWSMP, including data from chapters two, four, and previously published data from the Big Spruce Lake intrusive suite (Cavell, 1986). The Blatchford Lake intrusive suite displays the largest range in ϵ_{Nd} values, ranging from +3.4 to -3.0. A nepheline syenite phase in the Big Spruce Lake alkaline intrusion and a peridotite phase in the Blatchford Lake intrusive suite record the most positive ϵ_{Nd} values amongst the intrusions,

Figure 5.4 - Nb/Ta vs Zr/Hf (ppm). Data from this study, and B. Cousens (unpublished data, 2012). Primitive mantle from McDonough and Sun (1995). Symbols as in Figure 5.1. Symbols with centered black circles indicate nepheline syenite samples; centered grey circles indicate carbonatite samples.

Figure 5.5 - Initial Nd isotopic range of intrusions in the southwestern Slave magmatic province.

Data from this study, Mumford *et al.* (2010, 2012), Cavell and Baadsgaard (1986), and B. Cousens (unpublished data, 2012). All $\epsilon_{Nd(initial)}$ are calculated to 2182 Ma, with the exception of the Simpson Island dyke (2220 Ma). Abbreviations as in Figure 1.1.

Rock type	Sample	Nd (ppm)	$^{143}\text{Nd}/^{144}\text{Nd}_{\text{meas}}$	Sm (ppm)	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}$	ϵ_{Nd}^T
BSLC-foyaite	647A	70.69	0.51151	12.16	0.104	0.510016	4.02
BSLC-carbonatite	650A	736.27	0.511061	93.54	0.0768	0.509957	2.87
DLS	654A	31.75	0.511897	7.25	0.138	0.509914	2.01
SLI-carbonatite	630A	581.79	0.511606	113.51	0.1179	0.509911	1.97
SID-ultramafic	450D	24.1	0.511918	5.62	0.1416	0.509847	1.69*
BSLC-gabbro	652A	61.98	0.511656	12.56	0.1226	0.509895	1.65
DLS	553A	21.23	0.511956	5.06	0.144	0.509887	1.48
SID-syenite	476A	61.58	0.511823	13.87	0.1361	0.509831	1.38*
DG	554A	8	0.512383	2.31	0.1745	0.509876	1.25
SID-syenite	1199A	69.93	0.511811	15.84	0.137	0.509807	0.9*
SID-ultramafic	450A	41.43	0.511654	8.74	0.1275	0.50979	0.56*
SLI-granite	640A	60.44	0.511147	9.64	0.092	0.509825	0.27
SLI-mafic autolith	633A	68.11	0.511409	12.57	0.1116	0.509806	-0.1

Notes: Epsilon Nd values calculated assuming an age (T) of 2182 Ma for all samples, *except SID samples, where an age of 222 Ma is assumed. Sm and Nd concentrations by isotope dilution. BSLC, Big Spruce alkaline intrusion; DLS, Duck Lake sill; SLI, Squalus Lake intrusion; SID, Simpson Island dyke; DG, Dogrib dike.

Table 5.1 - Nd isotope compositions for rocks of the SWSMP

+4.0 and +3.4 respectively. SWSMP samples exhibit a general trend of decreasing ϵ_{Ndi} with increasing SiO_2 (Fig. 5.6).

5.3 Discussion

A significant challenge of relating all units of the SWSMP to a single geologic/tectonic event is the wide range of rock types and compositions present. Rock types range from relatively simple fine-grained subalkaline dykes (e.g., Dogrib diabase dykes) to complex composite silica-saturated to undersaturated alkaline intrusive suites (e.g., Big Spruce Lake alkaline intrusion, Blatchford Lake intrusive suite). If all intrusions within the SWSMP are related to a single geologic/tectonic event, then either a single process (or a combination of processes) must be able to account for the spectrum of rocks observed. The detailed study regarding the petrogenesis of Blatchford Lake intrusive suite presented in chapters two and four describes the development of both the subalkaline silica-saturated western lobe and the peralkaline undersaturated eastern lobe. If this model illustrates the development of one of the most complex intrusive suites in the SWSMP, then perhaps it can provide insight into development of the entire SWSMP. Accordingly, the petrogenetic considerations and constraints presented in chapters two and four will be used to investigate the development of the SWSMP.

The major and trace element compositional data presented for rocks of the SWSMP reflect the wide range of observed rock types. Despite large variations in the mineralogy and composition of these intrusions, they share many common chemical signatures. However, it should be noted that in some cases, these signatures are obscured by both strong affinity of REE in carbonatites

Figure 5.6 - ϵ_{Ndi} vs SiO_2 , initial ratios calculated for an age of 2182 Ma. Data from this study, Cavell (1986), and B. Cousens (unpublished data, 2012). Abbreviations as in Figure 5.1.

Figure 5.7 - A-type granite discrimination diagrams for granitoid rocks of the SWSMP (modified from Whalen *et al.*, 1987), using $10000 \cdot \text{Ga}/\text{Al}$ vs: (a) FeO/MgO , (b) Zr, (c) Y, (d) Zn. Symbols as in Figure 5.1.

(Chakhmouradian & Zaitsev, 2012) and the behaviour of HFSE in highly evolved alkaline rocks (i.e., nepheline syenite). Caution should be used when interpreting samples from these evolved rock types.

The concave-up HREE patterns and low Sm/Lu ratio of many of the rocks in the SWSMP, suggests that the parental magma did not form in equilibrium with garnet (Fig. 5.3). The absence of large Nb anomalies in the SWSMP intrusions indicates that none of the intrusions contain a large subduction related component. These characteristics suggests that SWSMP rocks were not derived from the melting of lower crustal rocks, as suggested in chapter two, (e.g., crustally-underplated Kam formation, Cousens, 2000). The composition of rocks from the SWSMP suggests a strong mantle component, such as observed in the Blatchford Lake intrusive suite. The high $\text{Fe}_2\text{O}_3/(\text{Fe}_2\text{O}_3+\text{MgO})$ ratios, enrichment in large ion lithophile elements (LILE) and high field strength elements (HFSE), high Ga/Al, indicate that granitoid rocks of the SWSMP can be generally classified as A-type granites (Fig. 5.7, Bonin & Giret, 1985a, Whalen *et al.*, 1987). The genesis of A-type granites is generally associated with the differentiation of mantle derived melts (Bonin & Giret, 1985a, Frost *et al.*, 2001, Whalen *et al.*, 1987). In addition, the majority of SWSMP samples have incompatible element ratios comparable to those of primitive mantle (Fig. 5.4). While individual intrusions in the SWSMP exhibit modest variation in their Nd isotopic ratios (Fig. 5.5), all intrusions indicate an isotopically depleted source. The general trend of decreasing $\epsilon_{\text{Nd}i}$ with increasing SiO_2 suggests that most intrusions display evidence of mixing with an enriched source (crustal component?). As reviewed in chapters two and four, this trend is present in both the eastern and western lobes of the Blatchford Lake intrusive suite. However, in the eastern lobe the direction of

the trend was shown to be inverse (increasing ϵ_{Ndi} with decreasing SiO_2). This was interpreted to be related to the input of silica-rich crustal rocks into a silica-undersaturated magma. The presence of nepheline syenite in the Big Spruce Lake alkaline intrusion and carbonatite in the Squalus Lake intrusion suggests that either could have had a silica-undersaturated parental magma. Without additional samples and detailed knowledge of their relations, the trends within individual intrusions do not confer any information regarding the direction of the observed ϵ_{Ndi} versus SiO_2 trend.

In chapter four it was shown that even the least differentiated rocks in the Blatchford Lake intrusive suite were already considerably evolved, suggesting that their parental melt may have had more depleted Nd isotopic ratio, (i.e., $>3.4 \epsilon_{\text{Ndi}}$). If all intrusions were derived from a similar source, it seems plausible that the highest ϵ_{Ndi} samples from Big Spruce Lake alkaline intrusion merely reflect the addition of a smaller crustal component.

To summarize, the subalkaline to alkaline rocks of the SWSMP range from silica-saturated to undersaturated, display evidence of derivation from an isotopically depleted mantle source, and exhibit varying degrees of LILE and HFSE enrichment. Negative trends between ϵ_{Ndi} and SiO_2 suggest that the differentiation of individual parental melts of the SWSMP intrusions involved crustal assimilation.

5.3.1 Development of the Southwest Slave magmatic province

In the model proposed for the formation of the Blatchford Lake intrusive suite (chapter four), it is suggested that the spectrum of rock types observed in the eastern and western lobes can be related to processes involving the differentiation of two distinct

parental melts derived from melting a metasomatized depleted lithospheric mantle source. In this model, amphibole-rich metasomatic veins are formed and subsequently melted by either lithospheric extension causing upwelling asthenosphere, or by small intraplate plumes (Fig. 5.8). The melting of these metasomatic veins produces a magma that parallels all the major and trace-element signatures of alkaline magmas (Pilet *et al.*, 2011, Pilet *et al.*, 2008). The interaction between these ‘vein’ melts and their host peridotite can create a variety of compositions, ranging from nephelinite to alkali olivine basalt to tholeiitic basalt. The isotopic signature of these melts is controlled by the composition of the asthenosphere source (estimated by Pilet, (2011), to be DMM to E-DMM), lithospheric source, and the time delay between metasomatism of the depleted lithospheric mantle and melting. This model can account for the generation of silica-saturated and undersaturated melts with corresponding varying degrees of alkalinity and LILE-HFSE enrichment, as well as depleted isotopic ratios. These characteristics make this not only a strong possibility for the formation of the Blatchford Lake intrusive suite but also for the entire SWSMP.

Mumford *et al.* (2012a) suggested that the strong correlation between the degree of alkalinity and the slope of REE could relate to the degree of partial melting, (i.e., subalkaline intrusions with corresponding flat REE patterns could suggest higher degrees of partial melting). Using the model suggested above, this correlation could also be an indication of the degree of mixing between metasomatic vein melts and the depleted lithospheric source and/or the intensity of metasomatism. In this case, flatter REE patterns and subalkaline compositions would correlate to melts largely consisting of metasomatized depleted lithospheric mantle, (e.g., Dogrib diabase dykes).

Figure 5.8 - Schematic models for the metasomatism of continental lithosphere (modified from Pilet *et al.*, 2011): (a) upwelling asthenosphere due to rift related crustal thinning, and (b) induced by a mantle plume.

This mechanism could also account for the delay between the Simpson Island dyke and the SWSMP. Early transpressional motion along the Great Slave Lake shear zone could have caused localized asthenosphere upwelling in the East Arm, leading to the formation the Simpson Island dyke. Later regional rifting (active or passive) throughout the southwestern Slave could then have produced the relatively coeval SWSMP. While the timing and nature of the rifting mechanisms between the intrusions may have differed, comparable lithospheric and asthenospheric sources could explain the strong compositional resemblances between intrusions. Other workers suggest that the Simpson Island dyke may be related to the MacKay dyke swarm event (Buchan *et al.*, 2010). If this is the case, then rocks of the MacKay dyke swarm should also be compared against the SWSMP.

The general alkaline-subalkaline composition and punctuated temporal relation of intrusions in SWSMP suggests that they may be related by a common geologic/tectonic event. The alkaline nature of many intrusions in the SWSMP suggests that it is related to extension, and the timing is coincident with the break-up of the Sclavia supercontinent (Bleeker & Hall, 2007). However, it is unknown whether this extension is related to active or passive rifting. Active rifting is traditionally associated with active mantle upwelling, related to either discrete hot plumes or anomalously hot upper mantle (Sengor & Burke, 1978). Conversely, passive rifting is related to far-field stresses produced by plate boundary forces or the convective drag on the base of the lithosphere (Schmeling, 2010). Both passive and active rifting typically have associated magmatic activity, although relative timing between the two events is variable. The presence of large-scale topographic swells and widespread magmatism predating rifting are strong indications of

an active rifting environment, whereas magmatism in passive rifting systems is generally coeval or delayed with respect to rifting. Numerical modelling relating the timing between passive rifting and the subsequent magmatism indicates a delay of 1 to 10 Ma (Nielson & Hopper, 2002, van Wijk *et al.*, 2001). Thus, even if high-precision radiometric dating was available for the timing of rift formation, it would not be possible to resolve a delay given the variation in ages between intrusions (Table 1.1). The chemical/isotopic identification of a mantle plume is also unfeasible due to the evolved nature of even the most primitive rocks from intrusions in the SWSMP. Pilet (2011) and other workers have suggested that metasomatism of the lithosphere (Fig. 5.8) could be caused by either active (Halliday *et al.*, 1995, Wyllie, 1988) or passive rifting (Lloyd & Bailey, 1975, Wass & Rogers, 1980). As long as both the upwelling asthenosphere (source of metasomatic veins) and the host lithosphere have depleted isotopic signatures, then the model is blind with respect to the rifting mechanism. The non-radiating distribution of the Dogrib diabase dyke swarm favours a passive rifting model. However, based on the evidence presented it appears that determining the cause of the upwelling asthenosphere cannot be conclusively determined with the available data.

Considering their wide geographic distribution within the Slave Craton, rocks belonging to the SWSMP have a relatively small volume. If the SWSMP is related to a craton scale event, then the question becomes why they have such a small expression? A crucial element in the model proposed by Pilet (2011, 2008), is the presence of a CO₂ + H₂O rich asthenospheric source. This could potentially be the primary factor controlling the distribution of intrusions in the SWSMP. While the model requires large scale mantle upwelling, if the asthenosphere is particularly heterogeneous and only locally containing

pockets of material sufficiently enriched in $\text{CO}_2 + \text{H}_2\text{O}$, then it stands to reason that the distribution of alkaline melts formed by this process would be restricted. The scarcity of rocks in the SWSMP could also be influenced by the thickness of the lithosphere underlying the Slave Craton. Davis *et al.* (2003a) and other workers (Thompson *et al.*, 1996) have established that the lithosphere in the Slave Craton was relatively thin (~100 km) at *ca.* 2600 Ma, but had stabilized and thickened to >200 km by *ca.* 1800 Ma. Current models for the thickening of mantle roots involves either *in situ* subcretion from below (plume?) or shallow subduction of young oceanic plates (e.g. Abbott, 1991, DeWit *et al.*, 1992, Helmstaedt & Schulze, 1989). Thus the relatively small volume of magmatic activity related to the SWSMP could be an indication of: 1) thick mantle roots of the Slave Craton that were already stabilized at *ca.* 2180 Ma, essentially insulating the craton from upwelling asthenosphere and hindering the migration of magmas through the crust, 2) mantle heterogeneity and the small volume and distribution of material sufficiently enriched in $\text{CO}_2 + \text{H}_2\text{O}$, 3) that the event was very short lived, or 4) some combination of these factors. If the Slave Craton's thick lithospheric mantle was not already stabilized by *ca.* 2180, then it seems probable that the asthenospheric upwelling and melting associated with the formation of the SWSMP may have contributed via a process akin to plume subcretion, (e.g., Davis *et al.*, 2003b, Griffen *et al.*, 2004).

Due to heterogeneity in the mantle, it would be expected that both the absolute and relative abundances of CO_2 - and H_2O -rich phases would be variable. This variability would likely influence the chemical and mineralogical composition of the resulting metasomatic veins, as well as the products of their melting. Thus the absolute and relative abundances of volatile phases could affect the chemical and mineralogical make-up of

alkaline intrusions in the SWSMP. Carbonatites are present in both the silica-saturated Squalus Lake intrusion (Mumford *et al.*, 2012a) and the silica-saturated to undersaturated Big Spruce Lake alkaline intrusion (Cavell & Baadsgaard, 1986); however, to date no carbonatite rocks have been discovered within the Blatchford Lake intrusive suite. All major phases in the eastern lobe contain local primary carbonate, but no discrete coalesced body of magmatic carbonate has been observed, (i.e., a dyke or plug).

The origin of carbonatite melts is one of the most fiercely debated subjects in igneous petrology. Favoured petrogenetic models include (Hamilton *et al.* 1979, and references within): (1) direct partial melting of the upper mantle, (2) separation of an immiscible carbonate melt from a CO₂-rich alkaline silica melt, or (3) fractional crystallization of a CO₂-rich alkaline silicate magma.

If the occurrence of carbonatite in the Squalus Lake and Big Spruce Lake alkaline intrusions are related to either of the latter two models then absence of carbonatite in the Blatchford Lake intrusive suite becomes intriguing. One possibility is that the apparent absence carbonatite in the Blatchford Lake intrusive suite is a function of insufficient enrichment of CO₂ in the underlying source rocks. Another possibility for its absence relates to the formation of the rim syenite (see chapter two for details). A substantial loss of CO₂ during the emplacement of the ring dyke could influence both the stability of magmatic carbonate and its abundance, essentially restricting the formation of a carbonatite body. However, if the carbonatite observed in the Squalus Lake and Big Spruce Lake alkaline intrusions is derived from direct mantle melting then the above considerations are likely not valid. Additional work is required on the Squalus Lake and

Big Spruce Lake alkaline intrusions to determine the nature of their respective carbonatite bodies.

5.4 Implications regarding REE mineralization

The Blatchford Lake intrusive suite is among the three largest REE resources in North America (Castor 2008, Sheard *et al.* 2012), and is considered to have one the highest HREE/LREE ratios of large deposits worldwide. Results relevant to REE mineralization from the detailed investigations of the Blatchford Lake intrusive suite (chapters 2 and 4), local rocks (chapter 3), and regional comparison of the similar alkaline intrusions comprising the SWSMP (this chapter) are summarized below.

(1) The two stocks of the Compton intrusive suite that intrude into the Grace Lake granite mark the western most extent of the Nechalacho layered suite.

(2) While the two lobes of the Blatchford Lake intrusive suite are cogenetic, the silica-undersaturated, peralkaline nature of the eastern lobe favoured the formation of the Thor Lake deposits. Despite containing similar average REE abundances, the western lobe did not result in the formation of any notable localized economic to sub-economic REE concentrations. In fact, the worlds largest REE resources hosted in intrusive igneous systems (not considering carbonatites) were likely derived from silica-undersaturated parental melts (e.g., Ilímaussaq, Marks *et al.*, 2004b; Tamazeght, Marks *et al.*, 2008). It is therefore suggested that silica-undersaturated parental melts play a fundamental role in the evolution of intrusive alkaline REE deposits.

(3) The absence of a carbonatite body in the Blatchford Lake intrusive suite may have influenced both the concentration of REE as well as the characteristic

HREE/LREE ratios of the Nechalacho deposit. A global comparative study between intrusive peralkaline systems (with and without associated carbonatite bodies) and their REE resources may help to determine if a correlation exists.

