Geochemistry and U-Pb Geochronology of the 1450-1425 Ma Large Igneous
Province of Eastern Laurentia and 2480-780 Ma Large Igneous Provinces of
Western Laurentia

By

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ABSTRACT

Mesoproterozoic magmatism that is exposed on the eastern and western margins of Laurentia (North America) are interpreted to be parts of large igneous provinces (LIP). The western margin between Kimberley (British Columbia) and Yellowstone National Park (Wyoming), and the eastern margin between Labrador City and coastal Labrador are herein referred to as western Laurentia (WL) and eastern Laurentia (EL), respectively. WL intraplate magmatism was previously divided into two LIPs the: 1) ca. 1460 Ma Moyie-Purcell LIP (MPL) which consists of the i) Purcell lavas in the USA, ii) Moyie sills of the Belt-Purcell basin iii) dykes of the Tobacco Root Mountains and 2) the ca. 780 Ma Gunbarrel LIP. The MPL is composed of tholeiitic basalts, and associated with the world class Sullivan Pb-Zn deposit. EL consists of basalts of the non-mineralized Michael-Shabogamo Gabbros (MSG).

This research demonstrated that at least 17 geochemical groups are present in WL of which some belong to additional previously unrecognized events. Seven geochemical groups belong to the ca. 1460 Ma MPL; 1 with the ca. 780 Ma Gunbarrel LIP, 2 with a 1590-1550 Ma Mammoth-Western Channel LIP (MWCL); 2 with ages of 2480, and 1420 Ma; and 5 undated mafic pulses. The MWCL is similar to contemporaneous volcanic rocks within the South Australia craton, which was adjacent to NW Laurentia ca. 1590 Ma. This study proposes a shared 1590 Ma plume and LIP magmatism between Laurentia, and South Australia cratons.

The MSG of EL are subalkaline basalts enriched in P_2O_5 and K_2O and are shown to represent a single event with 2 pulses based on new U-Pb ages. Each pulse is defined by a distinct $[P_2O_5 \cdot 1000]/Zr$ (P/Zr) ratio: 1) a high P/Zr group at ca. 1425-1435 Ma; and 2) a low P/Zr group at ca. 1435-1450 Ma. Enrichment of P_2O_5 and K_2O is due to melting of a metasomatized subcontinental lithospheric mantle with melting facilitated by a slab window.

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Secondly, I would like to thank my supervisors, Dr. Richard Ernst and Dr. Brian Cousens, for accepting me as a PhD candidate after being removed from Earth Sciences for nearly 13 years. Their valuable supervision, mentorship and patience was most appreciated, but most importantly, for the arduous and grueling task of making my written work suitable for publication.

There is no way I can convey how thankful I am to all of the collaborators who provided assistance by supplying samples and productive discussions on the geology and problems that arose during this process. Without their help this research would not have been as fruitful. I would like to thank Dr. Stephen Harlan (National Science Foundation), Dr. Kevin Chamberlain (University of Wyoming), Dr. Russ Burmester (Idaho Geological Survey), Dr. Reed Lewis (Idaho Geological Survey), Dr. Wayne Goodfellow, Dr. Ken Buchan, (Geological Survey of Canada), Dr. Charlie Gower, Dr. Andy Kerr, Dr. James Conliffe, Dr. Andy Kerr, Pauline Hanover (Newfoundland and Labrador Geological Survey), Dr. Game

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I would like to thank Dr. Ulf Söderlund (Lund University),,and Dr. Mike Hamilton and Dr. Sandra Kamo (University of Toronto) for all their work separating and analyzing baddeleyite from my samples.

Thank you to my field assistants, Dan Stepner and Alana Mackinder. You helped make the fieldwork more enjoyable and as you posed questions about the rocks and landscape, it enabled me to think further and delve more into what the geology means. Thank you to all of the ranchers in Montana and Idaho that allowed me to collect samples on their property and to those that did not have me arrested when I mistakenly crossed onto their property. I would like to thank the Northern Lights Fishing Lodge, especially Millicent, who kept us well fed and watered for the six weeks we were working in the wilds of Labrador.

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Dr. Julian Pearce is acknowledged for suggesting and encouraging the use of his unpublished Sc-Co-Al₂O₃*4 ternary diagram to identify cumulate plagioclase, clinopyroxene and olivine samples.

Last but not least without the help of Dr. Vojtech Janousek, for assisting with the scripting of GCDkit, the petrographical software that generated all of the geochemical diagrams, it would have taken much longer to produce and analyze all the geochemical figures for this study.

Statement of Contribution

FIELDWORK AND SAMPLE COLLECTION

I (Chris Rogers) organized and executed all aspects of the fieldwork. A collection of 188 samples was assembled over two summer field seasons totaling 16 weeks in Labrador and British Columbia, Canada, and Idaho, Montana and Wyoming, USA. Logistics for the fieldwork program including lodging, travel, field supplies, and food purchasing were organized for myself, a field assistant and visiting scientific experts, in eastern and western Laurentia, in consultation with Dr. Brian Cousens and Dr. Richard Ernst. Arrangements were made to meet with scientific experts familiar with the areas. Traverses were arranged and led by myself with the aid of a field assistant. Traverses were conducted using multiple travel modes including small-motor boat, ATV, 4x4 vehicle and foot. The cumulative distance covered by all the traverses equaled approximately 25,000 kilometers.

An additional 101 rock samples (from Dr. S. Harlan, Dr. R. Burmester, Dr. R. Lewis, Dr. K. Chamberlain, Dr. K., Buchan, and Dr. A. Buddington) and 95 preprocessed rock powders (from Dr. C. Gower, Dr. A. Kerr, Dr. K. Buchan, and B. Wallace) were obtained.

Sample Preparation

Samples were processed by myself with the assistance of Kevin Ferris, a third year Earth Sciences student. I processed some of the samples, and instructed and supervised Kevin for the remainder. Kevin primarily cut rock slabs, removed tool marks, cut pucks for thin-sections and crushed samples to less than 2 mm. Areas for thin-section pucks were selected from the 1 cm rock slab by myself. The selected area was then cut to size and polished to 600 grit by Kevin Ferris. Standard and single polish thin-sections were made by Tim Mount (Carleton University). Kevin and I processed all crushed material to less than 200 mesh, and I arranged for samples to be sent to ALS Laboratories in North Vancouver for major and trace element analyses.

Additional geochemical data were obtained from Anderson and Goodfellow (2000) and Wade, C. (written comm. 2015) from the Moyie-Purcell LIP, Michael-Shabogamo Gabbros and Gawler Range-Benagerie volcanics, respectively. Data interpretation was under the supervision of Dr. Richard Ernst and Dr. Brian Cousens of Carleton University.

Isotopic Analysis

I performed sample preparation and all of the isotopic analyses for thermal ionization mass spectrometry (TIMS) at Carleton University's Isotope Geochemistry and Geochronology Research Facility (IGGRF).

Geochronology

I selected the samples submitted for U-Pb dating based on the association of specific geochemical groupings in both eastern and western Laurentia. Samples were then analyzed for the quantity and quality of the baddeleyite population via electron microprobe with assistance of Peter Jones (Carleton University) on an automated four spectrometer Cameca Camebax MBX electron probe by energy-dispersive x-ray analysis (EDX). Samples with the highest abundance of baddeleyite grains, without zircon rims were sent to the Lund University Geochronology laboratory for baddeleyite separation by Dr. Ulf Söderlund (Lund University, Sweden). The separated baddeleyite grains from one sample (TR-05) were sent to Dr. Sandra Kamo at the Jack Satterly Geochronology Laboratory at the University of Toronto for Isotope Dilution Thermal Ionization Mass Spectrometer (ID-TIMS) U-Pb analysis. Dr. Ulf Söderlund analyzed 5 samples at the Natural History of Museum in Stockholm Sweden. One additional sample (FA66045) was processed and analyzed by Dr. Mike Hamilton at the Jack Satterly Geochronology Laboratory at the University of Toronto.

After obtaining the U-Pb baddeleyite results from Dr. Ulf Söderlund, Dr. Mike Hamilton and Dr. Sandra Kamo, I then integrated the geochronological results with the geochemistry and tectonic characteristics of each event.

THESIS AND MANUSCRIPT CONSTRUCTION

I wrote each chapter and designed and drafted all figures, the exception being the Concordia diagrams or those otherwise referenced, for this PhD dissertation. I took the lead on the design and development of all geochemical and tectonic models. All aspects of the dissertation benefited from extensive discussions with Dr. Richard Ernst and Dr. Brian Cousens (Carleton University) and other collaborators with this project including but not limited to: Dr. Stephen Harlan (National Science Foundation), Dr. Charlie Gower and Dr. James Conliffe, (Newfoundland and Labrador Geological Survey), Dr. Andy Kerr (Memorial University of Newfoundland), Dr. Ulf Söderlund (Lund University), Dr Sandra Kamo and Dr. Mike Hamilton (University of Toronto).

This thesis is constructed around three interrelated chapters (Chapters 2-4) that are written for publication in peer-reviewed journals. Chapter 2 has been published in a Geological Society of America Special volume 510, Chapter 3 has been submitted to the Journal of Petrology and accepted with revisions, and Chapter 4 will be submitted to Lithos for review.

STATEMENT OF ORIGINALITY

This thesis was born out of the need to understand the postulated relationship between the Moyie-Purcell and the Michael-Shabogamo LIPs of similar age, but on opposite sides of North America (Laurentia). There was previous reconnaissance-level study on the Michael and Shabogamo gabbros in the east and the Moyie sills and Purcell intrusions in the west. The present study

represented a comprehensive geochemical and geochronological analysis that would fully characterize these magmatic events of eastern and western Laurentia to determine if they potentially have the same geochemical signature(s) and could be correlated across 4000 km and linked to a single geotectonic event (e.g., a single underlying mantle plume). Alternatively, it was postulated that if there were major geochemical differences between the approximately coeval ca.1460 Ma LIPs of eastern and western Laurentia, then this would indicate a distinct origin for each, resulting from contemporaneous but different geotectonic events.

Chapter 2

This chapter was the first peer-reviewed publication for this dissertation and the 55th publication to come out of the background project which has been funding my research, the Large Igneous Provinces – Resource Exploration – Supercontinent Reconstruction Project (www.supercontinent.org); also known as project 08E03 of CAMIRO, Exploration Division, www.camiro.org.

For this chapter the 2016 publication has been re-formatted to fit within the Carleton University Thesis Template. Also U-Pb baddeleyite ages that were incomplete or covered under confidentiality agreements mandated by the Project at the time of publication are now included in this chapter. As with all chapters, the illustrations and tables are placed at the end of this chapter. The online geochemical database can be obtained from the GSA Data Repository Item 2016072, Tables DR1: Previously published geochemistry used in this study, and DR2: Previously published material from Anderson and Goodfellow (2000), are

available at www.geosociety.org/pubs/ft2016.htm, or by request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA or Appendix 2.3 or Appendix 2.2 respectively.

I was responsible for field preparations, sample collection and preparation, and geochemical interpretation of the data for 16 of the 17 geochemical groups. The data on the final group, ca. 780 Ma Gunbarrel LIP were based on the 2014 M.Sc. thesis of Alana Mackinder (now Podlesny). However, I was responsible for integrating the ca. 780 Ma Gunbarrel LIP results of Ms. Mackinder (Podlesny) into the broader understanding of the Paleo- to Neo-Proterozoic magmatism in western Laurentia. I was responsible for generating all diagrams for this chapter, unless otherwise referenced. All co-authors added feedback and assisted with revision of the manuscript. Chapter 2 should be cited as follows:

Rogers, C., Mackinder, A., Ernst, R.E., and Cousens, B., 2016, Mafic magmatism in the Belt-Purcell Basin and Wyoming Province of western Laurentia, in MacLean, J.S., and Sears, J.W., eds. Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper 522, 243–282, doi:10.1130/2016.2522(10).

Chapter 3

This chapter was the second submitted for peer-reviewed publication and is the 65th publication to come out of the background project which has been funding my research, the Large Igneous Provinces – Resource Exploration – Supercontinent Reconstruction Project (www.supercontinent.org); also known as

project 08E03 of CAMIRO, Exploration Division, www.camiro.org. This chapter was submitted to the Journal of Petrology June 7th, 2017.

For this chapter I recognized that the rocks for the Michael-Shabogamo Gabbros were derived from a K- and P-metasomatized mantle source because of their peculiar chemistry. Using partition coefficients of different elements in different minerals allowed me to predict and model the mineralogy of the mantle that produced the MSG. Additionally, I was able to evaluate existing tectonic models for the area to help identify those that were plausible.

I wrote the entire manuscript and designed and drafted all of the figures unless otherwise referenced. All co-authors added feedback and helped with the revisions of the manuscript.

Chapter 4

Chapter 4 is presented as a pre-submission draft to Lithos for the third peer-reviewed publication for this thesis and the 69th publication to come out of the background project which has been funding my research, the Large Igneous Provinces – Resource Exploration – Supercontinent Reconstruction Project (www.supercontinent.org); also known as project 08E03 of CAMIRO, Exploration Division, www.camiro.org.

The focus of this chapter was to test the hypothesis in Chapter 2 that the two newly recognized geochemical groups in the Tobacco Root Mountain, Wyoming craton, western Laurentia, were distinct compared to the ca. 1460 Ma Moyie-Purcell LIP. U-Pb geochronological results showed the new 1550 Ma and

1590 Ma Tobacco Root Mountain dykes were separate events from the Moyie-Purcell LIP. Other dykes of ca. 1590 and 1550 Ma age were sought, with the purpose to geochemically compare with those of the Tobacco Root Mountain. Mafic magmatism from the ca. 1590 Ma Western Channel Diabase, NW Laurentia, and ca. 1590 Ma Gawler and Curnamona cratons, South Australia, matched the age of the Tobacco Root Mountains dykes. However, no additional areas of 1550 Ma mafic magmatism were found in western Laurentia, but ca. 1550 Ma felsic magmatism was present in the South Australian craton

Because others (e.g., Thorkelson *et al.*, 2001, Hamilton & Buchan, 2010) have proposed a Laurentia-Australia reconstruction link I thought it useful to further investigate the link geochemically. I obtained published geochemical data for the Western Channel Diabase (Ernst & Buchan, 2010) and published and unpublished geochemical data from Claire Wade at the South Australian government (written comm., 2016), the OZCHEM database (Budd *et al.*, 2002 and references therein). I filtered the data to compare only the mafic volcanic and intrusive rocks to the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups of the Tobacco Root Mountains to make a comparison of all three areas.

I developed tectonic and mixing models to explain the geochemical characteristics observed in the rocks from these areas. I designed and drafted all the figures for this chapter unless otherwise referenced. All co-authors added feedback and helped with revision of the manuscript.

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Chapter 1: Introduction

1.1 SCIENTIFIC MOTIVATION

Large Igneous Provinces (LIPs) have become an important focus for study in recent years due to their potential as a tool for paleocontinental reconstruction, as an economic exploration tool, and for links with major environmental change including mass extinction events (e.g., Bleeker & Ernst, 2006, Jowitt & Ernst, 2013, Ernst, 2014, Ernst & Youbi, 2017). LIPs were originally defined by Coffin and Eldholm (1991, 1992) as mafic magmatism with a large aerial extent ($>0.1 \text{ Mkm}^2$) that represented “massive crustal emplacement of predominately mafic (Mg and Fe rich) extrusive and intrusive rock and originated other than ‘normal’ seafloor spreading”. This definition has been revised by Bryan and Ernst (2008), Ernst (2014), and Ernst and Youbi (2017): LIPs represent large volume ($>0.1 \text{ Mkm}^3$; frequently above 1 Mkm^3), mainly mafic (-ultramafic) magmatic events of intraplate affinity (based on tectonic setting or geochemistry), that occur in both continental and oceanic settings, and are typically of short duration ($<5 \text{ Ma}$) or consist of multiple short pulses over a maximum of a few 10s of Ma. They comprise volcanic packages (flood basalts), and a plumbing system of dyke swarms, sill complexes, layered intrusions, and a crustal underplate. LIPs can also be associated with silicic magmatism, including dominantly silicic events termed Silicic LIPs (SLIPs), carbonatites and kimberlites. LIPs occur at a variable rate that averages approximately every 20–30 Ma but with possible peaks associated with supercontinent breakup, back to at least 2.5 Ga. The rate of LIP occurrence in the Archaean is less certain due to its poorer preservation (Ernst, 2014). The cause of LIPs remains controversial with a number of suggested

mechanisms including mantle plumes, lithospheric delamination melting, rift related decompression melting, and edge convection melting (Foulger, 2007, Ernst, 2014, and references therein).

The LIP record can be used as one of a number of powerful tools to help identify crustal blocks that were previously adjacent or nearby. LIPs units (primarily dykes, sills, layered intrusions, and volcanic rocks) within a single crustal block and between formerly adjacent crustal blocks can be linked on the basis of matching ages (ideally based on precise U-Pb dating of zircon or baddeleyite), matching primary paleomagnetic directions, or on the criteria of restoring a simple geometric relationship of dykes (e.g., a radiating dyke swarm; Bleeker and Ernst 2006; Ernst, 2014). The LIP record for a crustal block can be displayed as a range of event ages resembling a supermarket barcode (i.e., matching barcodes; e.g., Bleeker & Ernst, 2006). Those blocks with multiple matches in LIP age and other criteria (i.e. matching barcodes) are inferred to have been formerly adjacent, and the matching LIPs components on each block to have originally been parts of single more widespread LIPs.

One underutilized geological tool that can aid U-Pb geochronology with the reconstruction of LIP fragments is geochemistry (Rogers *et al.*, 2016a). Trace element and isotope geochemistry can be used to recognize intermixed intraplate magmatic units with distinct compositions that can either represent separate events or distinct geochemical packages within a LIP (e.g., Rogers *et al.*, 2016a) Ernst, 2014 and references therein). Magmatic events with similar U-Pb geochronology but distinct geochemistry reflecting different tectonic

environments can be discounted as being linked to a common event (e.g., subduction vs. plume; cf Rogers *et al.*, 2016a).

1.2 THEMATIC LINKS AND METHODOLOGY

Unless specified, it should be noted that in this chapter any reference to the “1460 Ma event”, uses 1460 Ma as an average age and the magmatic units being referenced could be as young as 1425 Ma or as old as 1470 Ma (See Table 1.1 for details).

Major intraplate magmatic provinces of apparently similar ca. 1460 Ma age are exposed on the eastern and western margins of Laurentia (North America; Figure 1.1), and each has been interpreted to represent a separate LIP. This research aims to fill a gap in geochemical and tectonic understanding of this ca. 1460 Ma magmatism of eastern and western Laurentia.