5.5 Summary

The *ca.* 2180 Ma SWSMP consists of a group of intrusions that range from relatively simple fine-grained subalkaline dykes to complex composite silica-saturated to undersaturated alkaline intrusive suites. Despite their wide mineralogical and chemical compositions, trace-element and radiogenic isotopic ratios of rocks from the SWSMP suggest an inherent connection. Evidence presented above suggests that the link between intrusions of the SWSMP could relate to similarities in source rocks and melting mechanisms. The model outlined in chapter four for the origin of the Blatchford Lake intrusive suite, involving the variable melting of metasomatic veins and surrounding mantle rocks, provides a mechanism whereby a wide spectrum of melts similar to those observed in the SWSMP could be produced. It is hypothesized that the entire SWSMP, as well as the Simpson Island dyke, could be produced in a similar manner. While this model requires upwelling asthenosphere additional data are required to differentiate between active versus passive rifting.

6 Chapter: Conclusions

The primary objectives of this research project were to gain a better understanding of the petrogenesis of the Blatchford Lake intrusive suite, the nature of its source, and to characterize its relationship to the two monzonite-diorite intrusive stocks hosted in the Grace Lake granite. The data and interpretations presented in chapters two and four describe the intra-phase associations within the eastern and western lobes and characterize the chemical nature of their respective sources. Chapter three characterizes the two monzonite-diorite intrusive stocks hosted in the Grace Lake granite and defines their relationship to the Blatchford Lake intrusive suite. Chapter four reviews the multiple lines of evidence that suggest a genetic link between the two lobes of the Blatchford Lake intrusive suite and addresses the fundamental issues regarding the formation of parental cogenetic silica-saturated and undersaturated melts. Chapter five relates findings from this study of the Blatchford Lake intrusive suite to the regional geology of the southern Slave Craton, in particular, early Paleoproterozoic magmatism.

A summary of key elements derived from this thesis are described below:

1. Evidence presented indicates a petrogenetic relationship between the western and eastern lobes of the Blatchford Lake intrusive suite.
2. Parental melts in the eastern and western lobes were derived from the melting of metasomatized depleted lithospheric mantle. Interaction between melts from amphibole-rich metasomatic veins and host depleted lithospheric peridotite can account for the compositional spectrum and isotopic signatures observed in the

parental melts of the eastern and western lobes of the Blatchford Lake intrusive suite and other intrusions of the SWSMP—including the Simpson Island dyke. The nature of the heat source (passive or active rifting) driving the metasomatism and subsequent melting remains unknown.

3. Differentiation in the eastern and western lobes was largely controlled by crystal fractionation complemented by a significant degree of crustal assimilation. Crustal assimilants likely consist of lower crustal mafic rocks and local Archean granitoids. Using radiogenic isotopes and incompatible element ratios, the degree of crustal contamination in the most evolved western lobe granites is estimated to be 5-30 %.
4. The Caribou Lake gabbro, Whiteman granitic group and Hearne granitic group constitute the three primary rock units in the western lobe and are differentiated from a common silica-saturated parental melt compositionally similar to alkali olivine basalt – tholeiitic basalt. Phases in the western lobe represent discrete pulses from an unexposed deep-seated parental system. The Whiteman and Hearne granitic groups were emplaced at a depth of ~ 16 km (4 – 4.5 kbar), and crystallized at temperatures around 690°C. Phases of the eastern lobe are also inferred to have been emplaced at similar depths.
5. The Grace Lake granite, Thor Lake syenite, and Nechalacho layered suite constitute the three primary rock units of the eastern lobe and are differentiated

from a common silica-undersaturated, nephelinite parental melt. New geochronologic work indicates that the Grace Lake granite and Thor lake syenite represent coeval intrusions (2176 ± 1.6 Ma), whereas the emplacement of the Nechalacho layered suite may have been delayed by as much as 10 Ma.

6. The transition from silica oversaturated in the Grace Lake granite to the silica undersaturated Nechalacho layered suite reflects the progressive armouring of magmatic pathways from silica-rich country rocks. The Thor Lake rim syenite, an arcuate feature occurring near the contact of the Grace Lake granite and Thor Lake syenite, represents the basal remnants of an eroded ring dyke.
7. The two monzonite-diorite intrusive stocks hosted in the Grace Lake granite are chemically and temporally (1892 ± 4 Ma) unrelated to the Blatchford Lake intrusive suite, and likely represent the northwestern continuation of the Compton intrusive suite into the Slave Craton. The rhythmically layered magmatic rafts hosted within the northern intrusive stock are autolithic in origin. Relations between diabase dykes and the intrusive stocks suggest that NE-trending diabase dykes (i.e., Hearne diabase dykes) in the region have a complex and protracted history.

6.1 Potential areas of future work

This analysis of the Blatchford Lake intrusive suite and its relation to the two Compton intrusive stocks hosted within it highlights the need for future research in the region. These suggested topics would greatly enhance our understanding of

Paleoproterozoic magmatism in the southern Slave craton and the East Arm of Great Slave Lake.

- Two additional isotopic studies of the Blatchford Lake are suggested: 1) The Lu-Hf and Sm-Nd isotopic systems are both comprised of HFSE pairs and their behaviors typically parallel each other. However, due to the preferential partition of HREE into garnet, the Lu-Hf system is strongly influenced by garnet-rich source lithologies. Our research on the Blatchford Lake intrusive suite indicates that parental melts were formed above the garnet stability field, thus the use of the Lu-Hf isotopic system on rocks from the eastern lobe could inform models suggested in chapter 2 regarding the transition from silica-saturated to undersaturated. 2) The siderophilic/chalcophilic behavior of Re and Os is unique among other long-lived radiogenic isotope systems, such as Rb-Sr, Sm-Nd, and Lu-Hf. Rocks in the convecting mantle generally show evidence of a chondritic Re-Os evolution throughout Earth history, whereas portions of old subcontinental lithosphere are strongly depleted in Re and have subchondritic $^{187}\text{Os}/^{188}\text{Os}$ ratios. Thus use of the Re-Os isotopic system on the mafic rocks of the western lobe may help to further characterize the mantle source as either lithosphere or asthenosphere.
- Dating the Nechalacho layered suite using U-Pb TIMS may reduce analytical uncertainty in the age determined, and help further constrain the model presented.
- A detailed study of the geochronology and geochemistry of the Compton intrusive suite and Butte Island group would augment our understanding of Paleoproterozoic magmatism in the East Arm.

- Detailed geochronology and geochemistry of mafic dyke swarms in the region surrounding the Blatchford Lake intrusive suite would help to resolve the timing and petrogenetic relations between various swarms.
- Our brief visit and investigation of the Squalus Lake intrusion suggests that it may be larger than originally mapped. Improved mapping and diamond drilling is recommended.

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Appendices

Appendix A - Whole rock geochemistry

< or bld, below detection limit;

>, above calibration limit;

negative LOI values are likely due to oxidation of Fe,

A.1 Eastern lobe whole rock geochemistry

SAMPLE:	1029A	1034B	1060C	1061A	1082A	1198H	1198I	1198J	347A	359A	392B	535A
Unit:	GLG	GLG	GLG	GLG	GLG	GLG	GLG	GLG	GLG	GLG	GLG	GLG
EASTING:	414293	413564	417438	415554	412008	418245	418239	418233	411452	413605	412398	414237
NORTHING:	6883027	6883291	6889362	6886462	6893268	6889640	6889670	6889696	6893925	6891129	6886916	6887707
SiO ₂ (wt.%)	69.54	62.71	68.53	69.9	72.71	72.6	70	70.7	76.41	73.6	70.84	71.21
Al ₂ O ₃	9.82	8.76	12.74	13.68	11.65	11.5	13.15	12.7	10.92	11.71	12.04	10.96
CaO	0.67	3.09	0.95	0.5	0.55	1.04	0.71	0.72	0.39	0.24	0.76	1.05
K ₂ O	5.037	4.697	4.97	5.213	4.741	4.55	5.05	4.85	4.78	5.05	4.81	4.69
MgO	0.33	0.52	0.14	0.2	0.19	0.09	0.07	0.09	0.09	0.29	0.16	0.09
MnO	0.086	0.038	0.052	0.039	0.037	0.09	0.07	0.08	0.04	0.04	0.06	0.09
Na ₂ O	3.82	1.44	5.02	4.85	4.07	4.42	5.12	5.09	4.04	4.41	5.1	4.61
P ₂ O ₅	0.003	0.107	0.007	0.025	0.008	0.005	0.005	0.005	<0.01	0.01	0.03	0.01
Fe ₂ O ₃	7.284	14.735	4.788	3.279	4.007	4.97	4.37	4.94	3	2.99	4.98	6.25
TiO ₂	0.307	1.13	0.622	0.18	0.263	0.32	0.28	0.38	0.17	0.16	0.57	0.51
L.O.I.	1.24	2.31	0.91	1.08	0.46	0.7	0.89	0.4	0.45	0.57	0.57	0.47
Sum	97.166	97.684	98.05	98.027	98.396				100.3	99.07	99.94	99.94
Ba (ppm)	51.6	70.3	268.8		22.9	54.4	243	240	22.1	46.2	115.5	67.4
Be	8.97	4.04	10.32		6.36				5.72	10.82	6.86	8.31
Bi	0.19	<0.15	<0.15		<0.15				0.121	0.166	0.192	0.345
Cd	0.26	0.22	0.39		0.16				0.15	0.15	0.25	0.33
Ce	156.79	750.02	258.51		372.87	82.8	103.5	139	>310	>310	>310	257.13
Co	1.13	2.07	0.62		0.57	0.7	0.7	0.6	0.9	1.1	1.2	0.9
Cr	144	127	99		112	10	10	10	249	192	230	227
Cs	1.71	0.63	1.85		0.79	0.38	3.78	1.89	0.55	1.98	3.37	1.86
Cu	5.7	16.7	2.9		3.9	11	6	2.5	4	5	4	5
Dy	13.59	40.70	17.08		11.05	8.53	9.71	11.20	7.05	20.77	15.49	16.68
Er	6.67	17.85	7.60		4.98	4.03	4.62	5.52	2.56	10.44	6.29	7.49
Eu	1.73	5.36	3.10		1.61	1.47	1.83	2.11	1.21	3.48	3.00	2.96
Ga	46.86	43.9	53.6		47.56	55.9	54.3	53.3	45.33	54.07	56.58	54.24
Gd	16.36	57.76	21.93		16.77	10.60	12.80	14.75	14.49	28.59	26.01	22.57
Hf	28.62	>29	16.88		9.8	8.4	9.3	13.8	6.51	15.86	13.53	9.53
Ho	2.46	6.97	3.06		1.91	1.56	1.81	2.09	1.06	3.74	2.56	2.96
In	0.40	0.27	0.05		0.18							
La	64.34	333.42	124.73		191.3	37.6	45.7	63.8	166.62	>210	>210	114.11
Li	137.2	26.9	37.4		24.8				16.7	43.9	45	32.6
Lu	1.037	2.376	0.672		0.632	0.37	0.44	0.6	0.39	1.19	0.69	0.77
Mo	1.83	9.69	2.43		4.28	4	5	7	5.41	2.64	8.03	5.32
Nb	153.438	261.363	114.172		89.519	52.5	67.4	89.8	73.21	144.82	147.33	106.51
Nd	85.25	376.13	123.29		154.84	42.9	52.7	66.5	140.36	303.37	232.55	132.05
Ni	3.7	4	3.1		3.1				4	4	4	4
Pb	10.9	8.1	12.6		7.4	8	12	11	5	11.3	13.7	12.1
Pr	20.58	92.74	31.55		42.80	10.50	12.90	17.25	38.64	85.98	63.60	32.27
Rb	285.83	197.16	195.95		156.35	141.5	231	202	147.13	175.63	206.38	188.33
Sb	0.19	0.28	0.15		0.1				0.06	0.14	0.1	0.17
Sc	2.4	1.8	1.5		<1.1				<0.9	<0.9	0.9	<0.9
Sm	19.11	73.41	24.33		24.54	9.02	11.35	13.45	22.69	43.51	37.29	26.76
Sn	8.48	7.47	7.4		6.14	3	4	5	4.57	8.16	6.27	8.41
Sr	9.3	70.5	62.7		6.1	25.2	56.5	55.7	5	9	29	23
Ta	9.901	14.117	5.851		4.494	3.8	4.6	6.2	3.8	7.4	8.6	5.5
Tb	2.36	7.51	3.04		2.16	1.58	1.90	2.17	1.63	3.82	3.16	3.10
Th	13.60	17.40	20.20		14.27	7.92	10.90	13.10	12.53	37.79	26.97	24.64
Tl	0.683	0.358	0.684		0.458				0.31	0.41	0.81	0.39
Tm	0.96	2.40	0.93		0.67	0.50	0.59	0.72	0.37	1.44	0.81	0.96
U	5.346	8.203	3.35		2.109	1.44	2.09	2.94	1.57	5.01	4.48	2.74
V	<0.8	0.8	<0.8		3.3	2.5	2.5	9	<10	<10	<10	<10
W	2.69	2.77	2.48		1.31	2	2	3	0.85	1.33	1.68	2.16
Y	72.2	208.86	94.08		50.23	48.9	55.3	59.8	27.8	83.66	75.78	90.04
Yb	6.56	15.42	5.18		4.27	2.70	3.04	4.04	2.46	8.74	4.98	5.69
Zn	377	51	183		132	115	145	169	104.72	158.05	199.52	233.96
Zr	1070	1741	719	522	338	299	309	486	243	>600	589	400

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. GLG, Grace Lake granite; NLS, Nechalacho layered suite; TLS, Thor Lake syenite (l:leucosyenite, ol:olivine syenite, r: rim syenite)

Eastern lobe whole rock geochemistry cont.

SAMPLE:	600A	600B	600C	600D	600E	610A	610B	1171A	1202A	1008A	1037A	1060A
Unit:	NLS	NLS	NLS	NLS	NLS	NLS	NLS	NLS	TLSI	TLSI	TLSI	TLSI
EASTING:	416725	416725	416725	416725	416725	416715	416725	406187	416610	416411	418223	417011
NORTHING:	6886118	6886118	6886118	6886118	6886118	6886118	6886118	6893143	6885430	6885944	6887184	6888958
SiO ₂ (wt.%)	54.3	48.48	43.7	45.03	51.68	33	53	54.34	62.4	57.96	55.59	57.66
Al ₂ O ₃	19.74	17.94	15.53	15.05	17.08	10.75	17.7	15.74	13.59	14.18	11.53	13.06
CaO	2.11	5.65	4.06	2.93	2.01	3.94	2.47	0.57	1.04	2.67	2.58	3.31
K ₂ O	5.866	5.614	6.226	6.519	6.97	7.24	4.63	4.904	5.492	4.77	4.102	4.254
MgO	0.02	0.03	0.05	0.05	1.17	0.1	0.04	0.28	0.91	0.41	0.23	0.28
MnO	0.098	0.192	0.329	0.32	0.196	0.5	0.26	0.124	0.085	0.306	0.231	0.346
Na ₂ O	8.79	7.72	5.35	4.81	5.18	1.73	8.02	8.91	4.43	5.2	5.95	5.33
P ₂ O ₅	0.012	0.014	0.013	0.004	0.009	0.01	0.03	0.015	0.05	0.134	0.075	0.129
Fe ₂ O ₃	5.097	9.188	20.703	21.82	12.398	38.5	11.95	11.422	6.701	11.862	14.554	14.049
TiO ₂	0.105	0.202	0.426	0.443	0.245	0.94	0.26	0.042	0.477	0.629	1.051	0.725
L.O.I.	2	2.6	2.4	1.5	1.5	1.59	1.7	2.91	2.62	2.08	0.97	0.87
Sum	96.436	95.258	96.592	97.17	97.178	98.3	100	96.643	95.331	98.222	96.058	99.297
Ba (ppm)	2.7	2.6	2.1	4	15.4	33.6	9.2	10.8	269.4		61.1	
Be	15.68	11.74	4.4	3.02	6.2			14.63	5.71		7.72	
Bi	0.211	0.028	0.014	0.152	0.143			<0.15	<0.15		0.24	
Cd	0.90	0.18	0.04	0.13	0.37			1.02	0.18		0.46	
Ce	251.39	250.16	149.61	45.32	188.01	138	688	238.53	181.35		217.6	
Co	0.4	0.9	1	1.1	1.2	2.1	0.6	0.3	1.31		1.2	
Cr	36	31	<24	<24	<24	10	<10	23	68		31	
Cs	6.25	7.75	12.16	10.56	8.38	11.90	2.28	9.80	0.95		1.73	
Cu	4	4	2	3	9	<5	<5	3	5.7		11.6	
Dy	18.35	18.10	8.65	3.53	8.90	4.69	16.60	17.51	10.72		12.02	
Er	8.96	6.32	2.71	1.40	3.28	1.67	6.07	7.51	4.95		5.34	
Eu	3.23	3.91	2.19	0.78	2.19	1.48	6.84	2.58	3.60		2.77	
Ga	59.41	64.04	73.99	75.48	66.64	95.2	56.8	>58	54.66		>58	
Gd	19.87	25.85	14.24	5.12	13.28	8.36	33.60	19.76	14.37		16.48	
Hf	12.29	5.62	1.62	1.48	5.25	2.2	25	>29	13.63		13.86	
Ho	3.40	2.93	1.33	0.61	1.43	0.78	2.71	3.07	1.93		2.13	
In								0.06	0.15		0.40	
La	125.46	119.9	72.56	20.4	90.26	61.5	293	112.41	83.73		100.68	
Li	59	81.2	123.5	133.8	181.8			143	26.6		33.4	
Lu	0.76	0.35	0.13	0.1	0.27	0.12	0.86	0.676	0.627		0.68	
Mo	56.88	4.04	1.44	1.28	5.22	<2	6	0.73	4.18		7.24	
Nb	>200	>200	>200	>200	>200	427	140.5	102.618	85.301		105.836	
Nd	106.58	121.72	74.29	25.15	83.85	73.6	360	105.12	91.15		113.85	
Ni	<3	<3	<3	<3	<3	<5	<5	<1.6	2.6		2.1	
Pb	41.7	7.2	3.9	1.8	8.5	<5	12	15.2	8.7		9.3	
Pr	27.95	29.35	18.11	5.87	21.99	18.45	91.20	27.92	22.51		28.12	
Rb	280.46	>300	>300	>300	>300	1125	197	330.32	140.67		168.91	
Sb	0.24	0.34	0.06	0.04	0.12			0.11	0.17		0.1	
Sc	<0.9	<0.9	<0.9	<0.9	<0.9			<1.1	1.9		2.4	
Sm	22.74	27.38	15.97	5.49	16.37	11.70	54.10	22.01	17.79		21.97	
Sn	4.98	3.03	1.51	2.17	4.41	3	10	>14	5.46		6.21	
Sr	7	11	8	16	37	9.5	18.5	73.1	41.8		19.9	
Ta	13	8.1	6	6.3	10	9.7	5.7	3.195	4.588		6.167	
Tb	3.10	3.47	1.75	0.67	1.79	0.96	3.58	3.15	1.98		2.17	
Th	26.76	15.59	8.46	3.86	13.24	4.26	25.20	57.74	10.01		9.28	
Tl	0.59	0.75	1.13	0.98	0.75	0.8	<0.5	0.4	0.248		0.255	
Tm	1.15	0.65	0.27	0.16	0.40	0.17	0.79	0.90	0.68		0.74	
U	5.16	3.19	0.89	0.83	3.16	0.54	3.33	2.831	2.09		2.034	
V	<10	<10	<10	<10	<10	5	<5	1.2	2		<0.8	
W	4.74	3.86	1.74	1.4	2.01	<1	1	0.8	2.97		1.63	
Y	88.02	111.35	50.79	23.15	39.84	27.7	57.1	78.46	52.44		62.13	
Yb	6.30	3.09	1.22	0.80	2.17	0.91	5.14	4.91	4.30		4.58	
Zn	361.13	386.84	639.46	595.31	465.12	778	236	264	46		236	
Zr	1114	568	190	201	592	97	951	1408	515	185	541	267

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. GLG, Grace Lake granite; NLS, Nechalacho layered suite; TLS, Thor Lake syenite (l:leucosyenite, ol:olivine syenite, r: rim syenite)

Eastern lobe whole rock geochemistry cont.