1.2.1 Project Goals

The goal of this project was to geochronologically, geochemically and isotopically:

- 1) Characterize the geochemical variations within and between the ca. 1460 Ma magmatism of eastern and western Laurentia. Develop criteria to distinguish the 1460 Ma event from other intermixed swarms of different ages (including dykes of the 780 Ma Gunbarrel LIP) of western Laurentia;

2) Determine and characterize the origin (source, tectonic setting) and model the ca. 1460 Ma magmatism of eastern and western Laurentia in terms of source and subsequent differentiation processes;

3) Compare the petrogenesis of eastern and western Laurentia 1460 Ma magmatism to test three hypotheses for their origin:

i) a single superplume hypothesis (Figure 1.2 and 1.3),

ii) a multiple plume hypothesis (Figure 1.4) or

iii) a variable tectonic setting hypothesis that includes a different origin of magmatism for eastern and western Laurentia, comprising of one or more of the following: *a)* plume, *b)* subduction-back arc, and/or *c)* intra-continental rift basins (Figure 1.5).

The first hypothesis considers that a single mantle plume generated the 1460 Ma magmatism, in both eastern and western Laurentia (Figure 1.2). In this case the plume would have arrived beneath the Laurentian lithosphere and spread upward to shallower lithospheric levels to these opposite sides of the Laurentia craton (Figure 1.3; cf Sleep *et al.*, 2002, Bright *et al.*, 2014). The second hypothesis includes multiple plumes of the same age arriving at the base of the lithosphere in eastern and western Laurentia and independently producing ca. 1460 Ma magmatism. The third possibility is that one or both of the ca. 1460 Ma Laurentia margin events were caused by tectonic processes such as a back-arc spreading behind a subduction zone or passive extension leading to decompression partial melting (Figure 1.4).

1.2.2 Methodology to Develop The Geochemical Fingerprints for Eastern and Western Laurentia

1.2.2.1 Fieldwork

Samples collected for geochemical analysis need to have a geological context for the analysis to be meaningful. Selection of geochemical samples that are fresh and representative of the overall outcrop is critical. Samples that are differentiated or contain phenocrysts are to be avoided.

1.2.2.2 Geochemistry

Evaluation of geochemical analyses is critical in classifying a magmatic event. Distinguishing an event as being formed in an intraplate setting from that associated with plate margins (e.g., arc, spreading centre) is essential in determining whether the event is LIP related. Those samples that plot as transitional between environments or plot in different environments on different diagrams need to be further examined. An explanation needs to be developed on why those trends are observed and what tectonic setting produced the melt. Utilizing a combination of large ion lithophile elements, high field strength elements, and compatible and incompatible elements, is essential in determining geotectonic setting (e.g., Shervais, 1982, Pearce, 1996, Condie, 1997).

Being able to determine parental magmas from those that have been contaminated or fractionated is essential. Radiogenic isotopes are an important component that will not be impacted by degree of melting or subsequent

fractional crystallization but will be affected by assimilation of crustal rocks and their age.

1.2.2.3 U-Pb Geochronology

Geochronology is another important tool in determining the chronology of the ca. 1460 Ma events of eastern and western Laurentia. Using geochemistry to identify distinct magma groups is critical in determining sample selection and deciphering the magmatic history of eastern and western Laurentia. Additionally, precise U-Pb analyses of geochemically identified groups can reveal previously unknown magmatic events not related to the ca. 1460 Ma event(s).

1.3 REGIONAL GEOLOGY

Below is provided a summary of the tectonic and magmatic history of the host rocks for both eastern and western Laurentia.

1.3.1 Western Laurentia

The field area for western Laurentia extends from approximately 10 km north of Kimberley, British Columbia, through the Idaho Panhandle and east-southeast through Montana to approximately 20 km north of the Montana-Wyoming border near Yellowstone National Park. The study area covers ~750 km by 250 km, and it is split over two countries; in four states of the United States, and in one Canadian province. The ca. 1460 Ma Moyie-Purcell LIP

consists of (1) the Purcell lavas, dykes, and sills in the western United States, and (2) the gabbroic Moyie sills of the Belt-Purcell Basin and associated dykes in British Columbia, Canada and (3) the ca. 1450 Ma dykes of the Tobacco Root, Ruby Range and Highland Range Mountains of Montana (Höy, 1984, Höy, 1989, Anderson & Davis, 1995, Anderson & Goodfellow, 2000). These intrusions range in composition from tholeiitic basalts, basaltic andesites, and andesites to dacites and rhyolites, but the focus in this chapter is on the mafic units (basalts to basaltic andesites).

The Moyie sills and Purcell lavas are associated with a number of mineral deposits including the world class Sullivan Pb-Zn SEDEX deposit (Anderson & Goodfellow, 2000). The gabbroic sills are coeval with sedimentation and have been emplaced in shallow, wet, unconsolidated turbidite sediments (Anderson & Goodfellow, 2000).

1.3.1.1 The Moyie Sills and Host Rocks

The Moyie sills intrude the Belt-Purcell basin, which represents filling of a rift system by marine and fluvial sediments (Lydon, 2007). The Belt-Purcell basin combines the Purcell basin and Purcell Supergroup in British Columbia, Canada and the Belt basin and Belt Supergroup in Montana and Idaho, USA. Only 10% of the 200,000 km² of the Belt-Purcell basin is located within Canada (Figure 1.5; Lydon, 2007).

Mesoproterozoic rifting of Rodinia initiated formation of the Belt-Purcell basin near the continental margin of western Laurentia (Lydon, 2007). The rift

system that extended from western Laurentia to Missouri (Gower & Tucker, 1994) consists of two branches, the Main or Purcell Branch and the Helena Branch in the Belt-Purcell Basin (Lydon, 2007). The Main Branch consists of ~12 km thick turbidite sequences of the Aldridge Formation (Canada) and Prichard Formation (USA) and truncates on the north side of the east-northeast Helena Branch. The turbidites consists of an arenite base and a siltite top representing the A and E parts of a Bouma sequence, with parts B through D being indistinct (Hamilton *et al.*, 1982). The Aldridge Formation has been subdivided into three informal, but widely accepted members: the Lower Aldridge, the Middle Aldridge Formation and the Upper Aldridge Formation (Lydon, 2007).

The Lower Aldridge Formation consists of rusty weathering siltstone, quartz wacke and argillite, and is commonly intruded by the gabbroic Moyie sills (Höy *et al.*, 2003). The quartz wacke beds are commonly graded or cross-bedded and less commonly have well-defined basal scours, indicative of turbidite deposition (Höy *et al.*, 2003). They can form fining upwards sequences of tens of metres that may be interlayered with siltstone or argillite, and are capped by thinner bedded siltstone layers (Höy *et al.*, 2003).

The contact between the Lower and Middle Aldridge Formation is the base of the first prominent blocky, grey-weathering quartz wacke beds (Höy *et al.*, 2003). The Middle Aldridge is composed of more than 2000 m of well-bedded grey weathering quartz wacke and siltstone (Höy *et al.*, 2003). The upper part of the Middle Aldridge consists of quartz arenite and quartz wacke beds, which become thinner as the proportion of inter-bedded siltstone and argillite increases

(Höy *et al.*, 2003). The division also comprises of a number of distinct cycles of massive, grey quartz arenite beds that grade upward into an interlayered sequence of quartz wacke, siltstone and argillite, and are capped by siltstone and argillite load structures, including load-casted ripples (Höy *et al.*, 2003). The contact with the Upper Aldridge Formation is placed above the last bed of massive grey quartz arenite (Höy & Diakow, 1981). The Moyie sills are constrained to the lower part of the Middle Aldridge.

The Upper Aldridge is composed of approximately 500 m of rusty to dark grey weathering laminated argillite and silty argillite (Höy *et al.*, 2003). It is generally thin bedded and thinly laminated, with thin graded siltite-argillite couplets and lenticular bedding; tan siltstone lenses in argillite are common bed-forms (Höy *et al.*, 2003). Massive, or less commonly, cross-bedded syneresis cracks are observed near the top of the quartz arenite and quartz wacke beds occur near the top of the Upper Aldridge Formation. The contact of the Upper Aldridge Formation with the overlying Creston Formation is relatively abrupt, and is placed where green-tinged siltite layers first appear (Höy *et al.*, 2003).

The Moyie sills are sheet-like bodies that cover an area of over 8000 km² in British Columbia, Montana, Idaho and Washington (Bishop, 1973). The sills vary from 1 to 700 m thickness and can attain vertical thickness of up to 2 km (Anderson & Goodfellow, 2000). The Moyie sills constitute up to 30% of the Lower Aldridge Formation and the lower section of the Middle Aldridge Formation (Bishop, 1973, Höy, 1989). The sills are generally phaneritic and can be classified as gabbronorites, ferrodiorites and quartz diorites (Bishop, 1973). Field

relationships show diabase sills are locally heterogeneous; with some sills being fairly uniform in composition and other sills compositionally variable (Anderson & Goodfellow, 2000). Some of the Moyie sills have internal structures that suggest they were intruded into wet sediments (Höy *et al.*, 2003). These structures include soft-sediment deformation, obliteration of primary sedimentary structures adjacent to the sills and dewatering structures (Höy *et al.*, 2003). Structures at the base of some sills resemble load casts, flame structures and clastic dykes intruding the sills (Höy *et al.*, 2003). Other evidence includes mud-volcano activity and associated tourmalinization that are present in the Aldridge and Prichard Formations which may represent heating of sediments and fluids by intrusion of the hot sills (Lydon, 2000). Internal layering is developed uniformly within individual sills over a wide geographic area (Anderson & Goodfellow, 2000).

Bishop (1973) and Hoy (1989) classified the Moyie sills as subalkaline, high iron tholeiites on the basis of their major and trace element geochemistry. Most of the Moyie sills are low-potassium tholeiitic basalts consistent with continental basalts, while some of the sills are alkaline and typical of rift basalts (Höy *et al.*, 2003). Anderson & Goodfellow (2000) defined four groups based on stratigraphic position within the Aldridge Formation: Group a - intrudes the Lower Aldridge Formation below the "Mine Sill" that is host for the Sullivan SEDEX deposit; Group b - the "Mine Sill" and equivalents intruding the Lower Aldridge Formation; Group c - intrudes the Middle Aldridge Formation below Group d and Group d - the highest sills that intrude the Middle Aldridge Formation.

Geochemically Group a is geochemically and petrographically distinct from Groups b, c and d (Anderson & Goodfellow, 2000). REE abundances show that the Moyie sills were produced from a source similar to EMORB that has been contaminated with continental crust including possible Achaean crust (Anderson & Goodfellow, 2000).

The Moyie sills have been dated at 1468 ± 3 Ma by U-Pb zircon methods (Anderson & Davis, 1995, Anderson & Parrish, 2000). Correlated sills in Montana and Idaho (USA) have similar U-Pb zircon ages including the Plains Sill, 1469 ± 2.5 and the Paradise Sill, 1457 ± 2 Ma (Sears *et al.*, 1998). These sills also show geochemical characteristics similar to the Moyie sills (Rogers *et al.*, 2016b).

1.3.1.2 Dykes of the Tobacco Root Mountains

The Tobacco Root Mountains are one of a number of Precambrian terrains uplifted by the Laramide orogeny in Wyoming and Montana (Wooden *et al.*, 1978). The Precambrian rocks of the Tobacco Root Mountains consist of a high-grade metamorphic assemblage that include: quartzo-feldspathic gneiss, amphibolite, marble, pelitic schists, quartzite and ferruginous gneiss (Wooden *et al.*, 1978). The mafic dykes that intrude the Precambrian rocks trend west-northwest and intrude an area approximately 5 km by 35 km (Wooden *et al.*, 1978). Wooden (1975), identified three geochemical Groups, A, B and C, with an age of 1455 ± 125 Ma for Group A, 1120 ± 185 Ma for Group B and 1130 ± 130 Ma for Group C by Rb-Sr whole rock isochron ages. Harlan *et al.*, (2005) improved the ages of Group A and Group B dykes using Sm-Nd and U-Pb

geochronology, respectively. They correlated the Group A and C dykes to the ca. 1460 Ma Moyie sills based on a 1448 ± 49 Ma Sm-Nd isochron and paleomagnetic studies. Group A paleomagnetic data exhibited a normal remnant polarization while Group C data were reversed which could indicate that they belonged to the same event but exhibited a polarity reversal during the event (Harlan *et al.*, 2005). Because of the large error for the Sm-Nd isochron (± 49 Ma) on the Group A dykes it was unclear whether they were part of the ca. 1460 Ma western Laurentia magmatic suite or represented another distinct suite of intrusions (Harlan *et al.*, 2008). Harlan *et al.* (2008) also correlated the Group B dykes to the ca. 780 Ma Gunbarrel LIP based on a 782.4 ± 4.9 Ma U-Pb zircon age and paleomagnetic studies.

1.3.2 Eastern Laurentia

1.3.2.1 Eastern Laurentia Magmatism and Host Terranes

Ca. 1460 Ma eastern Laurentia intraplate magmatism consists of the non-mineralized Michael-Shabogamo Gabbros, situated within the Grenville Province (e.g., Ernst and Buchan, 2001; Fahrig *et al.*, 1974, Emslie, 1983, Gower *et al.*, 1990). The only known distinction between the Michael Gabbros and Shabogamo Gabbros is geographic. The Shabogamo Gabbros are exposed in western Labrador and the Michael Gabbros are exposed in the east (C. Gower, pers. comm., 2012).

The Grenville province in Labrador can be divided into the Exterior Thrust Belt and the Interior Magmatic Belt. The area of focus in this study is the Exterior Thrust Belt, which is composed of parautochthonous rocks in the eastern Groswater Bay terrane (Gower, 1996) and Churchill Falls as well as the Gagnon terranes in western Labrador (James, 1994). The geological evolution of the eastern Grenville Province in Labrador can be divided into three stages: 1st stage (>1710-1600 Ma), 2nd stage (1600-1230 Ma) and 3rd stage (1230-955 Ma; Gower & Krogh, 2002). Each stage is made up of the assembly of thrust-bound litho-tectonic terranes that are part of the Exterior Thrust Belt (Gower, 1996). The term “terrane” in Labrador defines regions that differ from each other (i.e. rock types, structural style and geological evolution) but does not imply that great distances separated them at some point in time. The terranes are significant in the Grenvillian context and existed prior to Grenville orogenesis (Gower, 1996).

The area west of Churchill Falls is not as well studied as the area to the east and the terranes are different. From north to south the terranes are the Gagnon and Churchill Falls terranes, which would be equivalent to the Groswater Bay terrane in the east, and the Molson Lake terrane, which would be equivalent to the Lake Melville terrane in the east (Figure 1.6). The Lac Joseph, Wilson Lake, Mealy Mountains and Hawke River terranes to the south are exotic to Laurentia at ca. 1460 and do not host the Michael Shabogamo Gabbros, and therefore will not be discussed further. All of the above terranes are within the Exterior Thrust Belt of the Grenville province (James, 1994, Gower, 1996, Kerr, 2007). The boundary that separates the Grenville province from the Superior,

Eastern Churchill, Nain and Makkovik provinces to the northwest is known as the “Grenville Front” (e.g., Gower, 1996, Kerr, 2007).

1.3.3 The Michael-Shabogamo Gabbros

The Michael-Shabogamo Gabbros are a suite of tholeiitic, subalkaline transitional to mildly alkaline basaltic rocks that are hypothesized to have been emplaced in a subduction setting (Gower & Erdmer, 1988) and later were reevaluated to be continental diabase (Emslie *et al.*, 1997). In addition, Gower *et al.* (1990) used Sr and Nd isotopic data to infer that the two suites were derived from a subcontinental lithospheric mantle source and had comparable evolutionary magmatic histories during their emplacement. The rocks were classified based on whole-rock geochemical data and it was concluded that they belong to a single event (Gower *et al.*, 1990, Rivers *et al.*, 1993, Rivers, 1998, Rivers & Corrigan, 2000).

1.4 ADDITIONAL CA. 1460 MA MAGMATISM

1.4.1 Within Laurentia

Another less well-studied area of ca. 1460 Ma magmatism in Laurentia is the Eastern Granite-Rhyolite province in the Ozark Mountains of Missouri and Arkansas containing mafic dykes that are poorly dated between 1.5-1.3 Ga. Accretion and growth of the Eastern Granite-Rhyolite province onto Laurentia occurred incrementally between 1.55 and 1.35 and involved accretion of juvenile

crust as well as large scale inboard magmatism (Figure 1.1; Griffin *et al.*, 2011, Bickford *et al.*, 2015, Bickford, 2017). This area was not part of the present study.

1.4.2 External to Laurentia

Outside Laurentia, intraplate magmatism of similar age is known in other crustal blocks (i.e. Baltica, northern Siberia, Brazil (Amazonia), western Australia, and India) that have been suggested to have links with Laurentia in the Meso- and Neo-Proterozoic supercontinents, Nuna and Rodinia (Figure 1.1; Goode & Hall, 1981, Airo, 1999, Söderlund *et al.*, 2005, Söderlund *et al.*, 2006, Ernst *et al.*, 2008, Morris & Pirajno, 2009, Siga *et al.*, 2011, Doe *et al.*, 2012, Puchkov, 2012). A better understanding of the ca. 1460 Ma magmatic history of eastern and western Laurentia, developed in this thesis, will improve future paleoreconstruction models involving these crustal blocks external to Laurentia.

Mafic intraplate magmatism of similar age to the Michael-Shabogamo Gabbro exist in Baltica (Sweden and Russia) as the Trond-Gotta and Lake Ladogta dykes, respectively (Söderlund, 2006, Lubnina *et al.*, 2010). Paleomagnetic-based reconstructions show that Laurentia and Baltica (Fennoscandia) were attached during this time, and so a genetic link between the Baltica units and Michael-Shabogamo units is plausible (Gower & Owen, 1984, Söderlund, 2006, Lubnina *et al.*, 2010, Buchan, 2014).

A Brazilian event is part of the Amazonian craton from the Betara region of eastern Paraná state. The Salto do Ceu Sill from this area has a U-Pb baddeleyite age of 1439 ± 4 Ma (Teixeira *et al.*, 2016). There remains debate on

the reconstruction of Amazonia with respect to eastern Laurentia (Söderlund, 2006, Lubnina *et al.*, 2010, Teixeira *et al.*, 2011, Teixeira *et al.*, 2016).

Some dolerite sills in the western Bangemall basin of western Australia have been dated at ca. 1465 Ma and cover an area of 143,000 km². The location of western Australia is not known at ca. 1460 Ma but is commonly placed outboard of south Australia that was near western Laurentia at ca. 1590 Ma (Morris & Pirajno, 2005).

Paleomagnetic analysis determined the alkaline to sub-alkaline ca. 1460 Ma Lakhna dykes from India could have been emplaced in four possible global positions at ca. 1460 Ma. Intriguingly, two of those positions for the Indian craton are near either the western or eastern margins of Laurentia (Zhang *et al.*, 2012, Pisarevsky *et al.*, 2013).

1.5 SCOPE AND INTEGRATION OF DISSERTATION CHAPTERS

To address the goals of this PhD dissertation, the main body is broken into three chapters that report on particular aspects of the project. Chapters 2, 3 and 4 address the geochemical variations in western Laurentia, eastern Laurentia and also the Tobacco Root Mountains area of western Laurentia, respectively. Chapters 3 and 4 also provide a tectonic framework for the magmatism in their regions. Chapter 2 reports the geochemical characteristics of Proterozoic magmatism in western Laurentia (Figure 1.5). Seventeen geochemical groups were identified including additional events that were likely distinct from the previously recognized ca. 780 Ma Gunbarrel and ca. 1460 Ma Moyie-Purcell LIPs.

A similar geochemistry approach was applied to the Michael-Shabogamo magmatism of eastern Laurentia and three magmatic pulses were identified (Chapter 4).

Chapter 2 evaluates the 17 geochemical signatures in terms of mantle source, subsequent assimilation and fractional crystallization. Because of the complex geochemistry and absence of additional geochronology at the time of publication it was not possible to produce any tectonic models for the geochemical groups. Where available and for the convenience of examiners, dates without errors have been added to the version of the publication that is included in this chapter. A future objective is to publish peer-reviewed manuscripts for those geochemical groups having a new U-Pb age. Chapter 4 represents the first of these additional manuscripts.

The purpose of Chapter 3 is to address the geochemical, geochronological and tectonic characteristics of the Michael and Shabogamo Gabbros in eastern Laurentia (Figure 1.6). Doing so allows assessment of whether the Michael and Shabogamo Gabbros are petrogenically, geochronologically and tectonically related to each other. Another goal has been to distinguish and characterize any units that could be related to other intermixed events. The final goal was to develop a petrogenetic and tectonic model for the ca. 1460 Ma Michael and Shabogamo Gabbros.

Chapter 4 addresses the two groups of geochemically distinct magmatism from the Tobacco Root Mountains of western Laurentia that were first identified in Chapter 2 (Figure 1.5). New U-Pb geochronology provides 1590 and 1550 Ma

ages that allows a comparison with NW Laurentia and formerly attached South Australia craton.

Achieving the objectives for each of these three chapters (2-4) allows addressing of the initial goal of this thesis, which is determining whether the ca. 1460 Michael and Shabogamo Gabbro LIP of eastern Laurentia and the ca. 1460 Moyie-Purcell LIP of western Laurentia are related, and how they were emplaced, and this point is addressed in Chapter 5.

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Figure 1.1: Map of 1460 Ma LIP events around the world. This study will focus on the Moiré and Michael-Shabagamo events of western and eastern Laurentia. Other events of interest to this study are the Betara Gabbros in South America, Tuna-Trond-Göta and Lake Ladoga events in Fennoscandia and the Bangemall intrusions in western Australia. All are candidates for connection to Laurentia at ca. 1460 Ma in the Mesoproterozoic supercontinent Nuna (modified from Global LIP database, R. Ernst, unpublished)

Figure 1.2: One scenario for possible dyke emplacement for ca. 1460 Ma LIP events. A hypothetical superplume rising beneath a major root below the Laurentian craton in the Mesoproterozoic. As the plume rises a number of things happen: 1) the plume comes in contact with the major lithospheric root, 2) the plume continues to rise and bifurcates, 3) the plume continues rising upward to fill topographic highs in the lithosphere, 3) the topographic highs fill and overflow and, 4) the magma continues upward to fill other lithospheric highs. In a lithospheric high the magma would continue to evolve and rise into the lithosphere where dykes would be emplaced into the crust.

Figure 1.3: Scenario 2 for possible dyke emplacement for the ca. 1460 Ma LIP events. Shows two separate hypothetical plumes rising beneath major lithospheric roots below the Laurentian craton in the Mesoproterozoic. Each plume producing separate magmatism for two LIP events. Another possibility for this model would be mixing from the two plumes if the lithospheric root between the two plumes had an insufficient depth to prevent the magma from over flowing the "dam" (not shown). Within each lithospheric high the magma would continue to evolve and rise into the lithosphere where the dykes would be emplaced into the crust.

Figure 1.4: A third hypothetical model using a combination of mechanisms for emplacement of the ca. 1460 Ma magmatism. There may have been decompression melting from extension (e.g., Tobacco Root Mountain dykes). There may have been emplacement into a back-arc setting (e.g., Michael-Shabogamo gabbros) or there may have been a plume rising beneath a subducting slab, producing magmas from differing sources which result in mixing of melt and isotopic signatures (e.g., Michael-Shabogamo gabbros).

Figure 1.5 Map of Proterozoic mafic magmatism originally thought to be part of the ca. 1460 Ma Moyie-Purcell LIP. Area outlined by black box is the focus of Chapter 4. TRM=Tobacco Root Mountains.

Figure 1.6 Terranes and Michael-Shabogamo Gabbros in Labrador. GT=Gagnon Terrane, MLT=Molson Lake terrane, CFT=Churchill Falls terrane, WLT=Wilson Lake terrane, MMT=Mealy Mountains terrane, GBT=Groswater Bay terrane, LMT=Lake Melville terrane, HRT-Hawke River terrane, ETB=Exterior Thrust Belt, IMB=Interior Magmatic Belt. Terrain boundaries modified from Gower (1996).

Table 1.1 Summary of studies in eastern and western Laurentia

LIP Units	LIP Location	Type of Study	Authors
Fennoscandia	Baltica	Geochemical	Airo (1999)
Moyie Sills	Western Laurentia	Geochronological and Geochemical	Anderson and Davis (1995)
Moyie Sills	Western Laurentia	Geochronological and Geochemical	Anderson and Goodfellow (2000)
Michael-Shabogamo Gabbros	Eastern Laurentia	Mapping and Geochemical	Emslie <i>et al.</i> (1997)
Michael-Shabogamo Gabbros	Eastern Laurentia	Mapping and Geochemical	Gower <i>et al.</i> (1990)
St. Francois Mountains	Southern Laurentia (?)	Seismic	Griffin <i>et al.</i> (2011)
Tobacco Root Mountains	Western Laurentia	Paleomagnetic and Geochronological	Harlan <i>et al.</i> (2005)
Tobacco Root Mountains	Western Laurentia	Paleomagnetic and Geochronological	Harlan <i>et al.</i> (2008)
Moyie Sills	Western Laurentia	Geochronological and Geochemical	Höy (1989)
St. Francois Mountains	Southern Laurentia (?)	Paleomagnetic	Meert and Stuckey (2002)
Edmund Gp	Australia	Mapping and Geochemical	Morris and Pirajno (2005)
Edmund Gp	Australia	Mapping and Geochemical	Morris and Pirajno (2009)
Lakhna Dykes	India	Geochemical and Paleomagnetic	Pisarevsky <i>et al.</i> (2013)
Siberia	Urals	Geochemical and Geochronological	Puchkov (2012)
Michael-Shabogamo Gabbros	Eastern Laurentia	Mapping	Rivers (1998)
Moyie Sills	Western Laurentia	Mapping (Structural)	Sears and Price (2000)
Moyie Sills and Urals	Western Laurentia and Siberia	Paleomagnetic	Sears <i>et al.</i> (2004)

LIP Units	LIP Location	Type of Study	Authors
Betara Formation	Amazonia	Geochemical, Mapping and Geochronological	Siga Jr <i>et al.</i> (2011)
Fennoscandia	Baltica	Geochemical	Söderlund <i>et al.</i> (2006)
Fennoscandia	Baltica	Geochemical and Geochronological	Söderlund <i>et al.</i> (2005)
LIP Reconstructions	LIP Location	Type of Study	Authors
Baltica, Amazonia, Siberia Laurentia, Australia, India	Global	Paleomagnetic and Literature Compilation	Zhang <i>et al.</i> (2012)
Baltica, Amazonia, Siberia Laurentia, Australia, India, China	Global	Paleomagnetic and Literature Compilation	Zhao <i>et al.</i> (2004)
Ur (Madagascar, India, Australia), Nena (Laurentia, Baltica and Siberia) and Atlantica W. Africa, Amazonia, San Francisco and Congo)	Global	Paleomagnetism and Literature Compilation	Meert (2002)
India, Laurentia, Siberia	Global	Geochemical and Paleomagnetic	Pisarevsky <i>et al.</i> (2013)
Laurentia and Baltica	Global	Paleomagnetic	Salminen <i>et al.</i> (2014)
Siberia, Baltica, Laurentia	Global	Paleomagnetic and Literature Compilation	Evans and Mitchell (2011)
Laurentia and Siberia	Western Laurentia and Siberia	Literature Compilation	Sears and Price (2002)

Chapter 2: Mafic Magmatism in the Belt-Purcell Basin and Wyoming Province of Western Laurentia

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Note that the version below has been modified with the addition of U-Pb ages that were not available at the time of publication

2.3 ABSTRACT

Proterozoic mafic magmatism exposed along the western side of North America, or western Laurentia, from Kimberley, BC through to northwestern Wyoming, has been previously divided into two Large Igneous Provinces (LIPs): the ca. 1460 Ma Moyie-Purcell and the ca. 780 Ma Gunbarrel LIPs. New geochemical analyses from the present study demonstrate the presence of additional previously unrecognized intraplate mafic magmatic events. Distinguishable by variable normalized rare-earth element patterns combined with differing slopes on a binary Ti vs. V plot there are 17 identifiable geochemical signatures in the 307 whole rock and trace element analyses from this study. Only 7 of these signatures can be linked to the ca. 1460 Ma Moyie-Purcell LIP, and 1 signature to the 780 Ma Gunbarrel LIP. Two groups of intrusions (ca. 1550-1590 Ma; see Chapter 4) with distinct geochemical signatures previously linked with the ca. 1460 Ma Moyie-Purcell LIP but now recognized to be separate events.

2.4 INTRODUCTION

Large Igneous Provinces (LIPs) are large volume, aerially extensive intraplate, and mainly mafic magmatic events of typically short duration or consisting of short duration pulses (Coffin & Eldholm, 1994, Bryan & Ernst, 2008, Bryan & Ferrari, 2013, Ernst, 2014). Minimum volume and areal extents are $100,000^3$ km and $100,000^2$ km. The duration of pulses can be less than 1 Ma

years. In some cases, multi-pulse LIP events span several tens of millions of years.

LIP events are composed of dominantly mafic to ultramafic magmatism but can also be associated with silicic, kimberlite and carbonatite magmatism (Ernst, 2014). LIPs and their different styles of associated magmatism can have a direct link to some world-class economic deposits. Specific examples include: Ni-Cu-PGE ores associated with mafic-ultramafic magmatism (e.g., Noril'sk, part of the Siberian Trap LIP) and IOCG ores associated with silicic magmatism (e.g., Olympic Dam, part of the Gawler Range LIP; Ernst and Jowitt, 2013). In this research we are focusing on Proterozoic mafic dyke and sill swarms interpreted to represent the plumbing system of LIPs that intruded the western margin of Laurentia (see Figure 2.1A-C).

Mesoproterozoic and Neoproterozoic intraplate magmatism that is exposed along the western side of the Laurentian margin between Kimberley, British Columbia, Canada and north of Yellowstone National Park in Wyoming, USA (Figure 2.1A-C) has previously been divided into the ca. 1460 Ma Moyie-Purcell and the 780 Ma Gunbarrel LIPs (Ernst & Buchan, 2001). The ca. 1460 Ma Moyie-Purcell event consists of i) the Purcell lavas and dykes and sills in the western USA, and ii) the gabbroic Moyie sills of the Belt-Purcell basin and associated dykes in British Columbia, Canada. These intrusions range in composition from tholeiitic basalt, basaltic andesite, and andesite, to dacite and rhyolite. The ca. 780 Ma Gunbarrel LIP consists of dykes, sills and volcanic rocks that are compositionally tholeiitic basalts, basaltic-andesites, and andesites. This

LIP is present in both western USA and adjacent BC, but also extends into NW Canada, where it includes the Hottah sheets and dykes in the Yukon Territory and Northwest Territories. While previous authors have examined both these events (ca. 1460 and 780 Ma) in localized studies (see references below), no widespread, regionally encompassing geochemical or isotopic work has been done to categorize and compare these LIP events of western Laurentia and to test for the presence of other unrecognized intermixed events.

We are concentrating on mafic events in western Laurentia from British Columbia through Montana to northern Wyoming. For the ca. 1460 Ma Moyie-Purcell event we are integrating our new geochemistry with geochemical and geochronological data from previous studies (Bishop, 1973, Bishop, 1974, Wooden, 1975, Wooden *et al.*, 1978, Höy, 1979, Höy, 1980, Höy & Diakow, 1981, Zartman *et al.*, 1982, Höy, 1983, Höy, 1984a, Höy, 1984b, McGimsey, 1985, Höy, 1989, Harlan, 1993, Anderson & Davis, 1995, Höy *et al.*, 1995, Harlan *et al.*, 1997, Sears *et al.*, 1998, Anderson & Goodfellow, 2000, Anderson & Parrish, 2000, Chamberlain *et al.*, 2000, Harlan *et al.*, 2003, Höy *et al.*, 2003, Harlan *et al.*, 2005, Sears, 2007, Harlan *et al.*, 2008, Aleinikoff *et al.*, 2012). For the 780 Ma event we are combining our new geochemistry with that of previous studies (Wooden, 1975, Wooden *et al.*, 1978, Park *et al.*, 1995, Park & Gower, 1996, Harlan *et al.*, 1997, Harlan *et al.*, 2003, Harlan *et al.*, 2005, Burtis *et al.*, 2007, Harlan *et al.*, 2008, Ootes *et al.*, 2008, Mackinder *et al.*, 2013). For both the 1460 Ma Moyie-Purcell and 780 Ma Gunbarrel LIPs, the goal is to model and

characterize the events in terms of mantle source, interactions with lithosphere (mantle and crust) and magmatic fractionation.

One locality that is interpreted to include both the Moyie-Purcell and Gunbarrel LIP units is in the Wyoming craton. Both ca. 1460 Ma and ca. 780 Ma ages are associated with NW-SE trending dykes. Specifically, in their Rb-Sr study within the Wyoming Craton (Tobacco Root Mountains, and Ruby Range), Wooden *et al.* (1978) found that there are three groups of NW-SE trending mafic dykes with distinctive chemistry and probable different ages (Group A, B and C, their study). Harlan (Harlan 1993; Harlan *et al.* 1997, 2003, 2005, Harlan *et al.* 2008) followed up on Wooden's work and was able to refine the geochronology by using other isotopic systems (Sm-Nd mineral geochronology, U-Pb zircon, Ar-Ar biotite and/or hornblende). Harlan *et al.*'s (2008) paleomagnetic work confirmed the existence of 2 dyke groups. They used Sm-Nd mineral geochronology to produce an age of 1448 ± 49 Ma for Group A dykes, and paleomagnetic orientations to correlate Group C dykes with Group A dykes. Group B dykes are 782.4 ± 4.9 Ma from U-Pb dating of baddeleyite (Harlan *et al.*, 2008). As we demonstrate in this paper, given the presence of multiple geochemical/geochronological groups in this small area of the Wyoming Craton, it is logical to assume that there may be additional mafic dyke swarms of differing ages and/or tectonic environments (i.e. plume-related vs. possible subduction and/or rifting) in the broader region of western Laurentia.

The primary goal of this study is to develop a geochemical fingerprint for both the Gunbarrel and Moyie-Purcell LIPs and to geochemically fingerprint other

pulses of mafic magmatism mapped as Proterozoic in western Laurentia to assess for the presence of any additional magmatic events (Figure 1A and 1C; Hadley, 1969, Cressman, 1981, Mudge *et al.*, 1982, Harrison *et al.*, 1986, Wallace *et al.*, 1986, Harrison *et al.*, 1992, Ruppel *et al.*, 1993, Kellogg & Williams, 1997, Miller *et al.*, 1999, Kellogg & Williams, 2000, Muntz, 2000, Vuke *et al.*, 2002, Lonn *et al.*, 2003, Miller & Burmester, 2004, Reynolds & Brandt, 2005, Reynolds & Brandt, 2006, Lonn *et al.*, 2007, Lonn *et al.*, 2010). This study will focus on the Proterozoic mafic dykes, sills and sheets through extensive sample collection and geochemical analysis. The field area for this study extends from north of Kimberley, British Columbia through the Idaho Panhandle and east-southeast through Montana to just north of the Montana-Wyoming border near Yellowstone National Park. The study area covers approximately 750 km by 250 km, and is split over two countries, four states in the US and one Canadian province (Figure 2.1A-C).

By geochemically fingerprinting mafic magmatic events in western Laurentia, future work will be able to compare their geochemical signatures with mafic magmatism on other cratons to aid in 'barcode matching' (e.g., Bleeker & Ernst, 2006) and continental reconstruction of Proterozoic continents. In order to fully resolve the magmatic association and age for several of the geochemical signatures, U-Pb zircon and baddeleyite isotopic dating will ultimately be required. This is true for geochemical signatures that were undated as well as those with larger U-Pb zircon analytical uncertainties ($\pm > 7\text{Ma}$) and/or only dated using whole rock geochronology (Rb-Sr and Sm-Nd).

On the basis of geochemistry, we test various models for emplacement of the ca. 1460 Ma, 780 Ma and other intermixed events. To assess the plausibility and/or validity of each model the following questions will be addressed: i) what geochemical variations exist within each event? ii) What is the origin (source, tectonic setting) of the mafic magmatism in each case?