SAMPLE:	1198A	1198B	1198C	1198G	1201A	1203A	373C	373D	1014A	1016A	1060B	1198D
Unit:	TLSt	TLSt	TLSt	TLSt	TLSt	TLSt	TLSt	TLSt	TLSt	TLSt	TLSt	TLSt
EASTING:	418277	418278	418271	418251	420494	416954	417730	417730	417513	418733	417214	418265
NORTHING:	6889390	6889425	6889466	6889611	6884494	6885817	6889500	6889500	6889349	6889551	6889196	6889508
SiO ₂ (wt.%)	61	63	61.4	59.9	62.21	61.01	41.62	47.33	60.22	61.91	62.21	58.7
Al ₂ O ₃	15.05	14.9	14.5	14.1	14.9	16.58	5.08	8.1	15	16.39	12.87	13.15
CaO	1.61	1.44	2.22	2.47	1.14	0.96	4.73	6.37	2.57	1.28	1.95	3.14
K ₂ O	5.01	4.91	4.79	4.32	5.61	5.928	1.63	2.69	4.92	5.473	4.597	4.14
MgO	0.27	0.15	0.13	0.18	0.3	0.97	0.51	0.57	0.38	0.13	0.2	0.22
MnO	0.18	0.19	0.23	0.19	0.14	0.134	1.23	0.79	0.177	0.16	0.226	0.32
Na ₂ O	6.32	6.18	6.09	6.6	6.34	5.92	2.55	3.31	5.96	6.37	6.08	5.59
P ₂ O ₅	0.08	0.04	0.09	0.04	0.037	0.071	0.31	0.32	0.148	0.08	0.068	0.13
Fe ₂ O ₃	8.2	8.4	9.34	8.92	6.792	6.03	43.31	30.13	8.348	5.402	9.672	12.15
TiO ₂	0.42	0.38	0.49	0.9	0.391	0.22	1.03	1.61	0.719	0.462	0.555	0.62
L.O.I.	1.59	0.38	0.05	2.2	1.08	1.65	-3.35	-1.61	1.05	1.54	1.23	0.1
Sum					98.105	97.944	98.65	99.62	98.588	97.753	98.732	
Ba (ppm)	198	242	254	124	219.4	239.5	113.7	128.1	524.9	183.6		305
Be					11.32	6.63	1.98	1.74	3.22	2.15		
Bi					0.22	<0.15	0.036	0.081	0.18	<0.15		
Cd					0.28	0.05	1.34	0.65	0.43	0.38		
Ce	166	162.5	153.5	139	396.05	181.9	177.68	134.01	86.67	64.91		148
Co	0.8	0.9	1	1	0.9	0.7	6.2	4.9	1.62	0.73		1.7
Cr	5	5	5	10	48	33	24	35	31	42		5
Cs	2.34	2.18	1.16	5.00	0.93	0.66	1.06	1.29	1.81	3.42		1.61
Cu	5	5	8	5	4.8	5.5	34	26	6.1	3.2		9
Dy	10.75	9.54	8.62	12.05	18.17	8.37	11.05	8.50	7.25	4.31		9.17
Er	4.92	4.49	4.10	5.64	7.68	3.81	5.26	3.77	3.20	1.78		4.24
Eu	3.89	3.80	3.77	3.13	5.15	4.21	4.02	3.94	4.32	3.26		4.56
Ga	49.7	51.7	48.7	53	>58	44.68	16.41	26.19	42.83	46.34		39.9
Gd	15.95	14.05	13.95	16.70	25.43	10.64	16.22	12.72	9.19	5.88		14.25
Hf	13.7	13.1	10.9	10.5	16.36	6.42	5.87	5.57	6.29	4.62		12.1
Ho	1.86	1.66	1.53	2.14	3.08	1.47	1.96	1.48	1.25	0.71		1.65
In					0.19	0.12			0.29	0.18		
La	75	75.2	65.8	56	188.49	91.4	69.64	54.7	35.25	27.78		66.2
Li					71.1	15.2	16.9	12.2	15.6	8		
Lu	0.67	0.62	0.62	0.78	0.884	0.459	0.93	0.62	0.414	0.251		0.63
Mo	3	2	3	5	3.83	5.85	3.9	6.48	2.44	1.45		4
Nb	85.2	84.2	76	93.5	139.669	46.318	74.98	45.47	54.71	40.056		73.1
Nd	86.4	80.1	79.4	76	182.17	79.13	107.47	79.51	52.39	37.53		81.9
Ni					1.7	2.1	<3	5	2.2	2		
Pb	8	10	9	13	9.7	4.7	5.3	4.3	9.8	11.4		9
Pr	21.20	19.80	19.55	18.45	47.18	21.18	24.60	18.32	11.94	8.82		18.95
Rb	135	137.5	114	139.5	240.23	137.84	55	61.19	115.7	149.12		102
Sb					0.13	0.18	<0.04	0.04	0.13	0.13		
Sc					1.6	2.6	8.4	15.1	6.4	3.1		
Sm	17.30	15.60	16.00	15.75	33.53	13.95	21.49	16.36	11.49	7.68		16.25
Sn	5	5	4	6	8.84	1.88	0.52	1.28	2.2	1.5		4
Sr	54.7	49.6	49.9	50.8	30.3	29.8	35	27	118.4	43.1		58.6
Ta	5.3	5.2	4.3	5.4	7.316	2.737	3.8	2.7	3.008	2.279		4.3
Tb	2.12	1.91	1.73	2.39	3.50	1.50	2.09	1.66	1.30	0.82		1.84
Th	9.92	8.41	6.43	16.75	14.34	7.85	2.28	3.48	5.40	2.45		7.50
Tl					0.397	0.291	0.12	0.14	0.316	1.214		
Tm	0.66	0.69	0.58	0.79	1.00	0.51	0.77	0.52	0.42	0.24		0.61
U	1.72	1.86	1.32	1.41	3.404	0.981	0.55	0.69	0.901	0.523		1.37
V	2.5	2.5	5	2.5	1.6	0.9	<10	<10	<0.8	<0.8		2.5
W	3	2	1	3	2.28	2.56	0.99	0.65	1.75	1.43		1
Y	45.2	42.6	36.6	45.4	76.51	38.33	45.22	36.48	31.1	17.64		39.3
Yb	4.29	4.06	3.85	4.92	6.10	3.16	5.57	3.64	2.67	1.56		3.96
Zn	169	238	224	239	186	21	726.36	352.07	164	129		260
Zr	487	478	404	356	652	248	221	217	249	176	801	422

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. GLG, Grace Lake granite; NLS, Nechalacho layered suite; TLSt, Thor Lake syenite (l:leucosyenite, ol:olivine syenite, r: rim syenite)

Eastern lobe whole rock geochemistry cont.

SAMPLE:	1198E	1198F	373E		
Unit:	TLSr	TLSr	TLSr		
EASTING:	418260	418258	417730	Precision	Detection
NORTHING:	6889551	6889572	6889500	Avg. diff (%)	limit
SiO ₂ (wt.%)	58	52.4	59.23	1.7	0.01
Al ₂ O ₃	13.65	10.6	13.8	1.6	0.01
CaO	3.1	4.86	2.46	0.0	0.01
K ₂ O	4.37	3.33	5	3.7	0.01
MgO	0.19	0.35	0.61	1.4	0.01
MnO	0.33	0.49	0.22	6.4	0.01
Na ₂ O	5.39	4.17	6.36	2.8	0.01
P ₂ O ₅	0.12	0.31	0.13	4.8	0.01
Fe ₂ O ₃	10.95	20.4	9.31	1.0	0.01
TiO ₂	0.66	1.26	0.63	2.5	0.01
L.O.I.	1.56	0.29	2.05	9.9	0.05
Sum			99.8		
Ba (ppm)	185.5	412	225.4	0.9	0.9
Be			5.22		0.06
Bi			0.08		0.009
Cd			0.33		0.01
Ce	130	138	191.99	6.3	0.2
Co	1.2	2.8	1.3	7.4	0.1
Cr	5	5	65	52.0	24
Cs	2.06	1.12	1.05		0.01
Cu	7	13	9	28.0	2
Dy	8.29	8.84	9.50	6.02	0.20
Er	3.97	4.00	4.18	5.80	0.01
Eu	4.23	4.58	4.41	5.61	0.01
Ga	41.4	33	46.57		0.05
Gd	12.70	14.20	14.65	0.97	0.02
Hf	11.6	6.8	9.45	13.6	0.09
Ho	1.47	1.51	1.62	5.57	0.00
In					0.00
La	57.7	57.6	83.73	8.8	0.09
Li			22.2		0.2
Lu	0.53	0.61	0.59	0.9	0.002
Mo	3	6	3.42		0.03
Nb	85.5	62	91.26	64.8	0.04
Nd	70.1	84.7	98.65	4.1	0.08
Ni		<3		6.7	3
Pb	12	2.5	9.2		0.4
Pr	17.25	19.55	24.24	4.77	0.02
Rb	111.5	65.1	141.35	5.3	0.2
Sb			0.14		0.04
Sc			2		0.9
Sm	13.90	16.85	19.41	6.27	0.02
Sn	3	2	4.95		0.08
Sr	39.4	86.8	64	2.2	2
Ta	5.8	3.6	5.9	47.9	0.2
Tb	1.66	1.84	1.88	0.81	0.00
Th	6.57	3.04	8.96	3.33	0.09
Tl			0.23		26
Tm	0.50	0.53	0.57	5.59	0.00
U	1.46	0.74	1.96	3.1	0.02
V	2.5	9	<10	0.8	10
W	4	2	1.43		0.5
Y	33.1	34.9	39.86	12.0	0.08
Yb	3.30	3.54	3.78	1.28	0.01
Zn	242	312	192.05	26.2	8
Zr	396	246	374	16.0	3

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. GLG, Grace Lake granite; NLS, Nechalacho layered suite; TLS, Thor Lake syenite (l:leucosyenite, ol:olivine syenite, r: rim syenite)

A.2 Chapter 3 whole rock geochemistry

Sample:	1022A	1058B	1053A	1055A	537B	1062A	534A	374B	1064A	1067A	1071A	1072A
Unit:	NS-LR	NS-LR	SS	SS	SS	NS	NS	NS	CIS	CIS	CIS	CIS
Easting:	414209	413869	413588	413282	413561	414462	414229	414485	425678	425274	424093	424669
Northing:	6887486	#####	6886358	6886386	6886606	6887411	6887717	6887301	6876858	6873452	6877977	6878185
SiO ₂ (wt.%)	46.97	48.45	59.36	63.51	58.35	54.96	51.99	52.18	56.99	52.64	47.66	52.31
Al ₂ O ₃	15.2	13.54	15.9	16.08	16.78	14.85	17.48	16.99	17.11	17.22	13.86	21.07
CaO	12.75	11.79	4.82	3.58	5.75	7.07	7.73	7.94	3.65	5.05	7.59	4.73
K ₂ O	1.166	1.001	3.798	4.112	3.26	2.788	2.84	2.8	1.37	1.025	1.104	3.523
MgO	8.59	9.9	2.42	1.68	3.12	5.45	4.27	4.7	3.88	4.7	6.57	2.54
MnO	0.161	0.201	0.126	0.087	0.13	0.149	0.13	0.13	0.115	0.087	0.217	0.105
Na ₂ O	1.54	1.56	3.88	4.27	3.77	3.12	3.48	3.55	6.61	6.21	3.69	4.84
P ₂ O ₅	0.101	0.155	0.244	0.216	0.2	0.176	0.3	0.22	0.2	0.178	0.384	0.34
Fe ₂ O ₃	10.818	11.44	6.559	4.807	7.06	7.803	9.62	8.48	7.276	8.17	11.845	6.383
TiO ₂	0.772	0.673	0.741	0.525	0.58	0.564	1.01	0.61	0.594	0.653	0.91	0.726
LOI	1.22	1.52	1	0.97	0.81	1.38	0.12	2.32	2.56	5.96	3.11	3.78
Total	98.225	98.91	98.074	99.1	99.8	97.148	98.99	99.94	97.919	96.051	93.967	96.794
Ba (ppm)	336.5	477.8	974.3	1039.3	878	711.3	749.9	750.4	317.3	294.9	214.3	1035.9
Be	0.72	0.5	2.3	2.69	1.47	1.66	1.34	1.46	1.67	1.74	1.09	1.69
Bi	0.15	0.055	bld	bld	0.061	0.15	0.041	0.04	0.17	bld	bld	0.76
Cd	0.11	0.12	0.08	0.09	0.10	0.13	0.11	0.07	0.07	0.03	0.37	0.09
Ce	20.1	22.87	63.53	68.44	54	48.73	51.73	51.78	50.29	46.62	45.87	44.6
Co	55.47	59.7	18.77	12.07	21.8	32.29	33.3	31.9	25.62	31.63	46.8	19.35
Cr	196	377	74	114	120	317	76	72	41	70	126	16
Cs	1.37	1.12	4.29	2.31	2.00	1.99	1.85	1.21	0.15	0.32	0.46	1.99
Cu	33.3	60	48.2	18	31	35.9	32	6	19.3	7.5	19.7	32.2
Dy	1.83	2.39	2.38	2.08	2.63	2.98	2.96	3.10	2.71	2.78	2.96	2.20
Er	0.83	1.21	1.13	0.97	1.34	1.56	1.33	1.56	1.48	1.44	1.44	1.14
Eu	1.04	1.03	1.49	1.34	1.41	1.34	1.74	1.43	1.07	1.17	1.35	1.37
Ga	16.35	13.66	20.58	20.92	19.13	17.56	20.76	18.47	17.91	19.09	17.16	21.73
Gd	2.45	2.96	3.47	3.02	3.36	3.75	4.42	4.08	3.25	3.60	3.96	2.85
Hf	1.07	1.08	3.39	4.26	2.54	2.48	2.46	2.87	2.98	2.72	1.87	1.93
Ho	0.333	0.45	0.428	0.359	0.49	0.566	0.53	0.57	0.519	0.528	0.541	0.41
In	0.05	0.04	0.04	0.04	0.05	0.05	0.05	0.04	0.04	0.05	0.05	0.03
La	9.87	9.9	34	36.95	28.24	24.48	24.47	24.97	25.76	22.78	22.72	24.78
Li	9.6	6.4	13	12.5	18.3	21.5	8.1	19	21.8	42.1	44.3	70.8
Lu	0.10	0.15	0.15	0.13	0.18	0.21	0.16	0.21	0.20	0.19	0.18	0.15
Mo	0.49	0.34	1.88	1.11	1.98	1.38	1.57	0.97	0.73	0.31	0.45	0.24
Nb	2.414	2.85	11.026	15.57	9.9	7.541	6.66	9.46	6.336	8.001	4.947	5.14
Nd	11.65	13.84	25.88	26.05	22.49	23.09	26.11	24.79	21.56	21.97	23.17	19.24
Ni	54.7	86	12.9	16.1	19	67.6	26	25	13.4	25	37	5.2
Pb	3.7	3.8	16.5	14	12.1	9.6	11.6	5.3	8.8	1.5	50.3	28.4
Pr	2.658	3.12	7.045	7.385	6.03	5.735	6.4	6.14	5.727	5.597	5.609	5.024
Rb	35.73	28.27	148.78	152.81	97.85	91.01	76.31	93.16	36.21	30.52	25.36	112.64
Sb	0.07	0.05	0.19	0.1	0.1	0.15	0.12	0.08	0.18	0.16	0.13	0.22
Sc	43.5	44.2	13.1	7.3	14.2	23.2	16.3	24.8	18.7	25.7	30.5	12.8
Sm	2.664	3.15	4.702	4.423	4.18	4.679	5.39	4.99	3.98	4.446	4.7	3.623
Sn	0.54	0.47	1.98	1.96	1.2	1.53	1.03	1.39	1.22	0.81	0.88	0.41
Sr	578.9	519	612.4	586.9	564	517.2	685	495	177.3	208.4	240.7	723.7
Ta	0.15	0.20	0.76	1.05	0.70	0.46	0.40	0.60	0.44	0.51	0.31	0.32
Tb	0.32	0.41	0.45	0.40	0.46	0.52	0.57	0.56	0.46	0.49	0.53	0.39
Th	0.923	0.57	11.179	14.079	5.98	4.471	3.77	5.55	7.068	5.25	3.199	3.51
Tl	0.16	0.13	0.73	0.58	0.39	0.36	0.20	0.38	0.08	0.05	0.08	0.34
Tm	0.11	0.17	0.16	0.14	0.19	0.22	0.17	0.22	0.21	0.20	0.20	0.16
U	0.30	0.25	2.77	3.00	1.81	1.24	1.44	1.48	2.11	1.82	1.11	1.12
V	346.8	259.6	110.8	58.2	101.09	137.8	162.54	166.71	149.9	200.9	308.5	129.1
W	0.31	bld	1.93	5.27	0.97	0.87	0.55	bld	0.38	0.29	0.36	0.31
Y	8.42	11.26	12.04	10.41	13.22	15.35	13.56	15.31	14.07	14.01	14.52	11.42
Yb	0.71	1.05	1.02	0.88	1.22	1.43	1.08	1.40	1.37	1.28	1.23	1.01
Zn	70	76.46	72	55	71.08	84	92.66	55.36	126	70	233	73
Zr	29	32	126	156	99	92	90	113	115	100	70	66

Note: Eastings and northings are in UTM zone 12, North American Datum 83. bld, below detection limit; odl, over detection limit; LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. LR, layered raft; SS, south stock; NS, north stock; CIS, Compton intrusive suite; Hearne, Hearne diabase; Camp-DB, camp road diabase.

Chapter 3 whole rock geochemistry cont.