2.5 SAMPLE COLLECTION, PREPARATION AND ANALYSIS

We collected 147 samples during fieldwork in 2012 through 2014, and S. Harlan, K. Chamberlain, R. Lewis, and R. Burmester provided an additional 57 rock samples for whole rock and trace element geochemistry. Reproducible accuracy analyses and 2 σ errors are located in Appendix 2.1. Location information for all these samples is provided in Appendix 2.2. Our new data complement the existing 99 geochemical analyses for dykes from this region (Wooden *et al.*, 1978, Anderson & Goodfellow, 2000). In an attempt to reduce differences in analytical procedures and techniques used in the various studies, we attempted to recollect and reanalyze from some of the sites of both Wooden *et al.* (1978) and Anderson and Goodfellow (2000) for comparison with this study. In some cases, precise coordinates were lacking, and we resampled as near to their sample sites as possible. Additionally, the precisions of modern analytical techniques are vastly better than those used in 1978, and therefore new geochemical analysis would help confirm the existence of distinct geochemical groups. To date, new whole rock and trace element geochemical analyses have been completed on 204 samples. Future work on this sample set will include a number of samples that

will be analyzed for Sr and Sm-Nd isotopes to further distinguish mantle sources, and U-Pb baddeleyite and/or zircon geochronology to determine age of emplacement of intrusive groups that have geochemical signatures distinct from ca.1460 Ma and ca.780 Ma LIPs.

Samples were collected from outcrop and fresh material obtained by breaking off the weathered sections in the field. Maps of dyke and sill exposures were compiled in an ArcGIS environment developed by and obtained from the federal, state and provincial governments (Figure 1A-C; Hadley, 1969, Cressman, 1981, Mudge *et al.*, 1982, Harrison *et al.*, 1986, Wallace *et al.*, 1986, Harrison *et al.*, 1992, Ruppel *et al.*, 1993, Kellogg & Williams, 1997, Miller *et al.*, 1999, Kellogg & Williams, 2000, Munts, 2000, Vuke *et al.*, 2002, Lonn *et al.*, 2003, Miller & Burmester, 2004, Reynolds & Brandt, 2005, Reynolds & Brandt, 2006, Lonn *et al.*, 2007, Lonn *et al.*, 2010, Brown *et al.*, 2011).

In the laboratory samples were cut into multiple 1 cm thick slabs and any remaining weathering surface removed. A single representative slab was selected and its flat surfaces were polished with 120-grit carborundum powder to remove any metal contamination introduced during the cutting process. Some of the slab material was repeatedly crushed and sieved until all crushed material was less than 2 mm before being milled to less than 200 mesh in an agate ring mill. A pre-contamination aliquot was processed prior to the crushing and milling stages before the sample was processed. Tools and working surfaces of the crusher and mill were cleaned with ethyl alcohol between each sample. These steps were used to reduce risk of cross-contamination of trace elements and

isotopes between samples.

Approximately 20g of <200 mesh sample were then sent to ALS Laboratories (<http://www.alsglobal.com/>) for major, minor and trace element analysis. At ALS samples were sintered with a lithium metaborate flux, before being analyzed for 55 major oxide and minor to trace elements via ICP-AES and ICP-MS. The sample analyses were normalized to 100% dry weight before plotting. The precision of repeat analyses of a blind internal standard and blind duplicate samples are listed in Table 2.1.

Magnetic susceptibility measurements were also taken at the outcrop to compare the magnetic susceptibility of the different sampled units within the Belt-Purcell and Wyoming Provinces (Table 2.4). Approximately 6 measurements were taken at each outcrop, evenly distributed over the area of the available outcrop, which varied from square decimeters to square meters. Measurements were obtained using a KT-10v2 magnetic susceptibility meter (www.terraplus.ca/) in SI units in kappa (κ) notation. The detection limit of the KT-10v2 device ranges from $0.001 \times 10^{-3}\kappa$ to $1999.99 \times 10^{-3}\kappa$ (SI). These data will be used in a future comparison with the Fe content of the different geochemical groups to further evaluate the use of magnetic susceptibility as a tool to discriminate between swarms (Bleeker, 2012).

2.6 GEOCHEMICAL ANALYSIS OF WESTERN LAURENTIA MAFIC MAGMATISM

From 204 newly analyzed samples and the 99 existing analyses from (Anderson & Goodfellow, 2000), a subset of 281 (summarized in Table 2.1; full data set in Appendix 2.3¹) were selected for data analysis that met the following conditions. Each of the 281 samples has major element oxide analyses with totals above 97% including LOI, and is intrusive. The geochemistry of the volcanic rocks sampled during fieldwork did not correspond to any of the dyke and sill geochemical signatures described in this work and thus the volcanic rocks will be separately described in a future manuscript.

One issue that had to be addressed when determining geochemical signatures of the mafic dykes and sills of this study is the nomenclature of previous authors, including Wooden et al. (1978), and Anderson and Goodfellow (2000). In their study of the dykes and sills in the Tobacco Root Mountains (TRM) Wooden et al. (1978) based their classification on major and trace element geochemistry, using major oxide, Ni and Zr vs. Mg# or MgO as the basis for dividing their dykes into three groups, "A, B and C". Group A and C roughly correspond to our geochemical signature (GS) 7 and 8, GS 1 corresponds to

¹GSA Data Repository Item 2016072, Tables DR1: Geochemistry used in this study and DR2: Comparison of previously published material with this study's sample plots, is available at www.geosociety.org/pubs/ft2016.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA. NOTE: data submitted to GSA is normalized to 100% dry weight, Appendix 2.3 is not normalized to 100% dry weight.

Group C. Anderson and Goodfellow (2000) took another approach and divided the Moyie dykes and sills based on their stratigraphic position within the Aldrich Fm. The geochemistry of the Moyie sills is described in detail in Anderson and Goodfellow (2000), and is briefly summarized below.

Anderson and Goodfellow (2000) determined that Ti vs. Zr plots were the best for distinguishing Groups a through d. In general, the four groups had light rare earth element (LREE) enrichment and heavy rare earth element (HREE) depletion relative to primitive mantle. They also determined that Group a, the bottom of the Lower Aldrich Fm. (BLA) is the only group that does not show a fractionation trend like that exhibited by Group d, top of the Middle Aldrich Fm. (TMA), Group c, Middle Aldrich Fm. (MA) and Group c, top of the Lower Aldrich Fm. (TLA). The BLA shows low Ti relative to the TMA through the TLA.

However, we add to their interpretation by using new types of discrimination diagrams (e.g., binary and/or normalized multi-element plots (MEPs)) developed since the Anderson and Goodfellow (2000) publication. To ease the issue of describing classifications of other studies with those of our study we link their Groups “a” through “d” to correspond to our Groups GS 5 thru GS 2, respectively.

Within my research area, at least 20 separate geochronological studies are published on the Moyie-Purcell LIP. Most studies lack detailed associated geochemical analysis (see Table 2.2A and B for summary and references). This work integrates my new geochemical data and the geochemical data from Anderson and Goodfellow (2000) with the separately published U-Pb

geochronological studies. The combined geochronological and geochemical data allow us to distinguish 17 geochemical groups. We correlate eight of the 17 groups with the Moyie-Purcell LIP, and one group with the Gunbarrel LIP. We were left with 2 poorly dated groups, GS 7 and GS 8, with imprecise whole rock dates, and six undated Groups, GS 9, GS 10, GS 14, GS 15, GS 16 and GS 17, all with newly discovered geochemical signatures. The undated groups cannot be correlated to other mafic magmatic events of known age within the Belt-Purcell or Wyoming Provinces. It is possible that these eight uncorrelated geochemical signatures may be different pulses of fractionated or evolved magmas belonging to either the 1460 Ma Moyie-Purcell or 780 Ma Gunbarrel events, or they may represent new, as yet undated, LIP events in western Laurentia.

Geochemical groups were identified based on rare-earth element (REE) slope (La/Lu), light REE (LREE) slope (La/Sm), heavy REE (HREE) slope (Gd/Yb), Ti/V values, and magnetic susceptibility values (Table 2.4). Additionally, a qualitative comparison of positive and negative anomalies (e.g., Nb-Ta, Pb, P, Ti, Sr, Eu) in extended REE plots were compared. These criteria identified the 17 geochemical groups in western Laurentia. Fenner diagrams (Mg# vs. major element) provide basic geochemical trends and are located in Appendix 2.4. Any trend in the Fenner diagram for a particular geochemical group would represent a liquid line of descent. In the sections below we integrate the new ages that were obtained after this chapter was published.

2.7 GEOCHRONOLOGY SUMMARY OF WESTERN LAURENTIA MAFIC MAGMATISM

We are including all the known geochronological age determinations for dykes and sills in western Laurentia in this summary. However, because some geochronological systems used in age determinations (i.e. Sm/Nd, Rb/Sr, K/Ar, Ar/Ar) are susceptible to perturbation of the isotope system and/or may have large analytical errors, we are focusing on more robust U/Pb baddeleyite and/or zircon analysis with small errors ($< \pm 7$ Ma) in our correlations (Figure 2.1A-C).

Geochronological studies of western Laurentia are numerous but commonly restricted to single dykes and/or sills that are geologically significant (summarized in Table 2A and B; Reed & Zartman, 1973b, Wooden *et al.*, 1978, Zartman *et al.*, 1982, Anderson & Davis, 1995, Doughty & Chamberlain, 1996, Sears *et al.*, 1998, Anderson & Parrish, 2000, Chamberlain *et al.*, 2000, Evans *et al.*, 2000, Harlan *et al.*, 2005, Doughty & Chamberlain, 2008). The Moyie-Purcell LIP and previously associated intrusions also had numerous geochronological studies on individual dykes and sills (summarized in Table 2.2A and B; located on Figure 2.1A-C). As mentioned earlier, Wooden *et al.* (1978) originally dated the dykes in the Tobacco Root Mountains with Rb-Sr whole rock isochrons; Group A (GS 7) at 1455 ± 125 Ma, and Group C (GS 8) at 1130 ± 130 Ma. The age of Group A intrusions were subsequently refined by Harlan *et al.* (2005) to 1448 ± 48 Ma from a Sm-Nd isochron and correlated to the Moyie-Purcell LIP by Ernst and Buchan (2001).

GS 1 intrusions within the Gunbarrel LIP have been dated by various

methods including Rb-Sr whole rock, U-Pb zircon/baddeleyite and ^{40}Ar - ^{39}Ar hornblende geochronology. Group B, which were correlated to the Gunbarrel LIP by Harlan et al. (1993) and are consistent with GS 1 in this study, was dated by Wooden at 1120 ± 185 Ma. Harlan *et al.* (2003) re-dated some of these dykes and showed the age on GS 1 intrusions to be 769 ± 7 Ma (^{40}Ar - ^{39}Ar) and 782.4 ± 4.9 Ma (U-Pb on baddeleyite). Park et al. (1995) and Harlan et al. (2003) correlated these dykes with a regional magmatic event termed the Gunbarrel Magmatic Event. Burtis *et al.* (2007) dated the Holland Lake sill in Montana (N $47^\circ 24' 0.0''$, W $113^\circ 34' 54''$) at 777.5 ± 2.5 Ma with U-Pb from zircon. The Wolf Creek Sill located approximately 6 km northwest of Wolf Creek Montana, was also dated by Harlan *et al.* (1997) and gave a hornblende ^{40}Ar - ^{39}Ar date of 776 ± 5 Ma. In the Beartooth Mountains of Montana and Wyoming, the Christmas Lake dyke was originally dated at 750 Ma by Mueller and Rogers (1973) using Rb-Sr whole rock analyses and then re-dated by Harlan et al. (1997; 2003) at 774 ± 4 Ma using the ^{40}Ar - ^{39}Ar method and 779.5 ± 3 Ma using U-Pb method from baddeleyite. The Mount Moran dyke from the Teton Range was dated by Reed and Zartman (1973a) using K-Ar methods with whole rock and mineral separate samples from a chilled margin, which yielded an age of 775 ± 50 Ma and younger ages of, 396 ± 6 Ma and 583 ± 8 Ma closer to the core of the intrusion. However, based on biotite isotopic ages in the wallrock concluded that the dyke was ca. 1450 Ma, similar to other dykes in the Wyoming Craton. Harlan et al. (1997) re-dated the Mount Moran dyke and obtained a discordant hornblende ^{40}Ar - ^{39}Ar age of 769 ± 5 Ma and found that the paleomagnetization was consistent for a

Gunbarrel LIP age.

2.8 OVERVIEW OF THE 1460 MA MOYIE-PURCELL LIP EVENT

The Belt-Purcell basin represents the filling of a Meso- to Neo-Proterozoic intra-continental rift basin by marine and fluvial sediments (see Figure 1 in Lydon, 2000). Although it is referred to as the Belt Basin in the United States and the Purcell Basin in Canada, the sedimentary packages are similar (Lydon, 2005). Belt-Purcell Basin rocks are up to 20 km thick and cover an area of ~ 200,000 km² with about 10% of this area in Canada, with the remainder in Montana and Idaho of the United States (Lydon 2005). Rocks of the Belt-Purcell Supergroup have been affected by at least three distinct episodes of deformation, called the East Kootenay Orogeny (1350-1300 Ma), the Goat River Orogeny (900-800 Ma), and Jurassic-Paleocene (160-60 Ma) regional metamorphism, deformation and granitic plutonism (McMechan & Price, 1982, Lydon, 2000). An older deformation event predating the Moyie-Purcell LIP consists of Proterozoic faulting in a west-northwest trending rift at about 1.5 Ga. (Chandler, 2000). The mafic sills and dykes intruding the lower Belt Basin in Idaho yielded U-Pb zircon dates of 1.43 Ga (Zartman *et al.*, 1982), 1.469 Ga and 1.457 Ga (Sears *et al.*, 1998), 1.468 Ga (Anderson & Davis, 1995) and 1.45 Ga (Höy, 1989).

Structurally the study area is dominated by right lateral strike-slip faults along the northwest-trending Lewis and Clark Line (Cressman, 1985). Some of these faults could have up to 18 km of displacement and record movement as recent as the late Tertiary (Cressman, 1985).

Sills and dykes of the Moyie-Purcell LIP event are continental tholeiites that intruded the Belt-Purcell Supergroup in southern BC and in the Highland Mountain Range in Montana. Some sills and/or dykes can be traced on maps for approximately 200 km (Figure 2.1A-C). However, on most geological maps there is no differentiation between Neoproterozoic and Mesoproterozoic mafic magmatism (Hadley, 1969, Cressman, 1981, Mudge *et al.*, 1982, Harrison *et al.*, 1986, Wallace *et al.*, 1986, Harrison *et al.*, 1992, Ruppel *et al.*, 1993, Kellogg & Williams, 1997, Miller *et al.*, 1999, Kellogg & Williams, 2000, Munts, 2000, Vuke *et al.*, 2002, Lonn *et al.*, 2003, Miller & Burmester, 2004, Reynolds & Brandt, 2005, Reynolds & Brandt, 2006, Lonn *et al.*, 2007, Lonn *et al.*, 2010).

A major difference between the northern and southern Moyie intrusions is that the northern Moyie sills intruded into wet unconsolidated sediments of Mesoproterozoic age (Höy, 1979, Höy, 1980, Anderson & Davis, 1995), whereas the southern dykes of southwestern Montana intruded into Achaean crystalline basement of the Wyoming Craton (Harlan *et al.*, 2008). The northern sills likely experienced more interaction with their host rocks via fluids within the sediments.

2.9 OVERVIEW OF THE 780 MA GUNBARREL LIP EVENT

The Gunbarrel LIP stretches for over 2500 km from NW to W Laurentia and the NE to NW striking dykes form a regionally radiating pattern, a feature commonly seen in continental LIPs. The dykes can be traced back to a convergent point west of Vancouver Island that is the projected location of the plume head center (Park *et al.*, 1995, Buchan *et al.*, 2010, Ernst, 2014), although

the plume center region itself is likely on another crustal block that rifted away (see later discussion).

Gunbarrel dykes and sills are found along the western margin of North America and intrude a variety of localities and host rocks (Table 2.2A and B; see Figure 1 in Buchan *et al.*, 2010; Park *et al.*, 1995, Buchan & Ernst, 2004, Buchan *et al.*, 2010, Buchan & Ernst, 2013). In northern Idaho and southwestern Montana, multiple sills and dykes from the Gunbarrel LIP intrude Arcana basement and the overlying sedimentary successions of lower Belt-Prichard Formation to upper Belt-Garnet Range Formation of the Belt-Purcell Supergroup (Harlan *et al.*, 1997, Burtis *et al.*, 2007).

The Tobacco Root Mountains of south-central Montana host multiple, sub-parallel, northwest trending dykes of Gunbarrel age (Harlan *et al.*, 1997, Harlan *et al.*, 2008). The Gunbarrel dykes intrude Precambrian basement-cored Laramide-age uplifts at the intersection of two Laramide-age tectonic provinces: the Rocky Mountain uplifts and Helena salient of Cordilleran thrust (Harlan *et al.*, 2008).

Within the Wyoming Craton, the Beartooth Mountains of south-central Montana and northwestern Wyoming host several generations of dykes that generally trend northwest, with some trending northeast, and intruding the Arcana crystalline basement that make up the cored uplifts (Harlan *et al.*, 1997).

The most spectacular of Wyoming's Teton Range dykes is the northwest trending dyke at Mount Moran which is 30 m wide and has a vertical exposure of 1.5 km and intrudes deformed gniesses, amphibolites and discordant plutons of

Archean Crystalline basement (Reed and Zartman, 1973 and (Harlan *et al.*, 1997).

2.10 ADDITIONAL GEOCHEMICAL SIGNATURES

To avoid confusion with existing nomenclature, we are referring to different geochemical classifications as GS (Geochemical Signature) 1 through GS 17. For example, Anderson and Goodfellow (2000) named their groups “Group a, b, c and d”, which mostly correspond our geochemical groups GS 5, GS 4, GS 3 and GS 2, respectively. Wooden *et al.* (1978) named their groups “Group A, B and C” which roughly correspond to our geochemical groups GS 7, GS 1 and GS 8, respectively. To divide the new data set into geochemical signatures a multi-step process was undertaken. Our new geochemical analyses that show geochemical characteristics similar to groups previously defined by others (e.g., Wooden (1975); Anderson and Goodfellow (2000)), were assigned to those groups. Table 2.3 gives our classification scheme with previously published nomenclature and ages are correlated herein. Appendix 2.2 gives our classification scheme for samples of other published articles.

The remaining geochemical signatures were defined by normalizing the REE abundances in the samples to primitive mantle abundances (Sun & McDonough, 1989) and the data grouped based on $(La/Yb)_{PM}$, $(La/Sm)_{PM}$ and $(Gd/Yb)_{PM}$ slopes (listed in Table 2.4). Figure 2.2A and B plots the average of the rare earth elements (REE) of the most primitive rocks ($SiO_2 < 52$ wt.%) from each of the groups. Figure 2.2A is normalized to REE chondrite and Figure 2.2B is

normalized to modified primitive mantle (McDonough & Sun, 1995). For groups with no primitive samples the sample with lowest SiO₂ value was selected for plotting. Complete primitive and evolved REE plots are presented in Figure 2.3A-M and 4A-K. Samples that were indistinguishable between two groups were assigned to a group based on their position in other binary geochemical plots and/or field relationships. From the remaining data we were able to separate out 10 additional geochemical signatures, GS 6 thru GS 17 (Figure 2.3E-M, and 4F-K). The geochemistry is summarized in Table 2.1 and new nomenclature is defined in Table 2.3. Each of the geochemical signatures GS 1 to GS 17 is discussed in turn below.