Sample:	549A	550A	1068A	1065A	1066A	1195A	1197A	338A	351A	373A	417A	448A
Unit:	CIS	CIS	CIS	CIS	CIS	Hearne	Hearne	Hearne	Hearne	Hearne	Hearne	Hearne
Easting:	386217	376726	425136	427953	429774	404243	400898	417520	412013	417730	408826	408510
Northing:	6867413	6866677	6874176	6877044	6876832	6881307	6879455	6891178	6892255	6889500	6890196	6884484
SiO ₂ (wt.%)	50.4	48.91	51.32	54.82	52.13	50.7	49.81	49.94	48.41	50.71	50.06	50.57
Al ₂ O ₃	19.7	20.43	16.89	17.35	17.38	14.72	14.45	11.99	11.98	12.04	11.87	11.64
CaO	6.35	9.58	7.21	3.6	4.71	8.45	3.62	7.72	9.85	5.24	6.8	7.69
K ₂ O	2.79	2.06	2.867	2.274	2.806	1.168	2.246	1.15	0.42	3.03	1.29	1.43
MgO	3.09	3.03	5.49	4.2	4.62	4.6	3.36	5.13	5.28	3.82	4.75	3.92
MnO	0.09	0.09	0.184	0.109	0.137	0.211	0.142	0.24	0.25	0.21	0.22	0.23
Na ₂ O	4.56	3.98	2.93	5.42	4.45	2.77	2.68	2.44	2.36	3.1	2.79	2.26
P ₂ O ₅	0.45	0.29	0.166	0.255	0.215	0.169	0.275	0.2	0.13	0.27	0.21	0.26
Fe ₂ O ₃	6.54	7.55	9.811	8.378	9.98	14.04	16.078	16.55	16.62	17.52	17.36	16.77
TiO ₂	0.88	0.89	0.647	0.786	0.914	1.505	2.265	2.02	1.63	2.4	2.23	2.31
LOI	3.71	3.29	3.36	3.46	5.64	1.33	3.84	2.62	2.14	2.37	2.43	3.3
Total	98.57	100.08	97.717	97.327	97.533	98.477	95.101	99.99	99.07	100.7	99.99	100.36
Ba (ppm)	1353.3	597.5				253.7	499.2	157	69.6	230.5	335.1	349.6
Be	1.31	1.02				0.91	2.2	1.47	0.79	3.61	1.2	1.87
Bi	0.039	0.099				0.16	bld	0.026	0.027	0.045	0.036	0.027
Cd	0.05	0.08				0.17	0.08	0.12	0.14	0.54	0.12	0.16
Ce	50.76	35.53				34.14	61.63	38.38	22.49	57.65	43.56	54.06
Co	17.8	23.1				48.06	44.07	52	60.5	47.8	51.4	50.7
Cr	32	37				96	45	47	80	26	30	43
Cs	0.27	0.73				2.29	1.63	3.83	4.01	8.24	1.07	11.10
Cu	29	32				185.9	284	78	102	102	53	84
Dy	2.88	2.06				5.09	7.83	7.33	6.37	9.04	8.01	8.41
Er	1.37	0.92				2.87	4.37	4.37	3.84	5.23	4.70	5.09
Eu	1.75	1.45				1.52	2.04	1.93	1.51	2.46	1.93	2.12
Ga	18.66	17.95				20.47	25.65	20.47	21.17	21.6	20.81	21.63
Gd	4.18	3.04				5.11	7.94	6.94	5.42	8.97	7.61	8.51
Hf	1.92	1.29				3.51	6.27	4.45	3.02	6.02	5	5.73
Ho	0.53	0.36				1.019	1.546	1.48	1.33	1.84	1.61	1.74
In						0.08	0.10					
La	24.4	17.39				14.96	27.03	17.68	9.47	26.95	20.22	25.61
Li	29.8	25.1				21.3	27.9	34.2	9.5	40.3	33.7	11.4
Lu	0.17	0.11				0.37	0.57	0.59	0.53	0.71	0.64	0.67
Mo	1.14	1.37				0.8	1.49	0.77	0.58	2.96	0.83	1.13
Nb	5.06	3.37				6.985	12.589	7.65	4.27	10.41	8.49	10.11
Nd	26.03	17.72				20.25	34.5	22.17	14.81	31.74	24.93	29.84
Ni	5	10				61.4	29.4	28	39	25	25	27
Pb	25	3.7				5.4	4.6	5.3	6.7	51.2	4.8	8.3
Pr	6.26	4.29				4.613	8.176	5.1	3.15	7.43	5.67	6.91
Rb	53.44	53.94				51.02	106.87	63.91	14.65	165.30	30.19	69.33
Sb	0.17	0.1				0.08	1.54	0.07	0.05	0.14	0.09	0.06
Sc	18.5	22.2				36.3	32.9	45.2	55.6	42.8	44.8	41.6
Sm	5.21	3.64				4.859	7.948	5.92	4.39	7.99	6.51	7.4
Sn	0.47	0.53				2.07	2.83	1.17	1.12	2.25	1.12	1.72
Sr	666	584				221.6	289.2	145	143	169	173	179
Ta	0.30	0.20				0.46	0.82	0.50	0.30	0.70	0.60	0.70
Tb	0.55	0.39				0.81	1.27	1.14	0.95	1.45	1.25	1.37
Th	3.66	1.5				1.961	3.427	3.9	2.34	7.11	4.83	6.86
Tl	0.16	0.17				0.25	0.42	0.19	0.14	0.58	0.13	0.51
Tm	0.18	0.12				0.41	0.62	0.62	0.55	0.75	0.67	0.71
U	0.81	0.63				0.55	0.89	0.70	0.40	1.43	0.83	1.37
V	169.34	254.52				269.8	251.8	397.09	432.31	421.71	412.39	405.33
W	bld	bld				0.65	0.6	bld	bld	0.63	bld	bld
Y	14.09	9.65				27.16	41.04	39.42	34.37	48.35	41.59	45.39
Yb	1.13	0.75				2.51	3.91	4.02	3.53	4.77	4.26	4.54
Zn	56.36	51.05				137	134	128.28	142.54	384.59	113.47	208.8
Zr	75	47	132	104	86	125	223	169	109	228	189	215

Note: Eastings and northings are in UTM zone 12, North American Datum 83. bdl, below detection limit; odl, over detection limit; LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. LR, layered raft; SS, south stock; NS, north stock; CIS, Compton intrusive suite; Hearne, Hearne diabase; Camp-DB, camp road diabase.

Chapter 3 whole rock geochemistry cont.

Sample:	495A	498A	499A	1021B	1021C	1024A	374A	542A	537A	607A		
Unit:	Hearne	Hearne	Hearne	Camp-DB	Camp-DB	Camp-DB	Camp-DB	Camp-DB	Camp-DB	Camp-DB	Precision	
Easting:	402512	404567	404191	414399	414363	414664	414510	413565	415104	412959	Average	Detection
Northing:	6879745	6881443	6881249	6887201	6887175	6887631	6887271	6886610	6889356	6886345	diff (%)	limit
SiO ₂ (wt.%)	48.48	39.7	42.98	38.08	43.47	50.63	49.55	50.77	50.49	51.2	1.75	0.01
Al ₂ O ₃	12.89	12.85	12.72	9.99	13.31	13.41	12.54	12.98	12.98	14	1.58	0.01
CaO	9.17	12.47	8.06	7.45	9.09	7.81	8.09	8.67	8.4	9.21	0.05	0.01
K ₂ O	1.02	0.17	1.12	3.343	1.176	1.197	1.57	0.94	1.12	0.78	3.71	0.01
MgO	6.65	2.98	7.01	5.52	4.71	5.38	5.95	4.86	5.29	5.15	1.38	0.01
MnO	0.24	0.43	0.29	0.407	0.269	0.215	0.27	0.25	0.25	0.22	6.37	0.01
Na ₂ O	2.21	4.53	2.39	2.29	3	2.75	2.8	0.25	2.89	3.16	2.77	0.01
P ₂ O ₅	0.11	0.12	0.12	1.074	0.491	0.169	0.1	0.18	0.18	0.16	4.84	0.01
Fe ₂ O ₃	13.06	11.33	12.71	23.554	17.857	15.536	15.79	16.24	15.85	14.7	0.99	0.01
TiO ₂	1.27	1.41	1.37	7.023	5.323	1.737	1.93	1.8	1.81	1.67	2.54	0.01
LOI	4.81	13.45	10.47	0.23	1.43	1.79	1.39	0.51	0.97	0.99	9.93	0.05
Total	99.89	99.45	99.23	99.093	98.869	98.964	99.97	100.32	100.23	101.5		
Ba (ppm)	77.7	60.7	150.5	107	137.8	209.8	193.7	146.4	145.8	146	0.89	0.9
Be	0.52	1.7	2.96	1.61	2.71	1.82	3.58	2.77	1.32			0.06
Bi	0.119	0.02	0.747	bld	1.04	0.23	0.257	0.037	0.092			0.009
Cd	0.06	0.05	0.15	0.17	0.15	0.21	0.12	0.09	0.11			0.01
Ce	16.46	19.34	20.96	34.39	20.06	29.97	30.1	36.35	32.9	36.4	6.31	0.2
Co	41.1	48.3	34	55.35	54.66	49.71	49.4	49.7	48.5	46.5	7.40	0.1
Cr	157	109	113	84	82	69	71	71	70	60	52.00	24
Cs	0.77	0.49	1.91	1.20	3.26	1.86	2.24	1.15	1.06	0.79		0.01
Cu	72	105	113	76	94.3	64.7	47	44	74	72	27.99	2
Dy	4.88	5.21	5.19	6.74	5.53	6.30	5.56	7.19	6.62	7.04	6.02	0.20
Er	2.99	3.16	3.24	3.97	3.35	3.86	3.30	4.42	4.01	4.21	5.80	0.01
Eu	1.16	1.20	0.95	1.48	1.38	1.49	1.38	1.58	1.57	1.72	5.61	0.01
Ga	16.83	16.84	17.35	21.86	21.28	20.09	19.65	19.95	19.74	20.6		0.05
Gd	4.17	4.75	4.60	6.19	4.91	5.57	5.16	6.75	6.18	6.37	0.97	0.02
Hf	2.38	2.46	2.49	3.22	2.2	3.83	2.34	3.25	2.61	4.3	13.62	0.09
Ilo	1.01	1.09	1.08	1.39	1.162	1.322	1.14	1.51	1.37	1.54	5.57	0.003
In				0.10	0.14	0.09						0.00
La	6.87	8.32	10.31	15.26	8.47	13.3	13.71	16.55	15.89	16.7	8.82	0.09
Li	36	34	132.2	22	16.9	26.9	27.8	18.1	25.9			0.2
Lu	0.41	0.45	0.44	0.54	0.46	0.54	0.45	0.60	0.55	0.61	0.95	0.00
Mo	0.65	0.84	0.23	0.71	0.5	1.75	0.5	1.37	1.13	<2		0.03
Nb	3.39	3.73	3.6	13.189	3.931	6.518	6.88	8.16	6.85	7.7	64.79	0.04
Nd	11.16	13.25	12.8	21.11	13.81	18.04	17.56	21.55	19.02	22.1	4.09	0.08
Ni	60	53	55	40.2	38.7	34.8	43	36	37	32	6.70	3
Pb	2.4	4.9	5.9	2.9	3.4	24.6	7.9	4	4.9	<5		0.4
Pr	2.34	2.77	2.77	4.68	2.885	3.997	4.05	4.86	4.31	5.09	4.77	0.02
Rb	53.65	4.05	10.21	61.15	74.74	52.14	73.28	45.78	52.01	33.10	5.35	0.20
Sb	bld	0.21	0.04	0.36	0.16	0.16	0.15	0.06	0.07			0.04
Sc	52.9	51.3	52.1	50.5	52.2	47.8	51	47.4	48			0.9
Sm	3.31	3.83	3.61	5.571	4.135	4.859	4.58	5.73	5.07	5.55	6.27	0.02
Sn	0.79	0.9	0.91	1.46	2.66	0.99	4.26	1.81	2.15	1		0.08
Sr	111	106	67	164.1	161.3	135.2	160	145	147	170	2.24	2
Ta	0.30	0.30	0.20	0.82	0.27	0.48	0.40	0.60	0.50	0.60	47.89	0.20
Tb	0.73	0.81	0.80	1.05	0.83	0.96	0.86	1.12	1.03	1.05	0.81	0.00
Th	1.42	1.53	1.62	4.036	2.542	5.449	2.92	5.49	4.41	6.04	3.33	0.09
Tl	0.21	0.11	0.03	0.30	0.48	0.25	0.42	0.19	0.25	bld		26.00
Tm	0.43	0.46	0.46	0.58	0.48	0.56	0.47	0.63	0.57	0.60	5.59	0.00
U	0.25	0.26	0.26	0.63	0.40	0.87	0.91	0.92	0.74	0.82	3.10	0.02
V	329.56	367.13	360.86	odl	odl	odl	422.57	397.81	403.76	403	0.81	10
W	bld	bld	bld	1.1	2.15	0.56	1.26	0.76	1.6	1		0.5
Y	26.85	28.82	28.83	37.03	30.33	33.9	29.49	39.59	35.98	39.6	12.04	0.08
Yb	2.76	2.97	2.98	3.65	3.09	3.67	3.05	4.09	3.73	4.03	1.28	0.01
Zn	107.77	83.14	173.41	144	134	138	136.29	178.91	106.86	105	26.19	8
Zr	87	90	91	444	84	132	81	116	91	141	16.01	3

Note: Eastings and northings are in UTM zone 12, North American Datum 83. bdl, below detection limit; odl, over detection limit; LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. LR, layered raft; SS, south stock; NS, north stock; CIS, Compton intrusive suite; Hearne, Hearne diabase; Camp-DB, camp road diabase.

A.3 Western lobe whole rock geochemistry

SAMPLE:	1075A	1075C	1076A	1076B	1077C	1078A	1079A	1079B	329A
Unit:	CLG-leucogabbro	CLG-gabbro	CLG-peridotite	CLG-pyroxenite	CLG-peridotite	CLG-gabbro	CLG-leucogabbro	CLG-ol-rich gabbro	CLG-gabbro
EASTING:	409023	408691	409457	409661	408589	408870	408385	408538	405717
NORTHING:	6893626	6893677	6893881	6893728	6893779	6893473	6893524	6893626	6887815
SiO ₂ (wt.%)	47.68	47.46	36.25	45.89	37.5	43.03	40.51	43.38	45.96
Al ₂ O ₃	18.2	11.56	1.39	3.27	1.65	13.22	12.17	14.08	13.33
CaO	11.83	13.37	0.81	12.91	3.64	9	12.03	10.55	9.98
K ₂ O	0.92	0.18	0.05	0.17	0.06	1.16	0.44	0.60	0.69
MgO	7.15	12.29	31.51	19.7	26.82	4.68	6.64	5.57	11.47
MnO	0.098	0.147	0.177	0.169	0.16	0.267	0.207	0.199	0.15
Na ₂ O	2.65	1.57	<0.01	0.33	0.02	2.98	1.8	2.74	1.94
P ₂ O ₅	0.01	0.038	0.067	0.032	0.016	0.485	0.039	0.144	0.01
Fe ₂ O ₃	8.368	11.735	20.07	12.86	22.308	17.741	19.95	15.686	13.34
TiO ₂	0.748	1.051	0.602	0.715	0.607	5.353	4.813	5.932	0.85
L.O.I.	2.01	0.12	11.38	5.22	7.29	1.1	0.48	0.95	1.56
Sum	97.81	99.59	91.39	96.40	93.13	98.09	98.77	99.05	99.28
Ba (ppm)	133.1	57.4	13.9	42	11.2	469	140.4	219.4	117.3
Be	0.26	0.35	0.28	1.02	0.31	1.09	0.41	0.58	0.38
Bi	<0.15	<0.15	0.18	<0.15	0.16	<0.15	<0.15	<0.15	0.39
Cd	0.08	0.14	0.06	0.12	0.27	0.19	0.11	0.12	0.21
Ce	3.12	8.11	7.39	21.21	10.14	40.16	11.49	17.69	5.49
Co	52.01	76.81	166.05	102.38	149.64	49.9	73.39	57.86	95.7
Cr	423	882	4221	2357	1527	20	35	27	465
Cs	0.74	0.24	0.62	1.51	0.67	1.59	0.75	0.65	1.47
Cu	80.9	165.7	93.8	409.5	281.9	23.1	73.8	21	345
Dy	0.67	1.412	0.847	1.889	0.691	3.595	1.937	1.929	1.01
Er	0.29	0.62	0.39	0.85	0.31	1.46	0.75	0.75	0.48
Eu	0.44	0.64	0.33	0.86	0.64	2.72	1.38	1.74	0.47
Ga	19.62	15.2	4.94	8.81	4.37	23.01	22.24	20.54	17.23
Gd	0.80	1.72	1.11	2.41	0.88	5.28	2.65	2.75	1.15
Hf	0.32	0.79	0.49	1.24	0.38	2.39	1.45	1.55	0.53
Hf	0.12	0.25	0.15	0.34	0.12	0.61	0.33	0.32	0.19
In	0.03	0.04	0.03	0.05	0.04	0.09	0.08	0.07	0.05
La	1.3	3.14	3.8	9.35	6.37	16.73	4.09	7.18	2.33
Li	29.8	6.4	22.6	37.8	15	34.4	11.8	15.6	21.1
Lu	0.03	0.06	0.04	0.09	0.03	0.14	0.07	0.07	0.05
Mo	0.21	0.41	0.2	0.9	0.45	1.48	0.48	0.55	0.4
Nb	0.28	2.72	2.49	4.72	0.63	27.78	4.80	18.33	2.37
Nd	2.63	5.95	4.74	11.65	4.01	26.2	9.8	12.57	3.74
Ni	181.1	332.9	2021.4	928.8	1633.2	11.2	72.1	10.2	713
Pb	4.5	1.1	1.8	1.6	6.2	6.1	0.6	1.7	3.4
Pr	0.49	1.20	1.04	2.77	1.01	5.69	1.88	2.59	0.80
Rb	33.32	4.52	2.59	16.6	3.43	34	15.63	14.67	22.38
Sb	0.1	0.04	<0.04	<0.04	0.05	0.04	<0.04	<0.04	0.05
Sc	25.4	41.3	12	59	20.7	19.3	30.6	21.1	22.4
Sm	0.73	1.67	1.18	2.60	0.92	5.96	2.75	2.97	1.08
Sn	0.43	0.58	0.46	0.79	0.74	2.64	0.48	0.54	0.96
Sr	548.9	354.7	16.9	42.6	30.7	742.8	768.6	1098.4	396
Ta	0.03	0.18	0.19	0.28	0.05	1.92	0.37	1.43	0.20
Tb	0.12	0.25	0.15	0.34	0.13	0.70	0.37	0.36	0.18
Th	0.05	0.29	0.17	0.76	0.10	1.10	0.11	0.34	0.45
Tl	0.09	0.03	0.47	0.36	0.31	0.21	0.10	0.11	0.22
Tm	0.04	0.08	0.05	0.11	0.04	0.17	0.09	0.09	0.06
U	0.02	0.16	0.09	0.27	0.08	0.29	0.03	0.08	0.30
V	271.3	319.6	149.1	222.3	171.3	167.6	>370	252.5	284.46
W	0.43	0.29	0.41	0.47	0.58	1.69	0.13	0.17	<0.5
Y	3.01	6.18	3.82	8.93	3.14	15.82	8.11	8.05	4.58
Yb	0.21	0.45	0.30	0.62	0.22	1.04	0.52	0.51	0.37
Zn	53	69	108	57	127	172	142	106	81.27
Zr	<10	21	17	30	11	87	35	46	14

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. CLG, Caribou Lake gabbro; LFD, leucoferrodiorite; HGG, Hearne granitic group; WGG, Whiteman granitic group

Western lobe whole rock geochemistry cont.