2.11 PETROGRAPHY, FIELD RELATIONSHIPS AND GEOCHEMISTRY

2.11.1 Group GS 2 Through GS 5 - Moyie-Purcell LIP - (N = 105; ca. 1458 Ma)

The Moyie-Purcell dykes and sills are exposed from Kimberley, British Columbia, to as far south as northern Idaho and southern Montana. The dykes and sills are named and grouped according to the stratigraphic position in which they intrude in the Belt-Purcell Basin. They are: GS 2 - highest dykes or sill in the Middle Aldridge Formation (TMA); GS 3 - dykes or sills in Middle Aldridge Formation (MA); GS 4 - dykes or sills at or just below the Lower Aldridge Formation boundary (TLA); and GS 5 - dykes or sills near the bottom of the Lower Aldridge Formation (BLA). They range from fine- to coarse-grained diabase. For most of the dykes and sills south of the US-Canada border it is difficult to see contacts; most contacts are traced in the overburden by either the

lack of large vegetation growing on them and/or the darker scree that pokes through the overburden. In general, the dykes and sills are 5-300 m in thickness and the dykes locally trend NNW-SSE to NW-SE. Most mafic sill and/or dyke outcrops tend to be highly fractured and some developed a strong cleavage. When outcrop can be seen the diabase rocks tend to weather a grey to greyish-black. More lichen-covered areas are commonly rusty-reddish tan in colour.

Hand sample and thin section analyses show the most common mineral assemblage is clinopyroxene (40-70% and 1-3 mm), plagioclase (30-60% and 1-5 mm), opaque minerals (1-2% and ≤ 1 mm). Other trace minerals vary in abundance but rarely exceed 2%. Orthopyroxene is rare but may compose 1-5% of the diabase in localized areas. Other accessory minerals include: amphibole, quartz, biotite, chlorite, calcite, and alkali feldspar. Plagioclase is generally fresh with sharp albite twinning but there is some alteration to sericite. Clinopyroxene is variably altered, including pervasive alteration in localized areas to amphibole and/or chlorite $\pm$ epidote. In all samples, hornblende partially replaced clinopyroxene (Table 2.5). Magnetic susceptibility of these rocks tends to be low with readings ranging between $0.034 \pm 8 \times 10^{-3} \text{ k}$ and $0.8 \times 10^{-3} \text{ k}$ (SI; Table 2.4).

On a MEP normalized to chondrites (Figure 2.2B-D), the heavy REEs show a slope $(\text{Gd/Yb})_{\text{PM}}$ range of 1.31-1.41 indicating a shallow depth of mantle melting, most likely in the spinel peridotite field (Rollinson, 1993). When Ba is plotted against Th for these groups a relatively good linear trend is seen, with the exception of a few outliers (Figure 2.5B). This correlation supports only minor remobilization of Ba after emplacement of the dykes and sills. Samples of the

Moyie-Purcell LIP plot above E-MORB on Pearce (2008) diagram. In general samples plotting above E-MORB indicate that they were derived from an enriched mantle that has interacted with a lithospheric component, possibly metasomatized subduction-modified mantle(Figure 2.6B).

The Moyie-Purcell LIP dykes and sills of the Belt-Purcell Basin area form a distinctive array within the Ti vs. V binary plot (Figure 2.7B) with a tight clustering ($R^2=0.79-0.99$) and steep slopes of 32.1 to 51 for each geochemical signature. They plot along the boundary between arc and oceanic flood-basalt magmas. As these data plot parallel to the OIB-ARC boundary line they indicate that the oxygen fugacity did not change within the evolving magma chamber(s).

2.11.2 Group GS 7 and 8 - Ramshorn Creek ($U-Pb_{bad}1550.6 \pm 5.2$ Ma) and Mammoth Groups ($U-Pb_{bad}1550.6 \pm 5.2$ Ma; N = 58); U-Pb ages detailed in Chapter 4)

These two groups are named for a road in the Tobacco Root Mountains of southwestern Montana where typical geochemistry for each group can be found (Figure 2.1C). Originally described by Wooden *et al.* (1978) as low K tholeiites, the newly reorganized 1550 Ma Ramshorn Creek Group and 1590 Ma Mammoth Group dykes and have an imprecise Sm-Nd isochron age of 1448 ± 49 Ma from Harlan et al. (2005). We collected new samples close to where Wooden et al. (1978) collected their samples, utilizing the dyke distributions from their published map. The present study confirms two distinct, geochemical signatures that are not related to either the Gunbarrel LIP (ca. 780 Ma) or the Moyie-Purcell LIP (ca. 1460 Ma). Wooden et al. (1978) based their groups on major oxide trends as well

as Ni and Zr vs. Mg#. For our samples from the same area we also see two distinct, non-Gunbarrel LIP groups in the Ti vs. V diagram (Figure 2.7A; Shervais, 1982). However, with the improvement of analytical techniques and procedures, our groups do not correlate exactly with Wooden et al. (1978) Group A and C dykes. Instead our samples intermix between the two original groups (Figure 2.8A). Therefore, we reorganized the samples from Wooden et al. (1978) A and C Groups and renamed them the 1550 Ma Ramshorn Creek Group and 1590 Ma Mammoth Groups to correspond to GS 7 and GS 8, respectively.

Both GS 7 and GS 8 data have moderate slope (19.5 and 21 respectively) on a Ti vs. V diagram (Figure 2.7A; Table 2.4). This slope is in contrast to most of the geochemical signatures for other groups in western Laurentia where their slopes are much steeper (slope ≈ 40) or shallower (slope ≈ 10 or less). This diagram helps to determine the oxygen fugacity or oxidizing-reducing conditions of the magma. The more oxidizing the magma the higher the valence state of vanadium and the more it resembles Ti. In more reducing environments V is in a lower valence state and resembles transition metals and can partition into sphene or pyroxene (Shervais, 1982). Additionally, under laboratory conditions Ti vs. V are virtually immobile up to hydrothermal alteration or greenschist regional metamorphism (Shervais, 1982). As with the Moyie-Purcell LIP and Gunbarrel LIP these groups plot above E-MORB on the MORB-OIB array. One distinction for these groups (GS 7 and GS 8) is that the samples plot in two distinct clusters above E-MORB, (Figure 2.6C) indicating that there may have been more crustal

influence on the 1590 Ma Mammoth Group (GS 8) relative to the 1550 Ma Ramshorn Creek Group (GS 7).

2.11.3 Group GS 6 - Goat Flat Group Dykes (N = 8; ca. 1471 Ma)

The Goat Flat Group of mafic dykes is named after a dyke in the Wind River Range of Wyoming that provided the U-Pb isotopic age for this group. Other than the Wind River Range in Wyoming this group is found predominately within the Highland Mountain Range of Montana (Figure 2.1B). Its geochemical signature is defined by the whole rock and REE chemistry of a sample from the Goat Flat dyke that has an in situ baddeleyite U-Pb age of 1471 ± 8 Ma (Chamberlain *et al.*, 2000; Chamberlain, pers. comm., 2014). Petrographically these samples are fresh and only contain minor alteration around the rims of primary minerals. Plagioclase (20-30%; 0.5-1 mm) is euhedral to subhedral, showing polysynthetic twinning and only minor amounts of sericitization around the edges of the crystals. Pyroxene (70-80%; 0.5-1.5 mm) is also generally fresh with minor chloritization around the edges but still preserves euhedral to subhedral grains. The opaque minerals (<1%) are globular and interstitial to the pyroxene and plagioclase (Table 2.5).

The geochemical signature shows a pattern similar to the Moyie sills, especially GS 4. In a Ti vs. V binary diagram base diagram after Shervais (1982) the data plot along the ARC-OFB field boundary similar to most of the Moyie sill samples (Figure 2.7D). This group was generated via moderate degrees of partial melting on the basis of REE data plotting with a small negative $(\text{Gd/Yb})_{\text{PM}}$

slope (1.27-1.77), indicating that there was some garnet in the source rocks during partial melting. The Goat Flat Group plots above E-MORB and directly overlies the Moyie-Purcell LIP samples on the MORB-OIB array (Figure 2.6D), especially GS 4.

2.11.4 Group GS 11 – Paradise Sill Group (N = 15; ca. 1457 Ma)

This group of mafic sills and dykes is defined based on the geochemical characteristics of the Paradise Sill dated by Sears *et al.* (1998) with an U-Pb zircon age of 1457 ± 2 Ma. The Paradise Sill Group is another widespread geochemical group ranging from Kimberley BC to south-central Montana just northwest of Yellowstone National Park (Figure 2.1B). Replacement of plagioclase by sericite is nearly complete and little of the original polysynthetic twinning remains. Pyroxene is replaced by biotite along edges, and crystals include oxide alteration rims and along fractures. Small (<0.5 mm) grains of quartz are present interstitial to pyroxene and plagioclase grains. Both plagioclase and quartz phenocrysts display signs of post-crystallization stress and exhibit fanning extinction typical of glide dislocation of the crystal lattice. In outcrop this group tends to appear a little more felsic than other dyke groups of this study, containing pyroxene (60-80%; mm) plagioclase (20-40%; 1-2 mm) with trace amounts of biotite, pyrite and iron oxides (Table 2.5). The outcrop weathers reddish-tan to rusty-tan and is distinctive especially when compared to the rusty-red weathering of the Gunbarrel dykes and sills. These outcrops also tend to be highly fractured and to shatter when struck. Magnetic susceptibility is

fairly consistent in all but two outcrops. Normally, the magnetic susceptibility ranges from $0.026 \times 10^{-3} \text{ k}$ to $0.39 \times 10^{-3} \text{ k}$ (SI), with the anomalous outcrops ranging in readings from $7.02 \times 10^{-3} \text{ k}$ to $0.499 \times 10^{-3} \text{ k}$ (SI; Table 2.4).

This group is the most distinctive of all the geochemical signatures that have a U-Pb date ($1457 \pm 2 \text{ Ma}$; Sears *et al.*, 1998) consistent with membership within the Moyie-Purcell LIP. This group only contains one primitive sample ($\text{MgO} = 6.76\%$) that has a steeper $(\text{La/Yb})_{\text{PM}}$ slope (3.92-8.12) compared to the rest of the geochemical signatures of the Moyie-Purcell LIP. This group shows a distribution of data points that are more similar to GS 5 than to other geochemical signatures within the age range of the Moyie-Purcell LIP (Figure 2.6D and 7D).

2.11.5 Group GS 12 – Plains Sill Group (N = 40; ca. 1469 Ma)

This group of mafic dykes and sills is defined based on the age and geochemical characteristics of the Plains sill dated by Sears *et al.* (1998) at $1469 \pm 2.5 \text{ Ma}$. It is the most widely distributed geochemical signature within the study area, ranging from Kimberley BC to just northeast of Yellowstone National Park in Montana (Figure 2.1B). This geochemical signature has not been identified previously within the study area. Petrographically, samples are similar to the rest of the 1460 Ma groups in western Laurentia.

Plagioclase is almost completely altered to sericite but still preserves remnant polysynthetic twinning. Oxides have blocky shape and are interstitial to pyroxene and feldspar. One sample does contain secondary hornblende, which grew at the expense of pyroxene. The hornblende has dark alteration rims and appears to also be breaking down. In outcrop the rocks weather reddish-tan and

generally have a medium-grained crystal texture with 70-90% pyroxene, 10-30% plagioclase and accessory minerals that include trace amounts of biotite and iron oxides (Table 2.5). Magnetic susceptibility is quite varied for this group ranging from $5.73 \times 10^{-3} \text{ k}$ to $0.021 \times 10^{-3} \text{ k}$ (SI). This large range in measurements was due to 6 out of 20 locations that have higher than normal readings that ranged from $0.7 \times 10^{-3} \text{ k}$ to $5.73 \times 10^{-3} \text{ k}$ (SI). All other outcrops have values ranging from $0.084 \times 10^{-3} \text{ k}$ to $0.021 \times 10^{-3} \text{ k}$ (SI; Table 2.4). These higher values do not appear to represent a subset of coarser or finer-grained dykes than the rest of the group. I could not determine if these anomalous readings were closer to a dyke or sill margin or if there were higher concentrations of oxide minerals within these sites.

This group shows less of a crustal contribution than the other groups based on MEP signatures (Figure 2.9J and 10J). The REE signature normalized after McDonough and Sun (1995) shows a flat signature with a minor negative Eu anomaly (Figure 2.3J and 4J), similar to GS 2, 3 and 6.

On the MORB-OIB array this group plots above the E-MORB array same as GS 2 thru 5, but this group spans a greater range along the X and Y-axis (Figure 2.6D). On the Ti vs. V plot there is considerable scatter and some samples near the top of the trend form a second trend that would intersect the boundary line between OFB and ARC lavas at a shallow angle. This could mean that these rocks have experienced more alteration than other samples within the Moyie-Purcell LIP or that these rocks had a greater lithospheric contribution to the melts. When Ba is plotted against Th, there is a cluster of data points near the origin with a vertical linear trend that displays minor scatter. This signature

could be interpreted by indicating that Ba has only been slightly perturbed by secondary geological processes (i.e. weathering, deuteric alteration and/or metamorphism; Figure 2.5D).

2.11.6 Group GS 1 - Gunbarrel LIP – (N = 54; ca. 780 Ma

(Section summarized from Mackinder (2014) now Podlesny)

Gunbarrel dykes and sills within the study area are composed of medium to coarse-grained diabase. The geochronology of this group is summarized above in Section 2.7. Dykes in the TRM (Figure 2.1A) display no crustal xenoliths or xenocrysts in hand samples or thin sections, and in most areas the contacts are obscured by overburden or scree, however, where we could find contacts they were sharp and well defined. Gunbarrel dykes and sills range in thickness from 5-50 meters. Gunbarrel dykes and sills tend to show a red rusty weathering surface in the field and are commonly fractured, but remain relatively pristine with rare quartz and calcite veins infilling fractures.

Hand sample and thin section analyses of GS 1 samples shows a common mineral assemblage of clinopyroxene (augite-ferroaugite and ferrosillite; 25-50%) + plagioclase (50-60%) + opaque minerals (ilmenite-titanomagnetite exsolution and chalcopyrite; 3-8%) ± minor amounts of amphibole, biotite, quartz and alkali feldspar (often seen in granophyre) with trace amounts of apatite and small, unaltered magmatic zircon and baddeleyite crystals (Table 2.5). These rocks commonly display an ophitic texture. Sericitization of plagioclase varies between localities, with some samples having relatively fresh plagioclase and

others almost completely replaced. Plagioclase is oriented in random laths. Some clinopyroxene crystals have alteration rims of amphibole or are completely altered to amphibole. Other minerals such as biotite are altered to chlorite. The opaque minerals are commonly skeletal to blocky and range from <1 mm to 2 cm. Opaque minerals are a major constituent in Gunbarrel rocks and can make up 3-8% of the modal mineral assemblage. Upon examination with SEM, the opaque minerals are almost exclusively titanomagnetite, with ilmenite mostly in skeletal exsolution lamellae. Magnetic susceptibility readings within the Gunbarrel LIP are consistent and generally higher than those of other geochemical signatures. Readings range from 1.4×10^{-3} k through 2.8×10^{-3} k (SI) and this is most likely due to the higher modal percentage of magnetite and ilmenite that is typical of this LIP (Table 2.5).

The Gunbarrel dykes and sills are Fe-tholeiites (Figure 11; Irvine & Baragar, 1971) that are basalts to basaltic andesites in a TAS diagram (Figure 12; Le Bas *et al.*, 1986). In a Pearce (1996) diagram plotting immobile Nb/Y vs. Zr/Ti (not shown), the Gunbarrel intrusions plot solely within the basalt field. Due to the highly fractured nature of the Gunbarrel dykes and sills in outcrops, and the presence of minor quartz and carbonate veins, major elements such as K and Na may have become mobile during weathering and minor hydrothermal alteration processes. On MEP and normalized rare-earth element (REE) plots, the Gunbarrel dykes and sills from all localities show remarkably similar geochemical signatures and almost completely overlap with one another (Figure 2.3A, 4A, 9A and 10A). These data suggest that magmas feeding the Gunbarrel

intrusions came from a common, homogenous source (Mackinder, 2014, Sandeman *et al.*, 2014).

Normalized to chondritic abundances, Gunbarrel REE signatures show a moderate slope from light to heavy REE with slight depletion in Eu (Sun & McDonough, 1989). This Eu depletion is also seen in MEP diagrams normalized to primitive mantle. There are also moderate negative Nb-Ta anomalies ($(\text{Nb/La})_{\text{PM}} = 0.79\text{-}0.99$) and Sr troughs in all of the samples as well as large Pb peaks.

The Eu and Sr depletion suggests plagioclase was fractionated from the melt, and the Nb-Ta anomaly is a common subduction signature suggesting the addition of some subduction-modified mantle component to the melt. The Pb peaks indicate crustal contribution and/or incorporation of subduction-related fluids (Rollinson, 1993). Involvement of a crustal component is also supported in the Pearce (2008) Th/Yb vs. Nb/Yb diagram where all the samples plot above E-MORB along the MORB-OIB array suggesting metasomatized lithospheric mantle melts (Figure 2.6A).

The diagram that best distinguishes the Gunbarrel LIP from the rest of the mafic magmatism in western Laurentia is the Ti vs. V binary plot of Shervais (1982). The Gunbarrel samples have a $V/(\text{Ti}/1000)$ range of 24-35, plot within the oceanic flood basalt field with a data array slope of 21.6, Y intercept of 141, and poor goodness of fit ($R^2=0.64$; Figure 2.7A; Table 2.3). They also form a trend at a low angle to the oceanic flood basalt and arc related magmatism. These magmas cross the Arc-Oceanic Flood Basalt boundary line at a much shallower

angle than the Moyie-Purcell LIP, indicating that the oxygen fugacity changed in a different manner than for the Gunbarrel LIP. This would indicate that the oxygen fugacity was changing within the evolving magma chamber(s). If the oxygen fugacity were not changing within the magma chamber(s), then data plotted on this diagram would parallel the boundary lines and intersecting at or near the origin.