SAMPLE:	329B	329C	330A	330B	330C	330D	330E	331A	332A
Unit:	CLG- gabbro	CLG- leucogabbro	CLG- peridotite	CLG- peridotite	CLG- peridotite	CLG- peridotite	CLG- peridotite	CLG- gabbro	CLG- melagabbro
EASTING:	405717	405717	406260	406260	406260	406260	406260	407097	407962
NORTHING:	6887815	6887815	6887841	6887841	6887841	6887841	6887841	6889117	6889931
SiO ₂ (wt.%)	41.96	46.49	36.11	38.94	36.97	40.21	36.84	37.97	37.24
Al ₂ O ₃	12.74	15.63	1.96	2.15	2.08	1.64	2.59	6.72	10.54
CaO	11.67	13.2	1.45	5.42	1.57	3.13	1.91	12.59	11.64
K ₂ O	0.35	0.30	0.11	0.16	0.10	0.03	0.10	0.39	0.60
MgO	8.04	7.83	30.69	25.54	29.58	26.4	29.82	13.9	7.44
MnO	0.16	0.12	0.17	0.22	0.18	0.1	0.22	0.23	0.2
Na ₂ O	1.93	2.18	0.09	0.22	0.1	0.1	0.18	0.45	1.38
P ₂ O ₅	<0.01	0.01	0.04	0.19	0.04	0.02	0.02	0.01	0.09
Fe ₂ O ₃	18.3	12.04	18.06	17.96	18.22	19.49	18.4	24.05	25
TiO ₂	2.83	1.5	0.6	0.53	0.59	0.48	0.29	3.59	3.65
L.O.I.	1.58	1.14	9.77	8.03	9.44	7.36	8.73	0.51	1.6
Sum	99.57	100.42	99.05	99.35	98.88	98.98	99.10	100.40	99.37
Ba (ppm)	61.3	57.4	22.2	59.9	17.7	8	48.6	63	193.1
Be	0.2	0.17	0.26	0.31	0.61	0.21	0.2	0.27	0.47
Bi	0.213	0.092	0.221	0.143	0.172	0.172	0.283	0.124	0.56
Cd	0.17	0.12	0.03	0.17	0.13	0.07	0.10	0.28	0.52
Ce	3.29	3.23	5.69	24.33	13.7	4.53	4.7	7.18	18.82
Co	86.3	63	166.3	156.6	181.9	193.6	196.7	136	184.9
Cr	218	401	>600	>600	>600	>600	395	>600	164
Cs	0.89	0.51	0.77	1.92	1.19	0.43	0.75	0.62	1.54
Cu	145	118	47	405	222	151	338	392	>800
Dy	0.96	0.85	0.75	2.44	1.01	0.56	0.51	1.67	2.43
Er	0.42	0.37	0.33	1.02	0.46	0.25	0.24	0.67	0.99
Eu	0.50	0.49	0.31	1.00	0.40	0.28	0.29	0.80	1.24
Ga	21.59	18.61	5.29	5.59	5.65	6.51	4.43	20.04	23.86
Gd	1.10	1.02	0.93	3.21	1.24	0.70	0.60	2.15	3.11
Hf	0.42	1.01	0.44	0.85	0.71	0.39	0.31	1.21	1.95
Ho	0.17	0.15	0.13	0.42	0.18	0.10	0.09	0.29	0.41
In									
La	1.28	1.21	2.84	10.24	6.37	2.05	2.03	2.25	7.5
Li	26.8	16	26.5	20.6	33.5	21.3	10.4	39.2	17.3
Lu	0.04	0.04	0.04	0.10	0.05	0.03	0.03	0.07	0.10
Mo	0.21	0.29	0.2	0.24	0.21	0.2	0.13	0.34	1.81
Nb	0.54	0.49	1.79	3.31	4.30	0.81	2.13	2.82	9.79
Nd	2.98	2.94	3.82	15.55	6.64	2.8	2.73	6.77	12.71
Ni	170	163	1978	1631	>2000	>2000	1982	500	1593
Pb	3	1.6	2.1	2.9	4	0.9	2.4	2.1	5
Pr	0.56	0.55	0.80	3.38	1.68	0.61	0.63	1.26	2.71
Rb	10.87	7.83	3.99	7.34	6.55	1.48	3.89	13.88	20.01
Sb	<0.04	<0.04	0.04	0.04	<0.04	<0.04	<0.04	<0.04	0.05
Sc	30.2	24.5	13.3	31.9	14.3	21.3	14	55.6	34.7
Sm	0.96	0.90	0.98	3.55	1.43	0.68	0.65	2.08	3.20
Sn	0.49	0.33	0.34	0.63	0.6	0.25	0.2	1.25	4.62
Sr	355	525	22	38	23	19	61	165	415
Ta	<0.2	<0.2	<0.2	0.20	0.40	<0.2	0.20	0.20	0.70
Tb	0.16	0.15	0.13	0.45	0.18	0.10	0.09	0.31	0.45
Th	<0.09	<0.09	0.21	0.34	0.66	0.16	0.27	<0.09	0.59
Tl	0.07	0.05	0.39	0.42	0.51	0.34	0.23	0.12	0.23
Tm	0.06	0.05	0.04	0.13	0.06	0.03	0.03	0.08	0.12
U	0.07	0.03	0.09	0.14	0.26	0.08	0.05	0.03	0.19
V	>500	474.83	141.71	152.53	137.89	185.05	59.62	>500	>500
W	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	<0.5	0.86
Y	4.12	3.6	3.38	10.25	4.63	2.47	2.35	7.04	10.22
Yb	0.30	0.26	0.28	0.71	0.37	0.21	0.22	0.47	0.72
Zn	116.06	57.57	86.33	106.28	133.89	149.97	100.88	143.03	170.23
Zr	9	38	14	27	24	12	10	30	62

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. CLG, Caribou Lake gabbro; LFD, leucoferrodiorite; HGG, Hearn granitic group; WGG, Whiteman granitic group

Western lobe whole rock geochemistry cont.

SAMPLE:	1149A	1149B	403A	1075B	1078B	420A	1077B	441A	1160A	1172A
	CLG- gabbro	CLG- gabbro	CLG-chill margin	LFD	LFD	LFD	LFD	LFD	HGG	HGG
Unit:										
FASTING:	404663	404663	405496	409252	408742	406641	409176	407245	406982	408265
NORTHING:	6884601	6884543	6889220	6893575	6893856	6888714	6893830	6885351	6884010	6881308
SiO ₂ (wt.%)	33.29	32.54	54.17	60.7	60.3	48.86	60.7	53.6	68.96	72
Al ₂ O ₃	14.49	14.15	13.26	13.69	15.12	18.53	14.96	20.25	13.11	12.84
CaO	9.47	7.88	5.41	3.17	2.67	9.79	2.79	5.85	1.34	0.98
K ₂ O	0.23	0.23	1.46	3.96	3.84	1.18	3.83	2.10	4.87	5.18
MgO	5.97	7.43	3.63	0.35	0.65	2.15	0.53	0.78	0.2	0.24
MnO	0.184	0.214	0.136	0.243	0.22	0.2	0.211	0.17	0.052	0.053
Na ₂ O	1.47	1.27	4.22	4.64	4.93	4.46	5.11	5.97	3.84	3.74
P ₂ O ₅	0.025	0.023	0.3	0.174	0.127	0.75	0.128	0.5	0.06	0.04
Fe ₂ O ₃	26.722	29.149	13.102	9.87	9.312	10.81	9.522	6.86	3.897	3.03
TiO ₂	5.277	5.389	2.691	0.932	0.843	2.44	0.87	1.16	0.375	0.297
L.O.I.	0.96	1.37	0.4	0.69	1.45	1.04	0.66	2.47	1.13	2.53
Sum	97.38	98.53	98.53	98.00	98.33	100.22	98.99	99.71	96.93	98.62
Ba (ppm)			216.5	1715.7	>1740	502	>1740	1277.7		578.6
Be			2.98	1.92	1.97	1.06	2.21	0.46		10.76
Bi			0.308	<0.15	<0.15	0.036	<0.15	0.043		<0.15
Cd			0.15	0.27	0.36	0.15	0.36	0.09		0.15
Ce			39.31	93.98	84.36	58.63	85.24	24.89		277.78
Co			43.4	3.08	5.42	18.7	4.87	4.2		1.86
Cr			58	56	73	37	70	34		131
Cs			12.96	1.59	1.71	3.79	3.48	1.70		2.64
Cu			59	7.7	16.7	5	14.9	3		6.3
Dy			3.68	6.432	6.296	4.58	6.39	1.68		15.872
Er			1.66	2.86	2.86	1.78	3.00	0.62		7.35
Eu			1.45	4.97	5.40	3.49	5.52	4.08		2.57
Ga			24.78	27.33	29.62	24.77	31.34	26.5		28.17
Gd			4.77	9.04	8.67	6.89	8.98	2.86		18.62
Hf			2.6	2.22	9.64	2.23	8.4	0.78		12.96
Ho			0.65	1.12	1.11	0.78	1.15	0.27		2.81
In				0.18	0.18		0.18			0.05
La			16.78	40.38	37.97	24.23	38.39	10.52		135.3
Li			21.4	5.2	6.9	20.9	7.5	37.5		7.5
Lu			0.19	0.38	0.39	0.17	0.42	0.07		0.68
Mo			1.22	3.28	2.11	1.33	2.16	0.88		2.86
Nb			21.89	55.31	63.60	29.63	67.16	8.22		66.83
Nd			22.25	53.54	49.54	36.62	51.36	16.41		110.98
Ni			27	3.6	15.1	4	12.5	4		3.9
Pb			6.7	10.2	11.6	3.8	10.6	3.9		21.4
Pr			5.13	12.46	11.29	8.00	11.59	3.52		31.15
Rb			162.64	68.17	51.87	64.32	61.59	50.71		220.15
Sb			<0.04	0.06	0.06	0.04	0.05	0.04		0.12
Sc			20.3	9.1	8.9	10.7	9.5	3.8		2.8
Sm			5.16	11.28	10.57	7.91	10.91	3.42		22.74
Sn			7.11	2.01	2.58	1.21	1.79	17		7.13
Sr			293	356.1	319.4	1065	329.4	1515		107.6
Ta			2.10	2.89	3.06	1.90	3.19	0.60		6.54
Tb			0.68	1.21	1.16	0.90	1.22	0.34		2.83
Th			3.14	4.49	3.79	1.48	4.11	0.62		52.54
Tl			1.03	0.28	0.26	0.30	0.27	0.35		0.77
Tm			0.23	0.38	0.38	0.22	0.40	0.08		0.95
U			5.55	1.21	1.08	0.45	1.09	0.17		10.02
V			405.96	4.8	21.1	43.78	18.8	<10		4.2
W			1.82	1.22	1.25	3.63	1.18	0.62		3
Y			16.68	27.75	27.45	19.06	28.85	6.78		75.57
Yb			1.34	2.45	2.49	1.19	2.61	0.46		5.40
Zn			116.56	168	191	101.11	210	103.48		67
Zr	24	18	86	76	419	78	414	28	496	415

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. CLG, Caribou Lake gabbro; LFD, leucoferrodiorite; HGG, Hearne granitic group; WGG, Whiteman granitic group

Western lobe whole rock geochemistry cont.

SAMPLE:	1179A	1183A	1190A	444A	449A	483A	492A	1076C	1080A	1102A
	HGG	HGG	HGG	HGG	HGG	HGG	HGG	WGG	WGG	WGG
Unit:										
EASTING:	409141	409360	405098	408090	408436	406438	408052	409635	408563	409968
NORTHING:	6883871	6882351	6881204	6885190	6884140	6881628	6881744	6893881	6893958	6890259
SiO ₂ (wt.%)	72.67	72.45	70.47	70.71	74.66	68.12	75.81	61.78	70.02	65.42
Al ₂ O ₃	11.66	12.98	12.98	12.6	11.91	13.06	11.87	14.19	12.84	13.61
CaO	0.65	0.62	1.04	1.09	0.72	1.87	0.52	2.01	1	2.35
K ₂ O	5.27	5.57	5.00	4.98	5.02	4.62	5.61	4.21	4.88	3.89
MgO	0.12	0.19	0.19	0.24	0.14	0.6	0.04	1.47	0.91	0.97
MnO	0.048	0.049	0.069	0.07	0.04	0.08	0.04	0.189	0.111	0.116
Na ₂ O	3.39	3.37	3.84	3.75	3.66	4.06	3.46	3.96	3.2	4.19
P ₂ O ₅	0.01	0.03	0.044	0.07	0.02	0.21	0.01	0.118	0.04	0.244
Fe ₂ O ₃	2.628	2.709	4.22	4.44	2.86	5.7	2.21	6.218	3.258	6.925
TiO ₂	0.198	0.243	0.35	0.36	0.23	0.67	0.15	0.762	0.346	0.851
L.O.I.	1.3	1.19	1.05	0.78	0.82	1.42	0.65	3.78	3.4	0.76
Sum	96.79	98.41	98.45	99.09	100.09	100.41	100.37	95.13	96.78	98.81
Ba (ppm)	159.3	701		785.2	438.9	941.4	128.5	1170	493.2	867.1
Be	6.81	4.42		5.58	4.66	4.1	5.62	2.42	3.03	3.1
Bi	<0.15	<0.15		0.361	0.026	0.116	0.032	0.25	0.19	<0.15
Cd	0.09	0.21		0.38	0.17	0.32	0.11	0.09	0.17	0.29
Ce	169.84	202.79		191.98	122.69	151.36	231.35	118.74	166.02	154.1
Co	0.75	1.09		2.3	1.3	6.6	1.5	5.69	3.08	6.52
Cr	124	72		197	235	164	301	102	107	80
Cs	1.99	1.04		6.94	2.01	4.91	2.06	0.93	1.91	3.36
Cu	4.2	3.4		8	3	4	3	35	6.4	8.1
Dy	10.181	7.966		10.11	10.02	8.3	9.77	6.519	6.739	8.263
Er	5.17	3.89		4.92	4.37	3.88	4.69	3.06	2.97	3.85
Eu	0.65	1.93		2.12	1.36	2.17	0.65	5.39	2.28	2.31
Ga	29.02	27.47		28.01	27.29	22.35	28.88	30.52	28.51	26.23
Gd	11.61	10.22		12.35	12.53	10.50	12.40	9.07	9.90	10.69
Hf	13.17	11.55		9.28	9.46	5.86	10.64	8.26	14.22	10.42
Ho	1.91	1.42		1.85	1.73	1.47	1.76	1.17	1.14	1.46
In	0.08	0.07						0.15	0.10	0.11
La	83.37	97.72		92.13	53.33	67.44	109.33	55.83	80.67	73.91
Li	8.5	8		15.8	10.2	27.9	4.4	25.7	11.9	16.8
Lu	0.56	0.43		0.57	0.43	0.38	0.51	0.40	0.36	0.44
Mo	2.48	1.6		8.3	2.02	2.61	4.96	4.33	3.54	2.51
Nb	55.19	42.77		42.34	51.17	51.15	50.99	50.38	52.42	50.45
Nd	71.86	82.47		82.54	64.45	67.74	90.49	60.75	72.11	72.92
Ni	3.5	2.4		7	3	3	4	13.2	7	4
Pb	13.9	14.9		32.3	14.6	37.2	22.3	7.7	4.7	15
Pr	19.36	22.42		22.54	15.70	17.70	25.35	14.90	19.50	18.63
Rb	259.92	193.08		256.65	185.57	234.27	278.23	54.77	147.04	135.7
Sb	0.1	0.1		0.08	0.04	0.05	0.09	0.12	0.19	0.07
Sc	1.6	2.7		4.5	2.1	6.7	1.2	8.2	3.1	6.5
Sm	14.03	13.79		15.61	14.59	13.40	16.60	11.80	13.18	13.79
Sn	2.97	3.92		10.67	3.76	8.55	5.09	5.6	5.28	4.16
Sr	17.7	94.9		125	88	197	26	211.7	64.2	254.6
Ta	4.83	2.91		3.10	3.80	2.90	4.30	2.87	3.85	3.27
Tb	1.79	1.44		1.83	1.85	1.51	1.77	1.23	1.32	1.50
Th	80.07	25.45		26.71	23.82	20.91	39.99	9.30	24.47	16.86
Tl	1.26	1.16		1.32	1.04	1.55	1.26	0.20	0.56	0.63
Tm	0.70	0.52		0.68	0.57	0.50	0.64	0.41	0.40	0.51
U	8.26	3.09		4.14	3.72	2.76	5.28	2.23	4.26	1.94
V	2.7	2.5	<10	<10		24	<10	11.6	4.4	20.6
W	1.89	1.89		7.57	1.98	2.13	1.97	1.98	2.98	1.83
Y	50.58	37.57		49.63	43.64	40.49	47.6	29.44	30.54	37.91
Yb	4.17	3.11		4.20	3.27	2.90	3.91	2.63	2.50	3.10
Zn	45	46		154.51	45.8	147.54	54.24	17	44	173
Zr	408	371	464	310	303	227	319	303	513	427

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. CLG, Caribou Lake gabbro; LFD, leucoferrodiorite; HGG, Hearne granitic group; WGG, Whiteman granitic group

Western lobe whole rock geochemistry cont.

SAMPLE:	1112A	1113A	1128A	1152A	1156A	1168A	1170A	367A	369A	404A
	WGG	WGG	WGG	WGG	WGG	WGG	WGG	WGG	WGG	WGG
Unit:										
EASTING:	407503	407856	407213	405508	406223	406814	407629	409753	409417	406150
NORTHING:	6888124	6888156	6890235	6885868	6884738	6886502	6886652	6889837	6889294	6889137
SiO ₂ (wt.%)	59.24	68.34	66.14	72.67	74.55	70.02	69.58	66.65	65.26	66.08
Al ₂ O ₃	14.5	13.32	13.69	12.59	12.67	12.92	12.74	13.67	12.96	13.43
CaO	2.78	1.41	1.77	0.74	0.27	1.21	1.17	1.7	1.99	1.78
K ₂ O	4.34	4.36	4.78	5.29	5.53	4.89	4.93	4.55	4.42	4.76
MgO	0.44	0.75	0.36	0.15	0.18	0.25	0.32	0.4	1.41	0.59
MnO	0.237	0.064	0.149	0.046	0.031	0.097	0.07	0.12	0.09	0.16
Na ₂ O	5.72	3.81	4.25	3.53	3.32	3.89	3.75	4.92	3.67	4.49
P ₂ O ₅	0.208	0.187	0.084	0.048	0.035	0.063	0.088	0.08	0.35	0.09
Fe ₂ O ₃	10.248	4.195	6.766	2.912	1.749	4.286	4.113	6.51	6.76	7.37
TiO ₂	0.922	0.665	0.632	0.271	0.251	0.398	0.429	0.55	0.98	0.63
L.O.I.	0.68	1.25	0.66	0.61	0.98	2.53	0.66	0.49	1.98	0.73
Sum	98.89	97.28	98.91	98.46	98.78	98.24	97.40	99.66	99.87	100.11
Ba (ppm)		738.3	1619.9			881.3	797.8	1420.5	749.6	1533.2
Be		2.56	2.53			1.7	3.51	2.7	2.98	2.77
Bi		<0.15	0.62			<0.15	<0.15	0.237	0.055	0.245
Cd		0.13	0.27			0.20	0.22	0.26	0.07	0.16
Ce		91.85	162.2			144.94	147.83	149.19	139.22	140.99
Co		5.29	2.53			1.45	2.44	4.2	8.2	3.5
Cr		93	134			95	104	145	143	144
Cs		1.02	3.14			0.93	3.58	2.93	4.30	4.61
Cu		5.8	11.9			5.6	7.1	12	9	10
Dy		3.91	7.683			7.358	8.003	8.02	6.25	9.05
Er		1.83	3.52			3.20	3.71	3.54	2.88	3.96
Eu		1.14	4.04			2.57	2.06	3.98	2.21	4.08
Ga		20.21	29.09			27.38	26.83	29.56	20.91	28.55
Gd		5.63	10.50			10.42	10.62	11.20	8.65	12.72
Hf		7.27	9.32			11.27	10.49	6.76	4.99	6.96
Ho		0.68	1.36			1.26	1.40	1.41	1.10	1.57
In		0.06	0.17			0.12	0.12			
La		42.77	77.01			67.46	69.38	69.16	66.05	65.6
Li		26.7	11.9			6.3	13.6	4.5	21.4	15.2
Lu		0.22	0.43			0.36	0.40	0.43	0.33	0.46
Mo		0.94	2.67			2.96	2.5	5.5	6.16	4.24
Nb		18.70	57.91			50.86	47.75	65.61	26.70	57.85
Nd		42.15	75.45			70.11	69.85	72.57	60.89	73.72
Ni		3.7	7.5			4.1	4.4	13	5	7
Pb		17.9	13.7			13.4	17.4	16.1	9.1	13
Pr		10.93	19.58			17.61	18.11	18.13	16.18	17.96
Rb		173.44	103.17			107.51	175.24	98.68	216.02	106.5
Sb		0.06	0.08			0.06	0.08	0.04	0.06	0.05
Sc		6.2	6			3.7	4.1	6.2	7.3	7.7
Sm		7.76	14.10			13.26	13.78	14.14	11.24	14.86
Sn		2.61	3.71			1.16	4.31	3.34	5.84	3.68
Sr		165.9	208.1			145	118.4	187	218	196
Ta		1.18	3.22			2.61	2.90	3.60	1.80	3.30
Tb		0.75	1.44			1.40	1.48	1.51	1.18	1.74
Th		18.10	11.50			9.92	13.90	11.05	26.16	11.78
Tl		0.83	0.47			0.45	0.79	0.42	1.04	0.61
Tm		0.25	0.47			0.42	0.48	0.47	0.38	0.51
U		2.48	1.56			1.88	2.77	2.36	3.51	1.81
V		36.4	8.9			4.6	10.9	17.46	31.48	<10
W		1.49	2.2			1.17	2.49	1.82	1.2	1.82
Y		18.81	34.46			31.03	36.03	34.04	28.82	39.01
Yb		1.55	2.93			2.50	2.88	2.96	2.36	3.16
Zn		81	151			114	112	169.87	64.24	112.79
Zr	138	277	373	380	457	477	420	278	169	282

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. CLG, Caribou Lake gabbro; LFD, leucoferrodiorite; HGG, Hearne granitic group; WGG, Whiteman granitic group

Western lobe whole rock geochemistry cont.

SAMPLE: 429A			
WGG			
Unit:	Precision		
EASTING: 408017	average	Detection	
NORTHING: 6888003	diff (%)	limit	
SiO ₂ (wt.%)	71.65	1.7	0.01
Al ₂ O ₃	12.71	1.6	0.01
CaO	1	0.0	0.01
K ₂ O	5.08	3.7	0.01
MgO	0.34	1.4	0.01
MnO	0.08	6.4	0.01
Na ₂ O	3.9	2.8	0.01
P ₂ O ₅	0.09	4.8	0.01
Fe ₂ O ₃	4.35	1.0	0.01
TiO ₂	0.41	2.5	0.01
L.O.I.	0.69	9.9	0.05
Sum	100.30		
Ba (ppm)	798.5	0.9	0.9
Be	3.56		0.06
Bi	0.091		0.009
Cd	0.14		0.01
Ce	145.45	6.3	0.2
Co	2.9	7.4	0.1
Cr	193	52.0	24
Cs	3.41		0.01
Cu	6	28.0	2
Dy	8.76	6.0	0.2
Er	4.02	5.80	0.01
Eu	2.07	5.61	0.01
Ga	26.86		0.05
Gd	11.49	0.97	0.02
Hf	8.14	13.6	0.09
Ho	1.57	5.57	0.00
In			0.00
La	66.34	8.8	0.09
Li	9.2		0.2
Lu	0.44	0.95	0.00
Mo	3.62		0.03
Nb	51.40	64.79	0.04
Nd	70.31	4.1	0.08
Ni	7	6.7	3
Pb	15.4		0.4
Pr	17.90	4.77	0.02
Rb	180.18	5.3	0.2
Sb	0.07		0.04
Sc	4		0.9
Sm	14.12	6.27	0.02
Sn	5.04		0.08
Sr	117	2.2	2
Ta	3.40	47.89	0.20
Tb	1.61	0.81	0.00
Th	16.83	3.33	0.09
Tl	0.83		26.00
Tm	0.53	5.59	0.00
U	3.31	3.10	0.02
V	11.29	0.8	10
W	1.12		0.5
Y	39.66	12.0	0.08
Yb	3.17	1.28	0.01
Zn	104.7	26.2	8
Zr	306	16.0	3

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. CLG, Caribou Lake gabbro; LFD, leucoferrodiorite; HGG, Hearn granitic group; WGG, Whiteman granitic group

A.4 SWSMP whole rock geochemistry

SAMPLE:	654A	553A	647A	648A	649A	650A	651A	652A	653A	630A
Unit:	DLS- ultramafic	DLS- ultramafic	BSLC- foyaite	BSLC- nepheline syenite	BSLC- urtite	BSLC- carbonatite	BSLC- gabbro	BSLC- gabbro	BSLC- syenite	SLI-carbonatite
EASTING:	332104	331308	254623	253973	253771	253942	257159	256940	256153	392509
NORTHING:	6931874	6934397	7056315	7056377	7056031	7057166	7058824	7059089	7058702	7088436
SiO ₂ (wt.%)	44.33	43.83	43.9	47.66	35.81	5.92	48.78	42.31	54.86	0.61
Al ₂ O ₃	11.37	7.95	14.32	17.6	13.07	2.4	20.99	10.38	16.27	0.11
CaO	8.63	7.26	7.48	5.21	7.88	45.78	9.33	10.17	4.3	33.29
K ₂ O	1.114	0.57	1.132	4.074	3.763	1.323	1.577	0.499	2.85	0.047
MgO	4.51	17.73	1.59	1.07	2.49	1.45	2.46	7.11	1.29	15.78
MnO	0.217	0.2	0.424	0.331	0.634	0.867	0.086	0.277	0.22	2.116
Na ₂ O	2.67	1.52	11.42	9.39	4.9	0.16	3.88	2.44	5.75	-0.03
P ₂ O ₅	0.348	0.2	0.057	0.073	2.086	0.054	0.083	1.194	0.409	0.013
Fe ₂ O ₃	19.075	17.42	14.04	9.55	19.952	4.481	7.677	19.812	10.019	5.128
TiO ₂	4.935	2.06	0.221	0.322	4.42	0.348	2.63	4.409	1.498	0.562
L.O.I.	2.2	1.24	4.2	3.7	4.1	36.6	1.7	0.9	1.1	45.4
Sum	97.4	99.97	95.005	95.772	95.47	63.725	97.801	98.862	97.953	57.89
Ba (ppm)	311.3	161.6	319.8	1435.2	935.3	86.7	530.6	412.1	2400	39.7
Be	1.26	0.85	12.9	11.94	7.39	3.98	0.54	0.57	2.58	0.27
Bi	0.023	0.098	0.031	0.063	0.068	0.217	0.063	0.009	0.043	0.009
Cd	0.2	0.09	0.63	0.52	0.69	1.75	0.06	0.2	0.23	0.11
Ce	67.06	36.37	226.72	248.26	297.92	310	24.9	107.55	129.82	310
Co	56.6	104.6	7.3	5.6	39.8	4.1	25.8	41.2	8.7	1.3
Cr	24	600	29	34	24	24	37	277	40	24
Cs	0.97	0.71	0.86	0.88	5.41	1.94	0.2	0.18	0.81	0.01
Cu	134	134	4	4	336	18	26	43	23	4
Dy	6.86	4.25	10.23	8.75	12.96	17.83	1.49	7.02	6.51	45.59
Er	3.15	2.03	4.04	3.54	4.45	7.23	0.55	2.51	2.71	17.88
Fu	2.9	1.77	6.01	5.27	8.93	23.05	1.78	4.56	7.61	28.7
Ga	24.51	16.89	24.08	34.14	24.1	12.54	21.91	18.85	24.42	1.68
Gd	8.62	5.24	14.48	12.5	21.96	45.31	2.32	11.6	9.4	74.97
Hf	5.89	3.79	26.4	19.94	6.48	0.16	0.97	1.67	5.12	0.13
Ho	1.24	0.79	1.65	1.42	1.99	2.87	0.24	1.14	1.11	7.37
In										
La	27.93	14.71	96.95	116.81	108.62	210	11.15	42.74	58.1	210
Li	6.3	12.9	9.6	35.3	48	43.9	12.6	5.2	7.4	0.8
Lu	0.33	0.22	0.86	0.68	0.48	0.69	0.05	0.19	0.27	1.65
Mo	2	1.52	1.85	4.14	2.45	1.25	1.13	1.48	3.93	1.43
Nb	27.83	14.81	32.24	200	200	28.71	11.49	30.57	51.81	84.3
Nd	40.4	22.6	108.35	103.84	168.52	736.27	13.75	71.48	65.21	581.79
Ni	21	956	7	4	35	7	16	111	9	5
Pb	5.2	2.6	7.9	36	4.3	45.9	2.2	2.7	10.7	4.2
Pr	9	5.06	27.64	27.82	40.19	120	3.19	15.32	16.09	120
Rb	28.13	14.59	38.2	92.19	189.83	103.16	22.08	6.96	46.71	0.5
Sb	0.07	0.05	0.07	0.1	0.04	0.04	0.04	0.04	0.21	0.07
Sc	27.8	25.3	3.2	1.3	2.9	0.9	9.9	23.5	7	0.9
Sm	9.25	5.38	19.94	17.64	30.96	93.54	2.87	14.53	12.19	113.51
Sn	2.53	0.99	18.65	9.24	5.01	1.35	0.57	0.55	3.87	0.13
Sr	413	283	1256	1227	1845	2300	2255	1036	1115	48
Ta	1.9	1	1.5	67.2	10.7	0.5	0.8	2.1	3.2	0.8
Tb	1.22	0.76	1.96	1.67	2.65	4.06	0.29	1.41	1.22	9.17
Th	3.56	1.7	7.28	18.04	6.02	10.38	0.98	1.15	9.5	55
Tl	0.13	0.08	0.19	0.26	0.62	0.35	0.06	0.03	0.18	0.02
Tm	0.40	0.26	0.57	0.51	0.54	0.96	0.07	0.28	0.34	2.30
U	0.76	0.46	0.81	55	0.65	1.05	0.23	0.22	1.56	1.5
V	433.47	255.4	27.23	16.28	76.89	10	140.05	305.01	14.55	10
W	0.5	0.5	0.56	1.52	0.5	0.54	0.5	0.5	1.12	1.13
Y	30.47	19.43	38.22	35.1	44.07	65.07	5.77	26.57	28.14	188.8
Yb	2.36	1.55	4.56	3.83	3.30	5.60	0.36	1.48	1.98	13.31
Zn	159.3	131.54	175.71	130.94	347.01	626.07	50.44	150.6	124.38	40.77
Zr	232	145	1753	1138	374	5	12	62	216	39

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. DLS, Duck Lake sill; BSLC, Big Spruce Lake alkaline intrusion; SLI, Squalus Lake intrusion; SID, Simpson Island Dyke; DG, Dogrib diabase.

SWSMP whole rock geochemistry cont.

SAMPLE:	633A	633B	634A	636A	640A	1199A	450A	450B	450C	450D
Unit:	SLI-mafic autolith	SLI-syenite	SLI- syenite	SLI- syenite	SLI- granite	SID- syenite	SID- ultramafic	SID- ultramafic	SID- ultramafic	SID- ultramafic
EASTING:	392558	392553	392984	392316	391880	415551	400560	400671	400734	400694
NORTHING:	7088451	7088434	7087097	7086616	7087010	6850341	6845718	6845782	6845828	6845830
SiO ₂ (wt.%)	58.44	65.55	60.41	58.98	70.18	48.67	46.15	35.95	37.46	38.42
Al ₂ O ₃	17.35	18	15.74	16.56	13.17	14.44	13.34	3.37	3.9	4.88
CaO	1.68	0.24	1.23	2.4	0.54	3.13	5.52	2.72	3.3	4.16
K ₂ O	5.32	6.224	5.214	4.653	5.367	2.205	0.88	0.43	0.53	0.63
MgO	0.8	0.14	0.7	1.13	0.26	4.61	5.36	23.94	23.74	21
MnO	0.131	0.015	0.129	0.119	0.055	0.132	0.19	0.23	0.22	0.22
Na ₂ O	5.82	6.81	6.03	6.02	4.71	4.55	4.05	0.46	0.78	1.15
P ₂ O ₅	0.268	0.044	0.22	0.364	0.052	0.811	0.48	0.21	0.2	0.24
Fe ₂ O ₃	7.321	1.747	7.572	7.167	3.668	14.503	16.21	22.9	23.44	22.83
TiO ₂	0.922	0.061	0.912	1.123	0.396	3.002	3.93	2.16	2.34	2.87
L.O.I.	0.6	0.6	0.9	0.4	0.3	4.29	3.42	6.62	3.68	3.08
Sum	98.366	98.974	98.412	98.977	98.529	96.313	99.53	99	99.6	99.48
Ba (ppm)	1475.5	139.4	551.7	2068.7	132.8	858	219.3	118.1	137.8	171.5
Be	2.53	5	5.04	3.14	2.62	3.95	1.73	0.72	0.96	1.37
Bi	0.033	0.013	0.015	0.029	0.011	0.15	0.155	0.042	0.018	0.023
Cd	0.15	0.09	0.18	0.21	0.05	0.098	0.1	0.12	0.11	0.14
Ce	207.62	60.26	286.06	241.3	250.16	118.38	76.88	28.97	31.95	41.34
Co	5.5	1.5	4.7	7.7	2.1	28.11	59.3	170.5	171.5	166.7
Cr	62	42	53	32	80	21	58	600	600	600
Cs	0.55	0.38	0.19	0.51	0.17	1.048	0.72	0.65	0.92	1.16
Cu	15	7	25	18	8	26.4	45	99	96	115
Dy	7.89	2.7	11.28	9.15	4.87	9.25	6.09	2.47	2.83	3.7
Er	2.89	1.21	4.58	3.51	1.76	3.213	2.78	0.84	1.01	1.3
Eu	4.56	1.03	3.8	5.88	1.16	5.432	2.98	1.3	1.49	1.89
Ga	29.82	51.26	33.65	28.53	35.36	37.65	25.26	11.84	13.35	17.5
Gd	11.85	3.78	15.6	13.62	8.91	14.012	8.31	3.72	4.13	5.34
Hf	6.12	6.65	13.5	7.99	3.07	10.91	6.21	3.09	3.77	4.67
Ho	1.26	0.47	1.89	1.5	0.75	1.44	1.09	0.39	0.45	0.59
In						0.133				
La	94.95	29.66	134.35	111.45	127.27	48.83	31.22	11.77	12.89	16.43
Li	22	5.9	14.5	20.5	14.7	61.1	33.7	11.9	15.7	25
Lu	0.25	0.14	0.46	0.3	0.2	0.255	0.31	0.07	0.08	0.1
Mo	2.1	2.8	4.64	4.39	5.68	2.59	1.59	0.79	0.93	1.19
Nb	84.06	20.11	104.63	79.02	42.02	49.589	27.11	12.88	14.81	19.05
Nd	95.66	27.44	129.92	110.66	95.62	74.76	45.5	18.17	20.22	26.18
Ni	3	3	3	6	3	8	56	1350	1337	1261
Pb	11.6	6.9	10.2	16.1	4.6	8.4	5.2	4.2	3	3.2
Pr	24.91	7.19	34.07	28.7	26.88	16.506	10.39	4	4.52	5.79
Rb	97.84	163.51	76.85	83.08	133.17	56.25	25.7	11.78	15.23	18.67
Sb	0.06	0.12	0.11	0.04	0.05	0.08	0.04	0.04	0.04	0.04
Sc	1.8	0.9	2.5	2.8	0.9	10.5	19.1	9.2	11.1	13.3
Sm	16.61	5.07	22.73	19.4	14.51	16.807	9.76	4.24	4.77	6.14
Sn	2.19	1.28	2.2	2.84	1.11	5.34	2.27	1.01	1.53	1.96
Sr	533	52	213	1467	49	650.3	427	142	237	309
Ta	3.8	1.2	5.8	4.1	1.5	2.934	1.7	0.9	1	1.2
Tb	1.52	0.50	2.12	1.77	1.01	1.86	1.14	0.49	0.56	0.72
Th	9.72	7.91	24.35	14.04	12.54	4.977	2.1	1.19	1.36	1.73
Tl	0.3	0.36	0.35	0.33	0.43	0.215	0.14	0.12	0.13	0.2
Tm	0.34	0.16	0.58	0.42	0.22	0.37	0.36	0.10	0.11	0.15
U	1.46	1.67	3.74	1.7	0.89	1.112	0.51	0.27	0.31	0.39
V	10	10	10	10	10	91.9	294.94	178.03	192.1	235.36
W	0.5	0.59	0.75	1.04	0.5	0.59	0.59	0.5	0.5	0.5
Y	30.77	11.87	47.87	36.89	19.21	35.76	27.6	9.45	11.03	14.28
Yb	1.86	0.97	3.37	2.33	1.34	2.01	2.14	0.56	0.62	0.80
Zn	106.63	18.94	76.75	107.83	72.63	121	70.31	177.4	182.46	201.23
Zr	383	630	832	394	292	410	255	123	148	185

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. DLS, Duck Lake sill; BSLC, Big Spruce Lake alkaline intrusion; SLI, Squalus Lake intrusion; SID, Simpson Island Dyke; DG, Dogrib diabase.