2.12 OTHER GEOCHEMICAL SIGNATURES

2.12.1 Group GS 9 – Highland Mountain Group (N = 10; U-Pb_{BAD}1418Ma)

This group is found in two locations within the study area: in the Highland Mountains of southwestern Montana extending into adjacent Idaho and at a second location east of Yellowstone National Park in Wyoming in the Beartooth Mountains (Figure 2.1A). Petrographically, samples range from fairly fresh with only minor limonite and oxide alteration around the olivine (<1%; <0.5 mm) through to samples where the pyroxene (60-80%; 0.5-1 mm) is almost completely replaced by chlorite. Plagioclase (20-40%; <0.5-1.5 mm) is generally unaltered but does show some indications that it has been stressed by exhibiting fanning extinction (via glide dislocations). Opaque minerals are generally interstitial to pyroxene and plagioclase, or in rare occasions, long and blade-like. Olivine (<1%; <0.5 mm) is generally fresh with only minor amounts of limonite and oxide alteration (Table 2.5). Magnetic susceptibility readings from six stations range from $5.76 \times 10^{-3} \text{ k}$ to $0.036 \times 10^{-3} \text{ k}$ (SI). Two of the six stations show anomalously high magnetic susceptibility readings from $5.76 \times 10^{-3} \text{ k}$ to 0.71

$\times 10^{-3}\kappa$ (SI; Table 2.4). The remaining four stations show susceptibilities of $0.036 \times 10^{-3}\kappa$ to $0.057 \times 10^{-3}\kappa$ (SI). This anomalously large range is not present for the other 11 groups. In outcrop, these rocks tend to weather dull-grey to greyish-black. They are massive and do not seem to be as fractured as other dyke/sill swarms within the study area. One thing to note is that the geochemistry of these rocks is similar to that of some of the volcanic rocks within the study area. The volcanic rocks will be addressed in a future manuscript.

Geochemistry indicates that melting was from a distinctive source not seen in other areas of western Laurentia. The melting depth also appears to be deeper than most other samples as there is a much steeper (Gd-Yb)_{PM} slope (1.43-1.82; Table 2.4). Melts came from an enriched garnet-bearing peridotite with low degree of partial melting.

2.12.2 Group GS 10 - Elbow Creek Dykes Group 11 (N = 4; U-Pb_{bad} 2480 Ma Unpublished Data C. Rogers)

This group of mafic dykes outcrops near the Stillwater mine, is named for a nearby creek, (Figure 2.1A) and cross cuts part of the 2710 Ma anorthosite of the Stillwater complex of Montana (Helz, 1985, Premo *et al.*, 1990, Wall *et al.*, 2009) suggesting an age potentially as old as late Achaean. In outcrop these dykes appear to be multi-generational, however the chemistries from the four observed dykes are nearly identical (Figures 4H, 10H, 6F, and 7F) and consistent with anastomosing of a single dyke rather multiple, independent dykes. Petrographically this group of samples is distinct from those of the other groups

in this study. Plagioclase tends to occur as small (30-50%; <1 mm) bladed crystals that show bending. Pyroxene is fairly coarse-grained (40-50%; 1-3 mm) and virtually unaltered. In some fractures are small dark rims of the pyroxene- indicating breakdown into iron oxides. Unlike other samples from other groups, specimens of this geochemical signature contain olivine (1-2%; 0.5-1 mm) that is breaking down into limonite and iron oxides. There are only trace amounts of biotite (<0.5 mm) in this group (Table 2.5). The dykes weather rusty-red and are highly fractured. Magnetic susceptibility readings were quite consistent within each dyke but were quite varied between each of the four dykes: $0.6 \times 10^{-3}\kappa$, $1.2 \times 10^{-3}\kappa$, $1.2 \times 10^{-3}\kappa$ and $2.6 \times 10^{-3}\kappa$ (SI; Table 2.4).

The geochemical signature for this group has not been seen elsewhere in dykes within the study area (Figure 2.4H). GS 10 dykes do not geochemically match known dykes of the Stillwater Complex (not shown graphically; Helz, 1985). Geochemically they are high magnesian basalts. A REE plot shows a distinct kink in the slope at Eu in the REE plot normalized to PM (Figure 2.4H) where the steep $(La/Sm)_{PM}$ slope (3.15-3.20) becomes nearly horizontal in the $(Gd/Lu)_{PM}$ slope (1.54-1.57). The nearly horizontal $(Gd/Yb)_{PM}$ slope (1.52-1.57) would indicate that melting took place within the spinel peridotite field of the mantle above 90 km depth. Figure 2.14 would also support the range of melting where all the samples plot within the spinel peridotite field. Given the high MgO content (16%-18.5%) of this group it is unlikely that these magmas have fractionated after leaving the mantle. The steep $(La/Sm)_{PM}$ slope (3.08-3.20) is

not due to low degrees of partial melt but rather indicates melting of a more enriched mantle source.

2.12.3 Group 13 - Nevada City Group (N=10)

This group is concentrated in the Tobacco Root Mountains, and in and around the Idaho Panhandle (Figure 2.1C). In outcrop these diabase tend to weather rusty-tan to tan; fresh surfaces are black to dark, chloritic-green. Hand specimens contain approximately 20-40%, 1-3 mm plagioclase laths, and 40-80% 1-2 mm blocky euhedral pyroxene crystals. This group contains mostly basaltic rocks that have a nearly flat $(La/Yb)_{PM}$ slope (1.98-3.68; Figure 2.9K) consistent with moderate degrees of partial melting at a shallow mantle level (above the garnet stability field). On a Ti vs. V binary plot (Figure 2.7F) these samples form a good linear array and plot within the oceanic flood basalt field and would cross the ARC-OFB boundary line at a steep angle. This would indicate that the oxygen fugacity was changing within the evolving magma chamber(s). As with all other groups discussed so far the analyses for this group plot above E-MORB along the MORB-OIB array (Figure 2.6F) indicating that there was involvement of crustal components during magma evolution.

2.12.4 Other Groups

The remaining four geochemical signatures within the study area are very distinctive with each interpreted to represent high degree partial melts of the

mantle. Because each of these groups only contains two or three samples, their characteristics are summarized in the following paragraphs but trends for magma evolution cannot be determined. They are described below with the intention of aiding future researchers so they may be able to build on these provisionally recognized geochemical characteristics and distributions.

GS 14 (Figure 2.1C) only includes two samples. In hand sample these samples are very fine-grained, with approximately 20% plagioclase and 80% pyroxene with an average grain size of approximately 0.5 mm. These mafic samples plot in the basalt field on a TAS. They have a flat $(\text{Gd/Yb})_{\text{PM}}$ slope (1.19-1.20) with slight enrichment in the $(\text{La/Sm})_{\text{PM}}$ slope (0.71-0.75; Figure 2.9L), indicating that this magma may have formed in the mantle near or below the garnet-spinel transition zone.

GS 15 (Figure 2.1C) only consists of two samples. On a fresh surface the outcrop weathered either tan or greyish-black. Hand samples contained approximately 50-60% plagioclase that are 1-4 mm. Pyroxene makes up about 40-50% of the rock and is generally 2-4 mm but can appear porphyritic in some locations. These samples have a flat $(\text{Gd/Yb})_{\text{PM}}$ slope (0.95-1.17) with a slight $(\text{La/Sm})_{\text{PM}}$ negative slope (1.98-2.26; Figure 2.9L), indicating that this magma may have formed in the mantle within the spinel peridotite field (Figure 2.14 F).

GS 16 (Figure 2.1A) is ultramafic in nature containing high MgO values that average 42.43%. The outcrop weathers dull-black and appears aphanitic on a fresh surface. On an HF etched sample, there are approximately 10-15%, 0.5 mm black to dark green crystals that appear to be olivine. Otherwise the

mineralogy is difficult to determine. Petrographic analysis confirms the presence of olivine crystals with thick rims of limonite. The three samples have a flat $(\text{Gd/Yb})_{\text{PM}}$ slope (0.77-0.98) with slight enrichment in the $(\text{La/Sm})_{\text{PM}}$ slope (1.15-2.77; Figure 2.9M), indicating that this magma may have formed in the mantle within the spinel peridotite field.

GS 17 (Figure 2.1A) consists of two dykes that are located in the Tobacco Root Mountains. They have a steep $(\text{La/Sm})_{\text{PM}}$ slope (4.12-4.65) indicative of a low degree of partial melt, and shallow $(\text{Gd/Yb})_{\text{PM}}$ slope (2.31-2.59; Figure 2.10K), indicating that this magma may have formed in the mantle within the spinel peridotite field.

2.13 DISCUSSION: MANTLE SOURCES

Inferred mantle sources for the sampled Proterozoic mafic magmatism along the western margin of Laurentia are not the same for all 17 geochemical signatures identified in this study. Major and minor element characteristics of six of these groups are distinct from groups belonging to the 780 Ma Gunbarrel LIP or the 1460 Ma Moyie-Purcell LIP, suggesting that these six groups represent additional events (GS7=1550 Ma, GS8=1590 Ma, GS9 =1418 Ma, GS 10=2480 Ma and 2 undated). In addition, the inferred depth of melting (based on MREE-HREE slope) is similar (above the garnet-spinel transition) for only ten of the 17 groups, with only subtle distinctions. Seven groups have a mantle signature consistent with more residual garnet in the source, indicating generation at depths greater than about 90 km.

To simplify the discussion and to eliminate repetition for the remainder of this section only unevolved mafic rocks are discussed. Therefore, only those rocks that plot within the basalt, picro-basalt or trachy-basalt fields of a TAS diagram or with a SiO₂ content of less than or equal to 52% are considered. MEPs in the remainder of this section are normalized to primitive mantle and shown in Figure 2.9, and REEs will refer to the data normalized to chondrite for elements La thru Lu, and are shown in Figure 2.3.

2.13.1 Moyie-Purcell LIP (GS 2- GS 5)

The Moyie-Purcell LIP data (GS 2-6, 11 and 12; Figure 2.1B) are significantly different from, and exhibit considerably more compositional variation than, the Gunbarrel LIP, based on the current database. The Moyie-Purcell LIP data also show the largest geographical distribution (within the study area), spanning the entire study area from Kimberley BC in the north to the Montana-Wyoming border in the south. Mafic rocks in GS 2, and 3 show a larger positive Pb anomaly and greater negative Nb-Ta deficiency than do samples belonging to GS 5. As seen on MEP's these four geochemical signatures show more variation in REE chemistry and wider range in degree of partial melting (Figure 2.9B-D) than the Gunbarrel LIP. The Moyie-Purcell LIP ranges in degree of partial melting (as shown by the range in LREE slopes). (Gd-Yb)_{PM} slopes indicate melting was near the garnet-spinel transition zone (Figure 2.14B and 14D).

2.13.2 Tobacco Root Mountain Groups (GS 7, GS 8)

The third significant grouping of magmatism within this study region belongs to the 1550 Ma Ramshorn Creek and 1590 Ma Mammoth Dyke Groups (GS 7 and GS 8; Figure 2.1C; ages from Chapter 4), which are compositionally distinct from the Gunbarrel and Moyie-Purcell LIPs and may represent separate magmatic events. The more primitive melts of the 1550 Ma Ramshorn Creek Group do not contain as large of a Nb-Ta deficiency as higher silica magmas of this group. The Nb-Ta deficiency for the 1590 Ma Mammoth Group is not as large as that of the 1550 Ma Ramshorn Creek Group. There is a small positive Pb anomaly in the 1590 Ma Mammoth Group, but there is no Nb-Ta deficiency. The chemistries of magmas from both of these groups are neither as dispersed as those of the Moyie-Purcell LIP nor as concentrated as those of the Gunbarrel LIP (Figure 2.3F-G and 9F-G). Additionally, on a $(\text{Nb/La})_{\text{PM}}$ vs. SiO_2 diagram (Figure 2.13C) data from both groups exhibit vertical trends indicating mixing between asthenospheric and metasomatized lithospheric components. A more comprehensive treatment of the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups is provided in Chapter 4, where links with coeval magmatism in NW Laurentia and formerly attached South Australian craton are considered.

2.13.3 Gunbarrel LIP (GS 1)

The geochemistry of the Gunbarrel LIP (GS 1; Figure 2.1A) is extremely consistent throughout the study area. The more MgO-rich dykes and sills within the Gunbarrel LIP have large positive Pb peaks and small negative Nb-Ta

deficiencies (Figure 2.9A), demonstrating that some crustal component was added to the primitive asthenospheric melts within the mantle. Specifically, the source for the Gunbarrel LIP must have been from a part of the lithospheric mantle already tainted with a metasomatized subduction contribution (Neumann *et al.*, 2011, Ernst, 2014). Minor crustal involvement is also supported on a $(\text{Nb/La})_{\text{PM}}$ vs. SiO_2 diagram (Figure 2.13A) with a near vertical trend. In the aforementioned diagram, mafic samples form a near vertical trend indicating that there was mixing of two sources, one with a high $(\text{Nb/La})_{\text{PM}}$ or asthenospheric melt and one with a low $(\text{Nb/La})_{\text{PM}}$ or similar to a metasomatized lithospheric mantle.

The moderate slope of $(\text{Gd/Yb})_{\text{PM}}$ (1.10-1.79; Figure 2.9A; Table 2.4) within the Gunbarrel LIP indicates that melts for this group were also produced near the garnet-spinel transition zone. If garnet were a major component of the residual mantle then the $(\text{Gd/Yb})_{\text{PM}}$ would be much larger as garnet would preferentially retain Yb in the crystal structure. The involvement of garnet in the source is also supported by $(\text{Gd/Yb})_{\text{PM}}$ vs. $(\text{La/Sm})_{\text{PM}}$ diagram (Figure 2.14A) where all the data plot just below the boundary line that separates the garnet and spinel fields within the mantle. Samples that plot close to this line could have been produced from partial melts of the mantle that still contain a small percentage of residual garnet.

2.13.4 Other Groups (GS 9, GS 13)

The Highland Mountain Group (GS 9; 1418 Ma, unpublished U-Pb age data C. Rogers; Figure 2.1A) cannot be related to either of the previous two LIPs, or to the Tobacco Root Mountains Event (GS 7 and GS 8). As the Highland Mountain Group does contain near-primitive magmas and is limited to only nine samples, we cannot establish robust trends for this geochemical signature. The data cluster separately from the other previously discussed LIPs (Gunbarrel and Moyie-Purcell) or Tobacco Root Mountains events. In a MEP diagram, this group shows that the magmas do not contain any crustal contribution signatures, a relatively flat Th to Gd MEP pattern, and a lack in both enriched Pb and Nb-Ta-deficiency anomalies. Similarly in the $(\text{Nb/La})_{\text{PM}}$ vs. SiO_2 (Figure 2.13F) diagram there is a clustering of data for this group indicating only one source for the melts that generated these rocks. The $(\text{Gd/Yb})_{\text{PM}}$ slope (1.81-2.55) on the other hand is much steeper than any of the geochemical signatures discussed above. This would indicate that melting within the garnet stability field was much more prevalent for generating the Highland Mountain Group dykes. It is not possible to tell if fractionation played a role in these magmas given the tight clustering of the data.

The last major geochemical signature is GS 13 - Nevada City Group (Figure 2.1C). This group cannot be related to any of the other previously discussed groups or LIPs. This group contains a minor Nb-Ta-deficiency and positive Pb anomaly (Figure 2.9K) indicating that a crustal component was added in the mantle. This interpretation is also supported on a $(\text{Nb/La})_{\text{PM}}$ vs. SiO_2

(Figure 2.13E) diagram where the trend for the primitive basalts is near vertical indicating that there was a high $(\text{Nb/La})_{\text{PM}}$ source mixing with a low $(\text{Nb/La})_{\text{PM}}$ metasomatized lithospheric mantle source.

2.14 CRUSTAL COMPONENTS: ACQUIRED FROM MANTLE OR CRUSTAL SOURCES?

To simplify the discussion and to eliminate repetition for the remainder of this section, only rocks that plot with more than 52% SiO_2 on the TAS diagram (Figure 2.12) are discussed. All references to REE-MEP and MEP refer to Figures 4 and 10, respectively.

2.14.1 Moyie-Purcell LIP (GS 2- 6, 11 and 12)

The higher silica melts of the Moyie-Purcell LIP (GS 2, 3, 4, and 5; Figure 2.1B) have large positive Pb anomalies and negative Nb-Ta anomalies which are nearly identical to the MEP signatures in the mafic Moyie-Purcell magmas. If a crustal component was added to evolved magmas as they resided in the crust, then the primitive, mafic melts would not show the same or similar Pb and $(\text{Nb/La})_{\text{PM}}$ deficiencies as the evolved magmas. This indicates that these magmatic groups obtained their crustal component from subduction-modified mantle.

Evolved samples from the Moyie-Purcell LIP show more crustal contribution relative to the Gunbarrel LIP on most MEP and binary diagrams (Figure 2.10B-E). The data also show considerable range of concentrations,

which would be representative of a wide range of partial melting and/or greater degree of crystal fractionation and assimilation.

2.14.2 Tobacco Root Mountain Groups (GS 7, GS 8)

Evolved magmas of the Tobacco Root Mountains events (Figure 2.1C) show a strong negative Nb-Ta anomaly and a stronger positive Pb anomaly compared to the mafic magmas of the same event. This relationship would indicate that a crustal contribution was acquired as the magma ascended through the mantle lithosphere. Higher silica magmas also show a wider range of element concentrations normalized to primitive mantle than do the more mafic magmas.

In addition, on the La/Sm vs. SiO_2 (Figure 2.13B) diagram the data from the Tobacco Root Mountains events are confined to an area that is roughly equant in shape. If there was a crustal contribution trend on this diagram there should be a negative trend in the data, which is imperfectly shown; if there was a mixing trend in the data there should be a positive trend, which is also imperfectly shown. Thus it is possible that both a crustal contribution and mixing with metasomatized mantle played roles in the evolution of these magmas.