SWSMP whole rock geochemistry cont.

SAMPLE:	451A	452A	453A	453B	458A	459A	462A	465A	466A	469A
Unit:	SID-syenite	SID-syenite	SID-syenite	SID-syenite	SID-syenite	SID-syenite	SID-syenite	SID-syenite	SID-syenite	SID-syenite
EASTING:	401155	403728	406323	406229	406639	408939	409526	412490	413815	415798
NORTHING:	6845980	6847632	6848052	6848138	6848810	6848837	6848924	6849268	6849644	6850448
SiO ₂ (wt.%)	43.03	45.63	45.59	39.5	44.73	48.85	47.07	47.93	50.3	40.81
Al ₂ O ₃	10.13	12.03	12.28	8.68	12.85	13.43	12.69	13.5	15.1	12.15
CaO	8.73	7.29	7.41	8.04	5.13	6.43	6.67	6.21	3.89	4.48
K ₂ O	1.54	1.95	1.73	1.13	1.26	2.07	2	2.14	2.67	1.03
MgO	6.09	4.98	4.86	7.88	4.77	4.19	4.28	3.62	3.31	5.14
MnO	0.19	0.19	0.19	0.25	0.18	0.18	0.18	0.18	0.15	0.17
Na ₂ O	3.01	3.76	3.87	2.1	3.87	4.55	4.26	4.49	5.2	3.35
P ₂ O ₅	0.39	0.57	0.69	0.35	0.8	0.42	0.81	0.91	0.78	0.49
Fe ₂ O ₃	19	16.89	16.58	22.83	16.16	14.92	16.46	15.33	13.16	18
TiO ₂	6.3	4.63	4.46	7.69	3.91	3.81	3.85	3.22	2.48	5.96
L.O.I.	1.29	1.8	1.43	1.21	5.35	1.29	1.54	2.66	3.29	7.72
Sum	99.71	99.72	99.11	100.23	99.02	100.14	99.82	100.19	100.33	99.31
Ba (ppm)	397.2	456.7	455.9	270.4	380.8	561.2	498.8	926.2	689	245.6
Be	1.93	2.23	2.09	1.48	2.14	2.58	2.54	2.49	3.54	2.18
Bi	0.045	0.019	0.02	0.076	0.03	0.068	0.024	0.023	0.075	0.166
Cd	0.2	0.22	0.19	0.15	0.08	0.26	0.2	0.3	0.09	0.06
Ce	74.6	92.51	94.06	59.51	109.68	104.45	117.02	129.41	142.13	84.27
Co	63.9	44.5	43.7	86.5	36.8	37.1	36.5	30.9	24	56.3
Cr	77	29	32	126	24	30	24	24	33	48
Cs	1.05	1.25	1.07	1.02	0.95	0.84	1.2	1.28	1.17	0.41
Cu	44	26	24	182	54	20	20	17	21	53
Dy	6.75	7.85	7.76	6.06	8.13	8.11	9.3	9.75	10.24	6.86
Er	2.32	2.72	2.67	2.09	2.87	2.91	3.2	3.36	3.59	2.45
Eu	3.48	4.23	4.32	3.16	4.24	4.34	4.9	5.25	5.31	3.69
Ga	31.35	34.27	33.3	30.13	35.31	36.22	34.55	35.82	39.81	34.34
Gd	10.1	11.89	12.19	9	12.62	11.93	14.14	15.28	15.33	10.33
Hf	8.36	9.29	8.92	7.66	8.73	10.92	9.95	10.19	12.54	8.69
Ho	1.07	1.23	1.23	0.94	1.29	1.3	1.44	1.53	1.61	1.09
In										
La	29.48	36.96	37.62	22.81	44.47	42.93	46.56	51.44	57.35	33.97
Li	26.4	33.4	41.8	22.2	25.3	48.2	31	21.9	30.3	33.3
Lu	0.19	0.21	0.21	0.15	0.22	0.23	0.24	0.25	0.27	0.19
Mo	1.83	2.16	2.32	1.56	2.7	2.63	2.83	2.63	2.45	2.41
Nb	34.76	40.91	39.24	31.23	39.88	46.37	46.13	48.19	53.25	34.76
Nd	47.71	57.75	59.43	39.48	67.37	60.52	72.21	79.16	81.74	50.59
Ni	71	23	20	159	14	19	15	9	6	50
Pb	3.6	4.2	5.2	4.5	21.3	37.3	4	4.8	6	6.4
Pr	10.39	12.87	13.24	8.55	14.99	14.11	16.16	17.72	18.75	11.54
Rb	38.95	48.69	42	38.7	28	47.01	56.55	59.63	67.12	23.89
Sb	0.04	0.04	0.04	0.04	0.18	0.04	0.04	0.04	0.11	0.19
Sc	24.7	16.3	15.5	30.9	12.4	12.9	12.2	10.6	7.4	18.5
Sm	11.19	13.56	13.9	9.91	15.06	13.8	16.51	17.87	18.12	11.87
Sn	3.41	4.25	4.1	3.35	4.6	5.5	5.06	0.97	2.36	4.03
Sr	466	632	798	383	479	761	437	631	657	334
Ta	2.3	2.6	2.5	2.2	2.5	2.9	2.8	2.9	3.3	2.3
Tb	1.35	1.56	1.60	1.21	1.64	1.59	1.84	1.97	2.04	1.36
Th	3.28	4.14	3.78	2.38	4.63	5.49	5.02	5.27	6.88	4.13
Tl	0.17	0.19	0.23	0.22	0.13	0.17	0.22	0.24	0.25	0.12
Tm	0.27	0.31	0.30	0.23	0.32	0.34	0.36	0.38	0.42	0.28
U	0.74	0.91	0.89	0.54	1.06	1.23	1.1	1.15	1.53	0.93
V	445.44	226.83	219.24	500	157.33	185.46	150.12	101.1	59.81	349.72
W	0.5	0.5	0.5	0.5	0.5	0.55	0.57	0.5	0.6	0.5
Y	25.74	29.97	29.9	22.73	31.74	31.58	35.29	37.42	39.43	25.67
Yb	1.45	1.67	1.63	1.25	1.70	1.87	1.97	2.02	2.24	1.50
Zn	185.5	171.78	132.65	130.27	123.14	157.85	131.1	179.08	94.65	44.6
Zr	317	365	355	276	351	438	392	403	503	333

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. DLS, Duck Lake sill; BSLC, Big Spruce Lake alkaline intrusion; SLI, Squalus Lake intrusion; SID, Simpson Island Dyke; DG, Dogrib

SWSMP whole rock geochemistry cont.

SAMPLE:	471A	473A	475A	476A	477A	554A		
Unit:	SID-syenite	SID-syenite	SID-syenite	SID-syenite	SID-syenite	DG		
EASTING:	410612	419393	421569	423995	428512	332629	Precision	Detection
NORTHING:	6847368	6852236	6854019	6856141	6857366	6931824	average	limit
							diff (%)	
SiO ₂ (wt.%)	45.68	44.76	49.07	46.78	49.41	47.62	1.7	0.01
Al ₂ O ₃	12.41	10.98	14.69	14.88	15.06	15.35	1.6	0.01
CaO	7.04	8.5	3.48	3.88	2.86	10.43	0.0	0.01
K ₂ O	1.91	2.73	2.54	0.43	2.76	1.56	3.7	0.01
MgO	4.32	4.69	3.75	4.37	4.13	9.36	1.4	0.01
MnO	0.27	0.3	0.21	0.11	0.16	0.19	6.4	0.01
Na ₂ O	3.76	3.84	4.8	5.77	4.52	1.55	2.8	0.01
P ₂ O ₅	0.9	0.72	0.72	0.9	0.77	0.06	4.8	0.01
Fe ₂ O ₃	11.12	7.07	11.22	12.42	12.32	10.39	1.0	0.01
TiO ₂	2.85	2.5	2.34	2.89	2.38	0.81	2.5	0.01
L.O.I.	10	13.97	7	6.02	5.13	2.74	9.9	0.05
Sum	100.25	100.07	99.81	98.44	99.49	100.06		
Ba (ppm)	287.5	753.5	652.7	234.6	667.8	251.5	0.9	0.9
Be	1.59	2.54	3.43	1.97	2.46	0.26		0.06
Bi	0.142	0.13	0.203	0.111	0.056	0.036		0.009
Cd	0.06	0.09	0.08	0.07	0.09	0.07		0.01
Ce	116.12	96.97	135.08	116.46	131.16	10.02	6.3	0.2
Co	24.9	9.8	26.2	24.7	24	53.3	7.4	0.1
Cr	29	51	24	24	27	511	52.0	24
Cs	0.52	0.7	0.45	0.25	0.38	0.8		0.006
Cu	5	4	14	6	199	93	28.0	2
Dy	9.53	10.6	8.95	8.93	10.77	2.83	6.0	0.2
Er	3.3	4.18	3.34	3.09	3.97	1.7	5.8	0.01
Eu	4.88	4.24	5.04	5.08	5.17	0.77	5.6	0.005
Ga	33.84	29.66	39.07	39.05	41.3	14.91		0.05
Gd	14.59	13.99	13.74	13.82	15.12	2.52	1.0	0.02
Hf	9.96	13.47	12.06	9.62	14.97	1.25	13.6	0.09
Ho	1.48	1.77	1.46	1.4	1.73	0.6	5.6	0.003
In								0.0018
La	46.29	35.54	53.44	46.71	52.05	3.99	8.8	0.09
Li	14	3.5	17.3	20.5	30.1	39.5		0.2
Lu	0.25	0.33	0.26	0.23	0.31	0.23	0.9	0.002
Mo	2.91	2.83	2.49	2.36	3.4	0.78		0.03
Nb	41.39	50.62	44.53	41.25	60.79	3.08	64.8	0.04
Nd	72.5	62.77	78.4	71.29	76.8	7.02	4.1	0.08
Ni	20	17	13	6	7	198	6.7	3
Pb	2.3	2.8	3.7	2.2	3.8	2.9		0.4
Pr	15.99	13.65	18.01	15.95	17.84	1.45	4.8	0.02
Rb	62.99	73.58	66.14	13.11	56.46	59.96	5.3	0.2
Sb	0.26	0.28	0.33	0.18	0.07	0.33		0.04
Sc	8.6	8.3	8.2	8.9	7	39.6		0.9
Sm	16.58	15.31	17.03	16.16	17.27	2.03	6.3	0.02
Sn	5.08	7.29	5.84	5.43	7.5	0.27		0.08
Sr	281	184	556	611	501	211	2.2	2
Ta	2.6	3.1	2.8	2.6	3.7	0.2	47.9	0.2
Tb	1.91	1.99	1.78	1.78	2.10	0.43	0.81	0.00
Th	5.54	7.47	6.44	4.84	7.4	0.46	3.3	0.09
Tl	0.18	0.2	0.28	0.07	0.3	0.3		26
Tm	0.38	0.48	0.38	0.35	0.46	0.24	5.59	0.00
U	1.18	2.09	1.49	1.07	1.75	0.1	3.1	0.02
V	80.63	59.44	61.25	73.82	46.5	245.75	0.8	10
W	0.5	0.61	0.52	0.59	0.78	0.5		0.5
Y	37.27	45.29	35.71	34.2	42.51	15.24	12.0	0.08
Yb	2.00	2.64	2.08	1.87	2.49	1.56	1.28	0.01
Zn	20.34	9.68	16.56	29.57	64.24	69.05	26.2	8
Zr	405	563	489	385	600	44	16.0	3

Note: Eastings and northings are in UTM Zone 12, North American Datum 83. LOI, loss on ignition during X-ray fluorescence fusion. Major element oxides in weight percent; trace elements in weight parts per million. DLS, Duck Lake sill; BSLC, Big Spruce Lake alkaline intrusion; SLI, Squalus Lake intrusion; SID, Simpson Island Dyke; DG, Dogrib diabase.

A.5 Whole-rock geochemistry standards and calculation of precision

Prior replicate analyses						Measured (this study)				Precision average
Sample	YK-25B	YK-25B	YK-25B	YK-25B	Average	YK-25B	% diff	YK-25B	% diff	% difference of
Type	In house std	dup	dup	dup	YK-25B					duplicates
SiO ₂	62.74	63.04	62.92		62.90	63.73	1.3	64.29	2.2	1.7
Al ₂ O ₃	14.25	14.61	14.67		14.51	14.81	2.0	14.35	1.1	1.6
MnO	0.05	0.0557	0.056		0.05	0.055	2.0	0.06	10.7	6.4
MgO	2.24	2.167	2.175		2.19	2.20	0.3	2.14	2.5	1.4
CaO	3.50	3.414	3.401		3.44	3.44	0.0	3.44	0.0	0.0
Na ₂ O	3.48	3.36	3.46		3.43	3.51	2.2	3.55	3.3	2.8
K ₂ O	2.31	2.424	2.419		2.38	2.449	2.7	2.5	4.7	3.7
TiO ₂	0.47	0.486	0.481		0.48	0.484	1.1	0.46	4.0	2.5
P ₂ O ₅	0.13	0.151	0.152		0.14	0.153	5.8	0.15	3.9	4.8
Fe ₂ O ₃	4.58	4.594	4.587		4.59	4.574	0.3	4.51	1.7	1.0
LOI	4.93		4.8		4.87	5.50	12.3	5.25	7.6	9.9
TOTAL	98.68	94.30	99.12		97.37	95.56	1.9	100.7	3.4	2.6
Nb	6	8	7	8	7.25	2.08	110.8	6.007	18.8	64.8
Zr	130	160	161	162	153.25	156	1.8	113	30.2	16.0
Y	14	14	14	14	14.00	12.5	11.3	12.32	12.8	12.0
Sr	196	198	196	202	198.00	203	2.5	194.1	2.0	2.2
Rb	60	63	62	66	62.75	67.49	7.3	64.93	3.4	5.3
Ba	799	778	751	709	759.25	758.9	0.0	746.2	1.7	0.9
Cr	26	25	23	22	24.00	<24		76	104.0	52.0
Co	9	11	11	16	11.75	11.2	4.8	10.63	10.0	7.4
Cu	8		11.84	11.96	9.98	12	18.4	14.6	37.6	28.0
Ni	23	21	21	9	18.50	19	2.7	20.6	10.7	6.7
Sc	7		6.95	8	7.50	8.9	17.1	8.8	16.0	16.5
V	67	70	72	62	67.75	67.4	0.5	68.5	1.1	0.8
Zn	37	38	72	40	46.75	35.85	26.4	36	26.0	26.2
La	39.55		40.70	39.05	39.30	42.94	8.9	42.91	8.8	8.8
Ce	75.90		74.30	73.91	74.91	80.92	7.7	78.67	4.9	6.3
Pr	8.66		8.53	8.039	8.35	8.8	5.3	8.715	4.3	4.8
Nd	30.42		30.74	29.14	29.78	31.21	4.7	30.84	3.5	4.1
Sm	4.84		4.73	4.48	4.66	4.98	6.6	4.943	5.9	6.3
Eu	1.20		1.15	1.093	1.15	1.24	7.8	1.186	3.4	5.6
Gd	3.64		3.20	3.099	3.37	3.37	0.0	3.305	1.9	1.0
Tb	0.48		0.42	0.392	0.44	0.435	0.2	0.43	1.4	0.8
Dy	2.29		2.14	2.09	2.19	2.35	7.0	2.302	5.0	6.0
Ho	0.43		0.43	0.389	0.41	0.44	7.2	0.426	3.9	5.6
Er	1.15		1.11	1.092	1.12	1.2	6.8	1.176	4.8	5.8
Tm	0.16		0.17	0.153	0.16	0.167	6.5	0.164	4.7	5.6
Yb	1.07		1.05	1.01	1.04	1.067	2.6	1.04	0.0	1.3
Lu	0.17		0.16	0.15	0.16	0.16	0.0	0.157	1.9	0.9
Th	12.56	13.86	11.90	11.53	12.65	12.79	1.1	11.965	5.6	3.3
U	2.85		2.79	2.849	2.85	2.97	4.1	2.909	2.1	3.1
Hf	3.2		4.22	3.7	3.45	2.9	17.3	3.81	9.9	13.6
Ta	0.49		0.82	0.5	0.50	0.2	84.9	0.552	10.9	47.9

Appendix B - Mineral Chemistry

Unit abbreviations as in Appendix A.