The Tobacco Root Mountain events (GS 7 and GS 8) show similar genesis, but distinct evolutionary histories. On most plots (Figures 7C, 11C, and 12C) GS 7 and GS 8 plot with considerable overlap. The mafic rocks from both groups show a slightly higher $(\text{Gd/Yb})_{\text{PM}}$ (1.18-1.97) indicating that melting took place at or near the garnet-spinel transition zone (Figure 2.14C). Where these two groups are distinct is with respect to the interaction with the lithosphere

and/or crust. GS 8 shows more crustal/lithospheric interaction and/or assimilation-fractional crystallization (AFC; Figures 6C, 13C and 14C) than GS 7. More information on these events GS 7 and GS 8 is provided in Chapter 4

2.14.3 Gunbarrel LIP (GS 1)

The higher silica rocks from the Gunbarrel LIP (Figure 2.1A) do not show any more variability than the more mafic rocks when plotted on a MEP. As explained above, this suggests that most of the crustal signature in this group was imparted to the melt within the mantle. If only the evolved magmas showed the Nb-Ta and Pb anomalies (Figure 2.10A), then the source for these anomalies could have been at shallower levels (i.e., the crust). The easiest way to add Nb-Ta and Pb anomalies into primitive melts is if the primitive melts were modified by the interaction with ancient, subduction-modified lithospheric mantle (e.g., Neumann *et al.*, 2011, Ernst, 2014). We conclude that only minimal modification of Gunbarrel magmas occurred by addition of crustal melts or crustal fluids as it ascended through the lithosphere.

In binary diagrams like Ti or V vs. MgO, Zr or FeO/MgO, all Gunbarrel samples plot with positive trends, and have anomalously high Ti/V ratios, which would indicate that magnetite or hornblende are not fractionating phases from these magmas (Figure 11A; Shervais, 1982). Additionally, if clinopyroxene or spinel was a crystallizing phase then trends would cross the Ti/V trend lines at low angles (Shervais, 1982). Furthermore, in a La/Sm vs. SiO₂ diagram (Figure 2.13A) there is a positive trend within this group indicative of magma mixing. The

Gunbarrel dykes and sills share remarkably similar trace element and REE geochemistry throughout western Laurentia.

2.14.4 Other Groups (GS 9 and GS 10)

Of the other two geochemical signatures (GS 9 and GS 10; Figure 2.1A) only the Elbow Creek Dykes (GS 9; 2480 Ma) include higher silica magmas, and are only seen near the Stillwater complex in Wyoming. These have a distinct geochemical signature, strong negative Nb-Ta anomalies and moderately strong positive Pb anomalies that do not match any of the other geochemical signatures within this study area. From the four samples collected, we cannot tell if the primitive magmas were contaminated in the lithospheric mantle or during ascent through the crust. However, the moderately steep $(\text{Gd/Yb})_{\text{PM}}$ slope (1.81-2.55) indicates that some melting did occur within the garnet stability field in the mantle. Because this group only has four samples that are nearly identical in composition, it is difficult to discern a trend to determine the evolution of these magmas.

2.15 DEPTH OF MELTING

The depth of melting for the Proterozoic mafic magmatic events in western Laurentia is similar for most of the 17 geochemical signatures, with some minor variations. Average middle-heavy REE slopes $(\text{Gd/Yb})_{\text{PM}}$ range from 1.29 - 1.97 for eleven groups (Groups 1-8, 10, 12-15), indicating that melting took place over a range of depths, above and below the garnet-spinel transition zone at

approximately 90 km depth (Winter, 2010). The exceptions would be GS 9, 11, and 17, which have $(\text{Gd/Yb})_{\text{PM}}$ values ranging from 1.81-2.85 consistent with residual garnet after melting. Therefore GS 9, 11 and 17 were generated deeper in the mantle within the garnet stability field.

The depth of melting for GS 1 (Gunbarrel LIP) is also consistent for all samples of this group. The moderate ratio of $(\text{Gd/Yb})_{\text{PM}}$ (1.43-1.82) indicates that melting took place over a range of depths at or above the garnet-spinel transition zone

Variations in REE systematics as shown by $(\text{Gd/Yb})_{\text{PM}}$ and $(\text{La/Sm})_{\text{PM}}$ ratios (Table 2.4) indicate that all of the mafic dykes and sills within western Laurentia have had some contribution from lithospheric mantle and/or an enriched asthenospheric mantle (Figures 9, 10 and 14). All of the groups show evidence of shallow mantle melting. GS 3, 5, 6, 7, and 13 (Moyie-Purcell LIP – GS 2-5, and the GS 13 (Nevada City Group) show strong trends towards increasing crustal contribution with increasing SiO_2 . GS 2, 9, 11, and 12 (Moyie-Purcell LIP and the Tobacco Root Mountain Event) include a smaller crustal contribution component. GS 9 (Elbow Creek Group; 2480 Ma) shows the deepest melting depth.

2.16 MOYIE-PURCELL LIP: STRATIGRAPHY VS. GEOCHEMISTRY

Anderson and Goodfellow (2000) subdivided their dykes and sills into groups based on stratigraphic position within the Aldrich Fm. (in British Columbia). We are unaware of any attempt to similarly subdivide the dykes and

sills in the Prichard Fm. (in the adjacent regions of the USA) based on the stratigraphic position. The geochemical data produced in this study shows that most of the sills in the four main stratigraphic groupings of Anderson and Goodfellow (2000) do correspond with separate GS groups defined herein (i.e. GS 2-4). Furthermore, our study allows tracing of these GS groups throughout the region.

Furthermore, the available U-Pb geochronology for dykes and sills in the region allows the GS groups to be combined into pulses on the basis of age. A ca. 1470 Ma pulse consists of two subgroups based on slightly different chemistry. The pulses are as follows: Pulse-1a - GS 2 and 6 (ca. 1471 ± 8 Ma) and Pulse-1b - GS 3, 5, and 12 (ca. 1468 ± 2 Ma). A distinctly younger Pulse 2 comprises GS 4 and 11 (ca. 1457 Ma) and has geochemistry distinct from the two ca. 1470 Ma pulses. The main geochemical difference between the three pulses is the steeper slope of $(\text{La}/\text{Sm})_{\text{PM}}$ in Pulse 3 (GS 4 (1.62-3.12) and GS 11 (1.66-2.83)) compared to Pulses 1a and 1b (GS 2 (1.36-1.73) and GS 6 (1.22-2.19), and GS 3 (1.51-2.80), 5 (1.34-3.13), and 12 (1.21-2.29)); complete values are listed in Table 2.4, plotted in Figures 9, 10 and 14).

A much younger U-Pb zircon age of 1433 ± 10 Ma (Zartman et al., 1982) may represent a still younger pulse (Pulse 3) of the Moyie-Purcell LIP. However, its distinct age may indicate that it belongs to an entirely separate event. A sample was collected from near the dating site of Zartman et al. (1982) to test the linkage with the Moyie-Purcell LIP and this sample gave a composition that corresponds to the 1b subgroup of Pulse 1 (defined above). However, given that

Zartman did not include sample coordinates and our sampling was guided by his published sketch map (Figure 2 in Zartman et al., 1982) it cannot be certain that our sample belongs to his specific dated sill.

2.17 LIP AND GROUP SIGNATURE (GS) SUMMARY

The ca. 1470-1455 Ma Moyie-Purcell LIP (GS 2 - 6, 11 and 12) exhibits a range in chemistry (that we have divided into two age groups, and that we view as separate magmatic pulses) but as a group they tend to plot separately from the 780 Ma Gunbarrel (GS 1) LIP. This is clearly displayed in bivariate and multi-element plots (Figures 3, 4, 9 and 10). One specific example is the Ti vs. V/1000 plot by Shervais (1982; Figure 2.11). We can see that the Gunbarrel LIP data plot within the Oceanic Flood Basalt (OFB) field compared to the Moyie-Purcell LIP data that plot along the boundary of the OFB and Arc related basalts. The primitive magmas of both LIPs exhibit a negative Nb-Ta anomaly reflecting interaction with subduction-modified lithospheric mantle (Figure 2.9). Some mafic geochemical units of the Moyie-Purcell event show a larger Nb-Ta anomaly (GS 5).

Another difference between the Gunbarrel and Moyie-Purcell LIPs is the homogeneity of the geochemistry of the former (e.g., Mackinder 2014). The geochemical signature for the Gunbarrel LIP is very uniform (Figures 3A, 4A, 9A and 10A) whereas the geochemistry for the Moyie-Purcell LIP is more dispersed (Figures 3B-D, 4B-E, 9B-D and 10B-E). There are a number of possible explanations for this difference. The first and foremost is the duration of the LIP.

The Gunbarrel LIP is constrained to 779.5 ± 5.5 Ma by U-Pb geochronology (see Table 2.2 for references), whereas the Moyie-Purcell LIP is more extensive in duration ranging from 1471-1457 Ma (and perhaps to 1433 Ma) on the basis of U-Pb geochronology and presumably representing multiple pulses over this time period. This longer time range for the latter allows for multiple mantle sources and for melting conditions to change, allowing a greater variation in the geochemistry.

Interspersed with these two dated events are additional intraplate mafic magmatic events that are of unknown age (Figure 2.3F-M; GS 7 - 10 and 13 - 17; Now GS7=1550 Ma, GS8=1590 Ma, GS9=1418 Ma and GS10=2480 Ma are known). These additional magmatic events are seen throughout the Belt-Purcell Basin and northern part of the Wyoming Province and show REE chemistry that is distinct from that of both the Moyie-Purcell LIP and the Gunbarrel LIP (Figures 3, and 9; GS 7 - 10, and 13 - 17). These non- Gunbarrel / Moyie-Purcell events (GS7=1550 Ma, GS8=1590 Ma, GS9=1418 Ma and GS10=2480 Ma) are not part of either of these two LIPs but belong to different LIPs and fed from different sources, and at different times. These four of newly dated geochemical groups (GS 7, 8, 9 and 13) are predominantly Fe-rich tholeiites (Figure 2.11) that have been variably affected by a crustal contribution (Figure 2.7).

It was originally thought that all NW-SE trending mafic dykes belonged to either the ca. 1470-1455 Ma Moyie-Purcell LIP or the 780 Ma Gunbarrel LIP. Our study confirms distinct compositional groupings within the Moyie-Purcell LIP (Figs. 3-7, 9). The ca. 1470-1455 Moyie-Purcell LIP is recognized herein to

consist of seven geochemical groups that can be divided into two pulses (ca. 1470 and ca. 1455 Ma) based on age, and Pulse 1 is subdivided based on chemistry: Pulse 1a consists of GS 2 and GS 6; Pulse 1b consists of GS 3, 5 and 12 and Pulse 2 at ca. 1457 Ma consists of GS 4 and GS 11.

The geochemistry framework allows a regional extent for some of the groups to be determined (Figure 2.1B and 1D). For instance, we can now correlate the 1471 ± 3 Ma dykes of the Goat Flat Group of Chamberlain *et al.* (2000), to GS 4 of the Moyie sills that intrude the TMA and MA.

The Tobacco Root Mountain events, GS 7 (1550.6 ± 5.2 Ma; U-Pb age chapter 4) and GS 8 ($1592 \pm$ Ma; U-Pb age chapter 4; Ramshorn Creek and Mammoth Groups) have an Sm-Nd age of 1448 ± 49 Ma (Harlan *et al.*, 2008). However, given the large uncertainty we cannot conclusively correlate these with the U-Pb-dated Moyie-Purcell events (Anderson & Davis, 1995, Sears *et al.*, 1998, Anderson & Parrish, 2000, Doughty & Chamberlain, 2008). Furthermore, the geochemistry of GS7 and GS8 is dissimilar to that of all the units confirmed to belong to the Moyie-Purcell LIP. In general, the light to heavy REE slopes of the Moyie-Purcell LIP are shallower when compared to those of GS 7 and GS 8 (Table 2.4). Additionally, on a V vs. (Ti/1000) plot the Moyie-Purcell LIP data tend to plot as a linear array with a steep slope (slopes of ~25-40) compared to the broad shallow slopes (slopes of 12 and 18) for GS 7 and GS 8 data (Table 2.4; Figure 2.6).

Due to the size and distribution of the 780 Ma Gunbarrel LIP (extending over 2500 km from the north-western to western Laurentia), the observed

homogeneity in composition could be attributed to multiple magma chambers tapping a common mantle source and undergoing similar differentiation and emplacement histories, or a single magma chamber that is feeding all intrusions. In both cases the magma is likely fed from a magma chamber(s) above the plume head center region and propagating laterally outward through the crust as dykes and sills (Halls, 1982, Fahrig, 1987, Ernst & Baragar, 1992, Baragar *et al.*, 1996, Ernst, 2014).

GS 13 (Nevada City Group) also shows a geochemical signature that is distinct from that of the Moyie-Purcell LIP, Gunbarrel LIP and the Tobacco Root Mountains events. The magma for GS 13 also formed over a depth range at or near the garnet-spinel transition zone.

Undated groups GS 9 or GS 10 are also distinct from the other groups as well as from each other. Both of these groups have magma compositions consistent with generation below the garnet-spinel transition zone, where garnet was left in residue (Figure 2.14). GS 9 Highland Mountain Group (1418 Ma) has a MEP pattern that is somewhere between MORB and island arc basalt that is generated within the garnet stability field. This group does not exhibit any crustal component as shown by the lack of Nb-Ta and Pb anomalies (see “Other Geochemical Signatures: Group 13 - Nevada City Group”) that are typical of the Gunbarrel and Moyie-Purcell LIPs. GS 10, the Elbow Creek dykes (dated at 2480 Ma), are also distinct in that GS 10 shows a significant contribution from either subduction-modified mantle or continental crust. The MEP signature is similar to melts generated from subduction-modified mantle with some garnet remaining

within the residue. We have compared both of these geochemical signatures to other published literature on dyke swarms within this local area of the Wyoming Craton (Stillwater Dykes; (Helz, 1985)) and the ca. 1900 Ma Sourdough swarm (Killian, 2014 pers. comm., unpublished data) and no matches were recognized.

2.18 CONCLUSIONS

I identified 17 geochemical signatures from NW-SE trending dykes and sills of the Belt-Purcell Basin, and Wyoming craton. Seven of them (GS 2, 3, 4, 5, 6, 11 and 12) can be correlated to the ca. 1460 Ma Moyie-Purcell LIP, and 1 group corresponds to the Gunbarrel LIP (GS 1). Geochemistry allows the units to be correlated over the region. I believe that the Moyie-Purcell LIP should be subdivided based on the age of the two major pulses. In particular, I think the Moyie-Purcell LIP should be divided into two pulses that are comprised as follows: Pulse 1 (1470 Ma) consisting of Pulse *1a*) - GS 2 (ca. 1468 Ma) and GS 6 (ca. 1471 Ma), and Pulse *1b*) ca. 1468 Ma pulse - GS 3 (ca. 1468 Ma), GS 5 (ca. 1468 Ma), and GS 12 (1469 Ma) and, a second younger Pulse 2 (ca. 1455 Ma; - GS 4 and GS 11).

Based on this work, two of the geochemical signatures (GS 7 and GS 8) previously correlated to the Moyie-Purcell LIP via imprecise Sm-Nd ages (1448 ± 49 Ma) are now recognized to be a geochemically distinct event and therefore do not correlate with the Moyie-Purcell LIP. Instead, we put GS 7 and GS 8 into their own groups called the Ramshorn Creek and Mammoth Groups, which as shown in Chapter 4 have U-Pb ages of 1550 and 1590 Ma, respectively. The Nevada

City Group (GS 13) has been correlated with the ca. 1460 Ma Moyie-Purcell LIP by geological association. However, because of the different geochemical characteristics of the Nevada City Group, we cannot correlate it with the Moyie-Purcell LIP. Neither can the remaining two groups (GS 9 and GS 10) be correlated to either the Moyie-Purcell LIP or Gunbarrel LIP.

It is now apparent that there are additional Proterozoic intraplate events present in western Laurentia besides the long-recognized ca. 1460 Ma Moyie-Purcell and 780 Ma Gunbarrel events. The Gunbarrel LIP is tightly constrained to approximately 782-769 Ma by U-Pb methods (using all known dates). Moyie-Purcell LIP is protracted event covering nearly 14 Ma from 1471-1457 Ma based only U-Pb dating results, and not using other less precise and accurate dating methods (Rb-Sr, Sm-Nd, K-Ar, and ^{40}Ar - ^{39}Ar).

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Figure 2.1A: Location of study area marked by a black box (inset). Area includes southern British Columbia, Northern Idaho, western Montana and northwestern Wyoming. Sample locations for Geochemical Groups GS 1, 9, 10, 16, and 17, this study. Each field boundary is defined in the legend (Table 2.3) and refers to the geochemical signatures found. The ArcGIS compilation of dyke and sill traces are modified from published maps from the USGS, state and provincial surveys (Hadley, 1969; Cressman, 1981; Mudge et al., 1982; Harrison et al., 1986; Wallace et al., 1986; Harrison et al., 1992; Ruppel et al., 1993; Kellogg and Williams, 1997; Miller et al., 1999; Kellogg and Williams, 2000; Munts, 2000; Vuke et al., 2002; Lonn et al., 2003; Reynolds and Brandt, 2005, 2006; Lonn et al., 2007; Miller and Burmester, 2009; Lonn et al., 2010).

Figure 2.1B: Location of study area marked by a black box (see inset). Area includes southern British Columbia, Northern Idaho, western Montana and northwestern Wyoming. Sample locations for Groups GS 2, 3, 4, 5, 6, 11, and 12, this study. Each field boundary is defined in the legend (Table 2.3) and refers to the geochemical signatures found. The ArcGIS compilations of dyke and sill traces are modified from published maps from the USGS, state and provincial surveys (references as in Figure 2.1A).

Figure 2.1C: Location of study area marked by a black box (inset). Area includes southern British Columbia, Northern Idaho, western Montana and northwestern Wyoming. Sample locations for Groups GS 7, 8, 13, 14, and 15, this study. Each field boundary is defined in the legend (Table 2.3) and refers to the geochemical signatures found. The ArcGIS compilations of dyke and sill traces are modified from published maps from the USGS, state and provincial surveys (references as in Figure 2.1A).

Figure 2.1D: Geochronological sample sites. See Tables 2A and 2B for ages and references. Each field boundary is defined in the legend (Table 2.3) and refers to geochemical signatures found. The ArcGIS compilation of dyke and sill traces is modified from published maps from the U.S. Geological Survey and state and provincial surveys (Hadley, 1969; Cressman, 1981; Mudge et al., 1982; Harrison et al., 1986, 1992; Wallace et al., 1986; Ruppel et al., 1993; Kellogg and Williams, 1997, 2000; Miller et al., 1999; Munts, 2000; Vuke et al., 2002; Lonn et al., 2003, 2007, 2010; Reynolds and Brandt, 2005, 2006; Miller and Burmester, 2004).

Figure 2.2: Summary of rare earth element plots (REEs) and multi-element plots (MEPs) for the geochemical groups for western Laurentia. Only the most primitive samples with $\text{SiO}_2 < 52\%$ were used. Each line was generated by taking the average of each element and normalizing it to chondrite (A) or primitive mantle (B) from Sun and McDonough (1995). GS 4, 10, and 17 did not have any samples with SiO_2 less than 52% so the analysis with the lowest SiO_2 value was plotted.