B.1 Microprobe detection limits

Oxide/Element	Na ₂ O	CaO	K ₂ O	FeO	SiO ₂	TiO ₂	Cr ₂ O ₃	MnO	Al ₂ O ₃	BaO	Cl	MgO	F	ZrO ₂
1-sigma	0.056	0.067	0.028	0.18	0.32	0.032	0.006	0.029	0.05	0.003	0.013	0.051	0.037	0.028
2-sigma	0.112	0.134	0.056	0.36	0.64	0.064	0.012	0.058	0.1	0.006	0.026	0.102	0.074	0.056

B.2 Eastern lobe clinopyroxene compositions

Analysis	Unit	SiO ₂	CaO	FeO	Al ₂ O ₃	MnO	MgO	TiO ₂	Na ₂ O	Total
373C-cpx4-1	TLSol	47.63	20.34	27.22	0.84	0.85	1.62	0.75	0.59	99.85
373C-cpx4-2	TLSol	47.81	20.39	26.86	0.82	0.76	1.58	0.67	0.88	99.78
373C-cpx4-3	TLSol	47.47	20.30	27.67	0.73	0.81	1.28	0.42	0.73	99.44
373C-cpx6-1	TLSol	48.50	18.88	28.21	0.32	0.76	0.86	0.45	1.62	99.61
373C-cpx6-2	TLSol	48.30	18.16	28.57	0.21	0.81	0.83	0.41	1.89	99.20
373C-cpx7-1	TLSol	47.12	20.23	27.06	0.84	0.85	1.63	0.69	0.56	98.99
373C-cpx7-2	TLSol	47.02	18.61	27.69	0.25	0.73	0.86	0.46	1.82	97.45
600B-cpx1-1	NLS	52.44	1.30	27.66	1.56	0.19		0.82	12.72	96.72
600B-cpx1-2	NLS	52.64	0.46	30.12	1.04	0.10		0.16	13.32	97.86
600B-cpx2-1	NLS	52.78	1.40	27.48	1.44	0.26		0.85	12.53	96.75
600B-cpx2-2	NLS	53.75	1.43	28.12	1.38	0.23		0.76	12.96	98.66
600B-cpx3-1	NLS	52.94	0.84	29.92	1.06	0.06		0.16	13.21	98.20
600B-cpx3-2	NLS	52.59	0.58	29.16	1.16	0.06		0.10	13.34	97.01
600B-cpx4-1	NLS	52.49	0.75	29.10	1.21	0.09		0.21	13.00	96.87
600B-cpx4-2	NLS	52.22	0.64	29.10	1.08	0.11		0.12	13.03	96.34
1201B2-cpx3-1	TLSl	52.50	1.49	29.07	0.25	0.28	0.03	1.90	12.24	97.94
1201B2-cpx3-2	TLSl	51.76	0.16	29.79	0.53	0.00	0.09	0.36	13.01	95.82
359A-cpx1-1	GLG	52.41	0.35	29.24	0.23	0.14		1.63	13.34	97.36
359A-cpx1-2	GLG	52.93	0.37	29.33	0.25	0.15		1.52	13.30	97.91

blanks indicate below detection limit

B.3 Eastern lobe amphibole compositions

Analysis	Unit	SiO ₂	CaO	K ₂ O	FeO	Al ₂ O ₃	MnO	MgO	ZrO ₂	TiO ₂	Na ₂ O	F	Total
359A-amp2-1	GLG	50.65	0.85	1.85	33.95	0.68	0.84	0.03		0.68	7.27	1.82	98.65
359A-amp2-2	GLG	50.27	0.27	1.73	34.06	1.01	0.75	0.02		0.64	7.39	1.19	97.38
359A-amp4-1	GLG	49.21	0.49	0.92	35.31	1.03	1.28	0.01		0.60	7.57	1.12	97.58
359A-amp4-2	GLG	48.54	0.51	1.47	35.01	1.08	1.08	0.02		0.56	8.07	1.50	97.88
359A-amp5-1	GLG	49.27	2.37	1.84	33.66	0.74	0.77	0.01		0.48	7.19	1.70	98.06
359A-amp5-2	GLG	50.38	0.20	1.91	34.13	0.75	0.82	0.02		0.73	7.38	1.64	97.99
373E-amp1-1	TLSr	48.96	3.44	1.73	34.65	0.59	0.97	0.37		0.67	5.77	0.76	98.15
373E-amp1-2	TLSr	50.06	14.89	0.02	28.57	0.23	0.74	0.16	0.32	0.22	4.91	0.00	100.24
373E-amp1-3	TLSr	49.18	17.19	0.01	28.88	0.18	0.86	0.26	0.34	0.10	2.91	0.00	100.07
373E-amp1-4	TLSr	48.44	18.06	0.02	29.21	0.22	0.68	0.44	0.16	0.42	2.22	0.00	100.07
373E-amp2-1	TLSr	49.84	3.47	1.69	34.12	0.67	1.06	0.34	0.09	0.56	6.34	0.87	99.10
373E-amp2-2	TLSr	49.20	2.97	1.90	34.80	0.85	1.08	0.28		0.58	5.76	0.64	98.33
373E-amp2-3	TLSr	49.99	13.93	0.02	28.22	0.22	0.72	0.16	0.46	0.19	5.21	0.00	99.29
373E-amp4-1	TLSr	48.88	18.85	0.00	28.60	0.37	0.78	0.64	0.04	0.51	1.78	0.00	100.51
373E-amp5-1	TLSr	43.61	6.52	1.66	34.61	4.26	0.90	0.28	0.18	0.26	4.74	0.60	97.80
1201B2-amp1-1	TLSl	48.33	3.16	1.73	33.86	0.59	1.04	0.25	0.05	1.43	6.15	0.80	97.54
1201B2-amp1-2	TLSl	48.64	3.02	1.64	33.43	0.55	1.07	0.25	0.05	1.42	6.04	0.72	96.94
1201B2-amp1-3	TLSl	49.15	3.45	1.63	33.73	0.62	1.04	0.22		1.37	5.99	0.86	98.20
1201B2-amp1-4	TLSl	48.53	3.39	1.49	33.29	0.60	0.99	0.22		1.41	5.89	0.74	96.81
1201B2-amp2-1	TLSl	47.24	3.90	1.36	33.70	1.55	0.85	0.65	0.07	1.25	5.84	0.85	97.44
1201B2-amp2-2	TLSl	47.14	4.94	1.21	33.33	1.41	0.81	0.65	0.07	1.12	6.05	1.38	98.25

blinks indicate below detection limit

B.4 Eastern lobe olivine compositions

Analysis	Unit	SiO ₂	CaO	FeO	MnO	MgO	TiO ₂	Total
373C-ol1-3	TLSol	29.45	0.19	67.92	2.41	0.50	0.05	100.55
373C-ol1-4	TLSol	29.08	0.18	66.76	2.44	0.47	0.05	99.00
373C-ol1-5	TLSol	29.25	0.17	67.37	2.42	0.44	0.04	99.71
373C-ol1-6	TLSol	29.19	0.17	67.43	2.44	0.46	0.05	99.75
373C-ol2-1	TLSol	29.11	0.21	67.78	2.45	0.54	0.05	100.13
373C-ol2-2	TLSol	29.39	0.12	67.05	2.45	0.52		99.55

blanks indicate below detection limit

B.5 Chapter 3 clinopyroxene, amphibole, and orthopyroxene compositions

Mineral	Sample	Unit	SiO ₂	CaO	K ₂ O	FeO	Al ₂ O ₃	Cl	MnO	MgO	TiO ₂	Na ₂ O	F	Total
AMP	1055A-1	SS	47.19	10.75	0.66	17.47	5.89	0.27	0.50	11.88	1.33	1.66	0.30	97.89
AMP	1055A-2	SS	45.68	10.79	0.88	18.03	6.77	0.35	0.48	11.19	1.80	1.74	0.49	98.23
AMP	1055A-3	SS	45.72	10.65	0.87	18.32	6.83	0.34	0.54	10.88	1.80	1.67	0.37	97.99
AMP	1055A-4	SS	50.73	11.06	0.42	15.96	3.61	0.14	0.48	13.42	0.90	1.14	0.38	98.29
AMP	1055A-5	SS	45.34	10.59	0.83	19.41	6.59	0.33	0.56	10.17	1.72	1.69	0.30	97.54
AMP	1055A-6	SS	45.34	10.59	0.83	19.41	6.59	0.33	0.56	10.17	1.72	1.69	0.30	97.54
CPX	1055A-1	SS	52.75	21.82		12.40	0.52		0.67	11.55		0.30		100.11
CPX	22A-1	NS-LR	51.21	22.09		8.06	3.13		0.19	13.89	0.69	0.33		99.69
CPX	22A-2	NS-LR	51.00	22.28		7.49	4.01		0.20	14.08	0.82	0.27		100.32
CPX	22A-3	NS-LR	53.11	1.57		20.00	1.36		0.57	23.48	0.20			100.39
CPX	22A-4	NS-LR	53.32	1.36		19.58	1.34		0.51	23.76	0.18			100.13
CPX	22A-5	NS-LR	50.60	22.03		8.45	3.84		0.21	13.64	0.94	0.32		100.10
CPX	22A-6	NS-LR	48.54	19.86		8.81	6.12	0.04	0.17	13.66	1.33	1.03	0.04	99.71
CPX	534A-1	NS	52.74	20.79		11.63	1.36		0.42	13.00	0.40	0.32		100.66
CPX	534A-2	NS	52.39	20.95		10.44	1.77		0.29	13.93	0.68	0.38		100.83
CPX	534A-3	NS	52.71	20.83		12.96	0.88		0.40	12.22	0.22	0.29		100.55
CPX	534A-4	NS	52.61	20.98		10.51	1.64		0.29	13.68	0.55	0.37		100.63
CPX	534A-5	NS	51.56	20.89		10.43	2.10		0.27	13.49	0.77	0.33		99.86
CPX	534A-6	NS	51.39	21.35		11.63	1.13		0.37	12.67	0.34	0.28		99.17
CPX	550A-1	CIS	51.25	21.78		9.39	2.31		0.20	13.11	0.54	0.37		99.01
CPX	550A-2	CIS	50.95	21.40		8.78	2.90		0.17	13.22	0.84	0.37	0.06	98.71
CPX	550A-3	CIS	49.96	21.32		8.67	3.31		0.19	13.32	0.78	0.44		98.05
CPX	550A-4	CIS	51.10	22.70		8.54	2.36		0.20	13.14	0.61	0.16		98.84
CPX	550A-5	CIS	50.15	21.33		9.79	2.99		0.24	12.43	0.73	0.42		98.08
CPX	550A-6	CIS	50.41	21.34		8.72	3.28		0.18	13.32	0.88	0.41		98.53
OPX	534A-1	NS	51.97	1.46		27.67	0.60		0.74	17.81	0.21			100.51
OPX	534A-2	NS	51.40	1.43		28.11	0.62		0.71	17.27	0.19			99.77

AMP=amphibole, CPX=clinopyroxene, OPX=orthopyroxene, blanks indicate below detection limit

B.6 Chapter 3 feldspar compositions

Feldspars from layered rafts in the NS							<i>Molecular fraction</i>		
	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Na ₂ O	K ₂ O	An	Ab	Or
1022A-1	46.85	33.82	0.43	16.76	2.02	0.06	81.79	17.85	0.36
1022A-2	46.82	33.90	0.40	17.37	1.86	0.07	83.42	16.17	0.41
1022A-3	54.71	29.15	0.31	10.80	5.25	0.30	52.29	46.00	1.71
1022A-4	52.47	30.11	0.34	12.46	4.56	0.20	59.49	39.36	1.15
1022A-5	47.17	33.78	0.39	16.70	2.19	0.04	80.63	19.14	0.23
1022A-6	46.99	33.21	0.87	16.30	2.22	0.30	78.85	19.45	1.71
Feldspars from NS									
1055A-1	63.48	24.06	0.18	4.57	9.42	0.36	20.72	77.32	1.96
1055A-2	57.31	27.32	0.13	8.93	6.61	0.24	42.17	56.49	1.34
1055A-3	63.37	23.00	0.21	4.16	9.28	0.43	19.38	78.23	2.39
1055A-4	63.60	22.97	0.17	4.07	9.30	0.35	19.10	78.96	1.95
1055A-5	60.86	25.07	0.20	6.33	8.30	0.25	29.22	69.40	1.38
1055A-6	63.88	22.86	0.20	3.77	9.69	0.29	17.43	80.98	1.59
1055A-7	58.27	26.91	0.17	8.30	7.00	0.15	39.26	59.89	0.85
1055A-8	58.23	26.90	0.15	8.35	6.98	0.17	39.41	59.64	0.95
1055A-9	63.18	23.67	0.20	4.60	9.22	0.20	21.37	77.55	1.08
1055A-10	52.28	30.57	0.22	12.83	4.21	0.16	62.20	36.90	0.90
1055A-11	56.56	27.67	0.27	9.72	5.96	0.26	46.70	51.80	1.50
1055A-12	55.75	28.00	0.30	9.93	5.74	0.28	48.09	50.28	1.63
1055A-13	55.03	29.12	0.27	11.16	5.33	0.23	52.94	45.78	1.28
1055A-14	58.39	26.87	0.38	8.41	6.63	0.33	40.43	57.69	1.88
1055A-15	54.51	29.50	0.27	11.37	5.04	0.21	54.82	43.99	1.20
1055A-16	58.98	25.86	0.24	7.56	7.11	0.46	36.06	61.34	2.60

blanks indicate below detection limit

B.7 Chapter 3 biotite compositions

Sample	SiO ₂	CaO	K ₂ O	FeO	Al ₂ O ₃	Cl	MnO	MgO	TiO ₂	BaO	Na ₂ O	Cr ₂ O ₃	F	Total	Mg#
NS-1	37.45		0.00	21.35	13.38		0.16	10.71	4.69		0.19			87.94	0.47
NS-2	36.24		9.07	21.68	12.92	0.40	0.10	9.61	6.28	0.20	0.23		0.19	96.95	0.44
NS-3	36.28		9.05	21.15	12.93	0.49	0.16	10.29	5.86	0.12	0.13		0.29	96.78	0.46
NS-4	36.43		9.25	19.75	13.34	0.40	0.13	11.08	5.55	0.08	0.12		0.32	96.53	0.50
NS-5	35.61		9.01	21.76	12.98	0.56	0.13	9.69	5.26	0.66	0.15		0.22	96.03	0.44
NS-6	35.82		9.01	21.70	12.87	0.49	0.14	9.98	4.80	0.15	0.19		0.31	95.48	0.45
CIS-1	35.48		8.93	19.42	13.71	0.27	0.15	10.88	5.49	0.60	0.41		0.44	95.80	0.50
CIS-2	35.46		9.03	19.87	13.68	0.29	0.14	10.66	5.83	0.56	0.46		0.39	96.37	0.49
CIS-3	35.36		8.75	18.98	13.45	0.25	0.14	10.82	6.28	0.99	0.50		0.48	96.01	0.50
CIS-4	36.02		8.69	18.44	13.71	0.25	0.14	11.30	5.85	0.92	0.42		0.45	96.20	0.52
SS-1	36.72		9.62	22.48	12.36	0.43	0.31	10.06	3.98	0.10	0.06		0.41	96.53	0.44
SS-2	35.97		9.06	22.53	12.61	0.47	0.28	9.54	4.95	0.72	0.18		0.43	96.74	0.43
SS-3	36.46		9.37	24.02	12.15	0.44	0.24	8.94	4.39	0.12	0.07		0.41	96.63	0.40
NS-LR-1	37.99		7.72	9.64	16.28	0.31	0.10	19.11	2.83	0.09	0.44		0.18	94.70	0.78
NS-LR-2	38.24		7.58	10.10	15.95	0.31	0.04	18.89	2.87	0.19	0.40		0.12	94.79	0.77
NS-LR-3	37.56		7.57	13.23	15.53	0.37	0.06	16.33	3.66	0.35	0.45		0.17	95.30	0.69
NS-LR-4	37.89		7.67	12.92	15.92	0.35	0.10	16.71	3.13	0.36	0.45		0.09	95.71	0.70
CLG-1	38.13		8.34	11.68	16.23			17.39	2.85		0.17	0.13		95.02	0.73
CLG-1	37.97		8.37	12.03	16.29			17.08	2.60	0.13	0.22	0.06		94.82	0.72
WGG-1	42.40	10.43	0.99	28.64	6.69	0.41	0.45	3.37	1.84		2.21	0.04	0.58	98.06	0.17
WGG-2	34.26		7.08	37.12	11.25	1.36	0.56	0.88	3.34	0.28	0.05	0.05	0.07	96.32	0.04
WGG-3	34.21		6.79	36.47	11.71	1.15	0.39	1.31	3.05	0.30	0.03			95.43	0.06
WGG-4	35.48		6.73	37.12	12.16	0.60	0.40	1.55	1.40	0.21	0.06		0.08	95.80	0.07
LFD-1	34.22		9.11	29.14	13.28	0.60	0.15	4.07	6.09	0.44	0.12		0.28	97.49	0.20
LFD-2	34.22		9.17	29.27	13.41	0.74	0.18	4.64	4.45	0.61	0.12		0.19	97.01	0.22
LFD-3	34.38		9.11	28.53	13.56	0.57	0.18	4.53	5.45	0.41	0.14		0.29	97.16	0.22
LFD-4	34.97		9.09	28.38	14.38	0.53	0.18	5.32	4.10	0.41	0.13		0.25	97.76	0.25
HGG-1	33.87		8.72	36.32	11.16	2.31	0.09	1.64	1.84		0.04		0.22	96.22	0.07
HGG-2	28.26	0.47	0.26	35.77	13.81		0.19	6.73	0.05		0.03		0.09	85.67	0.25
HGG-3	35.66		9.05	34.16	11.16	1.25	0.06	2.48	3.17		0.01		0.43	97.48	0.11
NLSS-1	33.79		8.54	39.36	10.53		1.31	0.08	1.17		0.21			95.05	0.00
NLSS-2	33.99		8.73	40.28	9.94		1.15	0.08	1.11		0.10			95.47	0.00
NLSS-3	34.31	0.17	8.28	40.07	9.76		0.92	0.14	1.05		0.18	0.05	0.06	94.98	0.01
NLSS-4	34.16		8.36	39.74	10.14		0.83	0.15	1.15		0.19		0.09	94.98	0.01
NLSS-5	33.85		8.79	40.79	9.48		1.33	0.04	1.02		0.14		0.09	95.55	0.00
NLSS-6	34.74		8.97	38.42	11.58		0.87	0.05	0.89		0.07		0.07	95.66	0.00

blanks indicate below detection limit

B.8 Western lobe clinopyroxene compositions

SAMPLE	Unit	SiO ₂	CaO	K ₂ O	FeO	Al ₂ O ₃	MnO	MgO	TiO ₂	Na ₂ O	Total
329A-1	CLG-gabbro	52.58	22.29	0.00	7.36	2.16	0.19	14.45	0.58	0.37	100.04
329A-2	CLG-gabbro	52.05	22.63	0.01	6.96	2.47	0.17	14.52	1.12	0.38	100.41
329A-3	CLG-peridotite	51.18	22.48	0.00	4.94	4.11	0.11	15.04	1.20	0.57	100.34
329A-4	CLG-peridotite	51.66	23.24	0.00	4.59	3.37	0.11	15.16	1.26	0.51	100.59
329A-5	CLG-peridotite	50.77	22.77	0.00	5.06	3.94	0.11	14.62	1.43	0.58	100.07
329A-6	CLG-peridotite	52.74	23.22	0.00	4.63	3.33	0.08	15.16	1.30	0.52	101.66
420A-1	LFD	51.01	22.07	0.06	14.25	1.53	0.43	9.72	0.49	0.43	99.98
420A-2	LFD	48.57	19.49	0.47	16.73	3.95	0.44	8.83	0.96	0.77	100.22
420A-3	LFD	50.22	22.29	0.04	13.64	2.11	0.45	10.09	0.63	0.47	99.95
420A-4	LFD	51.60	22.08	0.06	12.04	1.58	0.38	11.46	0.35	0.40	99.97
420A-5	LFD	49.62	21.09	0.11	12.65	2.95	0.45	10.99	0.70	0.78	99.33
420A-6	LFD	50.50	21.52	0.12	12.54	2.22	0.38	11.32	0.51	0.58	99.69