Figure 2.3: REE plot of primitive magmas ($\text{SiO}_2 < 52\%$) of 15 western Laurentia geochemical groups arranged in order from left to right and top to bottom. There are differences in the REE slope (La-Lu)PM, heavy REE slope (HREE; (Gd/Lu)PM), Light REE slope (LREE; (La/Sm)PM). REE slopes are summarized in Table 2.2.

Figure 2.4: REE plot of evolved magmas ($\text{SiO}_2 > 52\%$) of 12 of the western Laurentia geochemical groups.

Figure 2.5: Plots of Ba vs. Th. Ba and Th are both immobile elements, but Ba is sensitive to alteration. So a linear relationship between Ba and Th indicates that there has been minimal disturbance of the Ba system (for Groups GS 1 through 10). However, when the Ba system has been perturbed (Ba added or removed) then the plot shows more scattering of the data (e.g., GS 11 and 12).

Figure 2.6: The MORB-OIB array base diagram after Pearce (2008) shows that all the mafic dykes and sills in this study are closely related to an EMORB signature with varying amounts of crustal contamination. Only Group GS 10 shows a trend towards the OIB signature and deeper crustal recycling. Groups GS 7, 8 and 11 also show deeper crustal recycling than the other groups but not as pronounced as for Group GS 10.

Figure 2.7 V vs. Ti of the 12 geochemical groups of Western Laurentia. This diagram highlights the similarities and differences between the WL groups. Groups GS 2, 3, 4, 5 and 8 are similar with steep trend along the ARC-OFB fields. The Gunbarrel LIP (GS 1) has chemistry that falls almost exclusively within the OFB with a moderate trend. Outliers omitted from inclusion in field boundary. Oversize symbols represent most parental sample. Base diagram after Shervais (1982).

Figure 2.8: Geochemical plot of our new data (from GS 7 and GS 8) corresponding to original Group A (open diamonds with crosses) and Group C (grey triangles) sites of Wooden et al., (1978). There are two distinct populations of samples as described, however, if we use the original Wooden et al. (1978) classification (based on major elements alone) we get an overlap of samples between the upper and lower groupings. It is more logical to divide to re-classify the samples based on these trace element geochemical data into upper lower groups. The new classification is only possible a result of the improvement of analytical techniques and equipment since the 1970's.

Figure

2.9: REE plots of primitive magmas ($\text{SiO}_2 < 52\%$) of geochemical signatures of Groups GS 1 thru 12 normalized to primitive mantle (Sun and McDonough, 1995). Groups GS1 through GS10 show a very similar melting history with large positive Pb anomalies, and varying degrees of negative Ta-Nb anomalies. All of these groups also show shallow slopes for the HREE's (Ga to Lu). GS 11 shows a minor Pb and Nb-Ta anomaly with a slightly steeper HREE slope is also slightly steeper than GS 1-10. GS 12 does not display either a strong Pb or Nb-Ta anomaly, but does have a steep HREE slope.

Figure 2.10: REE plots of evolved magmas ($\text{SiO}_2 > 52\%$) with geochemical signatures of GS 1 thru 12 normalized to primitive mantle (Sun and McDonough, 1995). Groups GS 1 through GS 10 show a very similar melting history with large positive Pb anomalies, and varying degrees of negative Ta-Nb anomalies. These trends indicate both contamination from a previously subducted source or melting of the upper crust and mixing with the magma.

Figure 2.11: AFM plots of WL geochemical signatures. A) Data from the Gunbarrel LIP (GS 1). B) Data from the Moyie-Purcell LIP (GS 2, 3, 4, and 5). Only GS 5 shows an increase of alkali's with increasing iron indicating that there may be a crustal contribution to that magma. C) GS 7 shows increasing iron content with no increase in alkali elements. GS 8 shows that there is an increase of alkali elements as iron increases. D) Only GS 11 shows any evidence for crustal contribution with increasing iron. GS 6, and 12 do not show any increase of alkali elements with iron. GS 11 is the only Mg-tholeiite in this sample set. The other 11 GS units are Fe-tholeiites. E) Chemistry from the GS 13, which shows a tight clustering of the data points. F) Chemistry from GS10, the only Mg rich tholeiite in the study area, and from the remaining groups that only contain 2-3 samples each.

Figure 2.12: TAS plots of WL geochemical signatures. A) Data from the Gunbarrel LIP (GS1). B) Data from the Moyie-Purcell LIP (GS 2, 3, 4, and 5). C) Data from the Tobacco Root Mountain events, D) Data from GS 6, 11 and 12, of which only GS 11 shows the most evolved magmas. E) Data from Group GS 13, F) variation among the smaller groups of geochemical signatures within the study area.

Figure

2.13: Plot of $(La/Sm)_{PM}$ vs. $(Gd/Yb)_{PM}$. This diagram shows the approximate location relative to the garnet-spinel transition in the mantle in which the melt was produced. Samples that plot close to the spinel boundary may have higher contributions of melts produced in the garnet stability zone. PM—primitive mantle; LIP—large igneous province; MPL—Moyie-Purcell LIP; TMA—top of the Middle Aldrich Formation; MA—Middle Aldrich Formation; TLA—top of the Lower Aldrich Formation; BLA—bottom of the Lower Aldrich Formation; Gp—Group.

Figure 2.14: Plot of $(\text{Nb/La})_{\text{PM}}$ vs. SiO_2 . In this diagram trends along the vertical represent mixing of two sources. One is a low $(\text{Nb/La})_{\text{PM}}$ source (i.e. lithospheric mantle), and the second from a high $(\text{Nb/La})_{\text{PM}}$ source (i.e. asthenospheric mantle). Any trend that forms a slope between vertical and horizontal would represent assimilation-fractional crystallization (AFC). This would represent assimilation of the country rock as fractionation is occurring. Any trend along the horizontal would represent fractionation where the magma has cooled significantly enough to lose its ability to heat the country rock to the point of generating any new partial melt. In this diagram Groups GS 1, 6, 7, 8, 9, 11, 12 and 13 show vertical trends in the data that would show mixing of asthenospheric and lithospheric mantle. Groups GS 1, through 6, 8, 12, show AFC. GS 4, 5, and 11 show fractional crystallization.

Table 2.1: Summary of geochemical data collected for this study. Major element oxide values have been normalized to 100 wt.%. ND = not detected, Fe₂O₃ was recalculated to 100% FeO. Each geochemical group (GS) is summarized by average, maximum, minimum and standard deviation of all samples within that geochemical grouping. The n=X to the right of the GS number represents the number of samples used in the calculations. IBS represents the average of repeated analysis of an internal blind standard.

		IBS	GS 1 n=21		Min	Std Dev	GS 2 n=15		Min	Std Dev
			Ave.	Max			Ave.	Max		
SiO ₂	Wt %	0.28	51.57	53.56	48.50	1.18	50.37	53.24	45.24	2.19
TiO ₂	Wt %	0.08	2.63	3.59	2.04	0.39	1.86	2.38	1.52	0.27
Al ₂ O ₃	Wt %	0.03	12.64	13.41	11.19	0.68	13.37	15.24	12.48	0.81
FeO	Wt %	0.01	15.85	18.28	14.15	0.99	16.58	19.76	13.61	1.91
MnO	Wt %	0.03	0.24	0.27	0.21	0.01	0.24	0.29	0.19	0.02
MgO	Wt %	0.00	4.71	6.01	3.27	0.76	5.36	7.12	4.32	0.67
CaO	Wt %	0.02	8.40	10.08	7.17	0.86	8.97	11.44	7.20	1.20
K ₂ O	Wt %	0.01	1.26	1.92	0.78	0.30	0.46	0.82	0.24	0.19
Na ₂ O	Wt %	0.38	2.47	2.84	1.86	0.25	2.67	4.45	1.03	0.89
P ₂ O ₅	Wt %	0.03	0.26	0.35	0.20	0.04	0.13	0.16	0.08	0.02
Ce	ppm	2	41.79	54.29	29.86	6.98	23.07	27.00	15.00	3.35
Co	ppm	12	49	58	43	4	56	68	47	7
Cr	ppm	4	65	117	24	30	13	17	10	3
Cu	ppm	0.21	244	366	72	61	188	290	14	87
Dy	ppm	0.04	7.68	10.47	6.42	1.00	4.90	5.60	3.80	0.55
Er	ppm	0.07	4.35	6.07	3.67	0.60	2.83	3.30	2.30	0.31
Eu	ppm	0.30	2.01	2.45	1.69	0.23	1.40	1.80	1.10	0.17
Gd	ppm	0.15	7.62	9.70	6.50	0.92	4.95	5.80	3.90	0.54
Hf	ppm	0.05	4.68	6.20	2.65	0.89	1.95	2.60	1.20	0.38
Ho	ppm	0.87	1.53	2.07	1.30	0.19	1.04	1.20	0.83	0.11
La	ppm	-	17.82	22.97	12.01	3.16	9.42	11.00	6.10	1.44
Lu	ppm	0.29	0.56	0.82	0.47	0.09	0.45	0.51	0.37	0.04
Nb	ppm	0.89	12	15	7	2	7	8	4	1
Nd	ppm	6.53	26.06	33.24	20.17	3.99	13.87	16.00	10.00	1.68
Ni	ppm	1.22	50	71	25	12	42	79	18	15
Pb	ppm	0.30	6	13	3	2	8	16	5	3
Pr	ppm	0	6	7	4	1	3	4	2	0
Rb	ppm	0	44	61	25	10	15	34	1	11
Sc	ppm	0.41	36	44	29	4	49	56	41	4
Sm	ppm	0	6.78	8.43	5.58	0.91	3.76	4.30	2.90	0.44
Sr	ppm	0.04	172	277	120	35	166	340	77	62
Ta	ppm	0.11	0.80	1.00	0.50	0.13	0.58	0.76	0.28	0.13
Tb	ppm	-	1.21	1.58	1.02	0.15	0.85	0.99	0.67	0.10
Th	ppm	0.05	4.04	5.50	2.08	1.01	1.96	2.40	1.20	0.34
Tm	ppm	8.58	0.61	0.86	0.52	0.09	0.46	0.52	0.36	0.05
U	ppm	0.00	1.07	1.46	0.48	0.28	0.47	0.58	0.30	0.08
V	ppm	0.64	459	500	311	52	643	1000	440	201
Y	ppm	0.10	41	57	35	6	29	33	21	3
Yb	ppm	6	3.84	5.53	3.30	0.58	2.91	3.30	2.30	0.31
Zr	ppm		173	229	86	36	96	110	58	15

		GS 3 n=40				GS 4 n=15			
		Ave.	Max	Min	Std Dev	Ave.	Max	Min	Std Dev
SiO ₂	Wt %	52.23	56.80	47.59	1.73	57.74	76.61	52.38	7.22
TiO ₂	Wt %	1.26	2.27	0.68	0.43	0.94	1.43	0.47	0.27
Al ₂ O ₃	Wt %	14.12	16.55	12.25	0.91	13.66	14.76	12.05	0.82
FeO	Wt %	13.02	19.24	9.98	2.57	10.56	13.50	2.81	2.55
MnO	Wt %	0.21	0.28	0.16	0.03	0.17	0.22	0.04	0.05
MgO	Wt %	6.46	9.68	3.65	1.26	5.28	9.19	0.50	2.75
CaO	Wt %	9.96	12.07	5.70	1.26	8.43	11.70	2.00	3.22
K ₂ O	Wt %	1.97	3.71	1.01	0.53	2.10	3.54	1.23	0.65
Na ₂ O	Wt %	0.67	2.58	0.17	0.48	1.02	2.22	0.37	0.58
P ₂ O ₅	Wt %	0.11	0.16	0.07	0.03	0.10	0.18	0.06	0.03
Ce	ppm	1.47	39.00	13.00	5.09	32.92	68.00	17.00	18.14
Co	ppm	0.64	67	39	7	38	51	4	13
Cr	ppm	10.40	360	12	93	95	370	10	118
Cu	ppm	2.00	590	15	111	79	240	3	73
Dy	ppm	0.08	6.10	2.60	0.87	4.47	7.40	2.60	1.42
Er	ppm	0.03	3.80	1.50	0.53	2.74	4.52	1.60	0.97
Eu	ppm	0.06	1.60	0.75	0.22	1.09	1.90	0.60	0.33
Gd	ppm	0.32	6.30	2.70	0.92	4.49	7.90	2.50	1.49
Hf	ppm	0.05	3.80	1.20	0.52	3.13	8.50	1.30	1.91
Ho	ppm	0.03	1.30	0.55	0.18	0.97	1.60	0.57	0.30
La	ppm	0.70	17.00	5.70	2.23	14.76	32.00	7.00	8.98
Lu	ppm	0.01	0.60	0.24	0.08	0.44	0.72	0.27	0.14
Nb	ppm	0.29	10	4	2	7	13	3	3
Nd	ppm	0.70	22.00	7.60	2.95	16.55	33.00	8.90	7.86
Ni	ppm	5.44	130	14	24	46	83	2	27
Pb	ppm	1.50	27	1	7	10	19	4	5
Pr	ppm	0.25	5	2	1	4	8	2	2
Rb	ppm	0.14	130	4	25	45	103	16	25
Sc	ppm	0.48	55	31	4	38	45	10	10
Sm	ppm	0.31	5.00	1.90	0.71	3.82	7.00	2.00	1.54
Sr	ppm	17.28	270	79	40	117	177	59	27
Ta	ppm	0.05	0.84	0.30	0.13	0.63	1.10	0.37	0.22
Tb	ppm	0.03	1.10	0.45	0.15	0.75	1.30	0.44	0.23
Th	ppm	0.09	4.30	1.30	0.61	4.61	14.65	1.50	3.93
Tm	ppm	0.02	0.59	0.25	0.08	0.44	0.71	0.28	0.13
U	ppm	0.06	0.96	0.33	0.15	1.11	2.81	0.34	0.88
V	ppm	9.84	1200	230	224	251	400	26	110
Y	ppm	0.50	37	16	5	27	45	17	8
Yb	ppm	0.11	3.70	1.60	0.51	2.87	4.60	1.80	0.93
Zr	ppm	4.72	170	50	24	117	297	48	68

		GS 5 n=40			Std Dev	GS 6 n=10			Std Dev
		Ave.	Max	Min		Ave.	Max	Min	
SiO ₂	Wt %	54.65	66.17	48.03	3.68	50.65	53.64	49.81	1.13
TiO ₂	Wt %	1.00	3.92	0.39	0.76	0.93	1.28	0.62	0.21
Al ₂ O ₃	Wt %	14.25	16.10	12.40	0.90	14.09	15.39	11.57	1.17
FeO	Wt %	10.45	17.05	5.32	2.32	10.79	12.90	9.07	1.11
MnO	Wt %	0.17	0.25	0.10	0.03	0.18	0.21	0.16	0.01
MgO	Wt %	6.50	9.97	1.63	2.22	8.82	12.97	7.73	1.83
CaO	Wt %	10.41	13.38	4.10	1.92	12.12	13.56	10.59	0.99
K ₂ O	Wt %	1.75	2.84	1.03	0.48	1.92	2.46	1.47	0.32
Na ₂ O	Wt %	0.72	2.42	0.15	0.49	0.43	0.65	0.19	0.15
P ₂ O ₅	Wt %	0.10	0.34	0.02	0.07	0.07	0.08	0.04	0.01
Ce	ppm	25.50	69.00	8.50	13.83	13.75	16.80	11.40	1.68
Co	ppm	42	61	27	8	51	72	41	10
Cr	ppm	193	750	10	205	413	1160	180	333
Cu	ppm	91	390	3	82	152	280	100	65
Dy	ppm	3.86	8.76	1.80	1.67	2.90	3.60	2.50	0.32
Er	ppm	2.28	5.13	1.10	0.91	1.70	2.09	1.38	0.25
Eu	ppm	1.03	2.50	0.44	0.52	0.77	0.91	0.61	0.10
Gd	ppm	3.79	8.49	1.45	1.78	2.64	3.02	2.43	0.23
Hf	ppm	2.45	6.00	0.90	1.14	1.51	2.00	0.75	0.35
Ho	ppm	0.81	1.86	0.39	0.33	0.59	0.75	0.48	0.08
La	ppm	11.10	32.00	4.00	6.23	6.26	8.10	4.60	1.09
Lu	ppm	0.37	0.69	0.16	0.14	0.22	0.29	0.17	0.04
Nb	ppm	6	14	2	3	4	5	3	1
Nd	ppm	13.48	33.00	4.90	7.09	8.45	9.00	7.50	0.52
Ni	ppm	63	150	2	32	150	326	70	92
Pb	ppm	8	38	1	7	3	6	1	2
Pr	ppm	3	8	1	2	2	2	2	0
Rb	ppm	31	100	3	24	16	34	4	9
Sc	ppm	41	49	29	5	38	46	26	6
Sm	ppm	3.22	7.70	1.29	1.63	2.28	2.46	1.99	0.17
Sr	ppm	117	230	79	33	148	214	97	41
Ta	ppm	0.56	1.40	0.10	0.28	0.23	0.30	0.10	0.07
Tb	ppm	0.64	1.38	0.28	0.29	0.45	0.53	0.38	0.05
Th	ppm	3.21	9.90	0.85	2.13	1.26	2.15	0.61	0.54
Tm	ppm	0.37	0.74	0.16	0.15	0.24	0.28	0.18	0.03
U	ppm	0.80	2.20	0.24	0.52	0.31	0.52	0.14	0.14
V	ppm	291	535	100	87	296	437	232	62
Y	ppm	23	48	11	9	15	19	13	2
Yb	ppm	2.38	4.88	1.20	0.91	1.51	1.92	1.14	0.27
Zr	ppm	90	216	28	48	49	60	18	13

		GS 7 n=21				GS 8 n=37			
		Ave.	Max	Min	Std Dev	Ave.	Max	Min	Std Dev
SiO ₂	Wt %	49.81	50.97	46.91	1.09	54.23	62.60	49.50	2.61
TiO ₂	Wt %	1.67	2.49	0.99	0.45	1.31	2.96	0.54	0.64
Al ₂ O ₃	Wt %	14.32	16.44	13.39	0.97	13.90	16.83	10.84	1.16
FeO	Wt %	12.90	14.43	10.21	1.11	11.49	16.88	8.18	1.98
MnO	Wt %	0.22	0.26	0.18	0.02	0.21	0.48	0.14	0.06
MgO	Wt %	6.84	7.89	5.50	0.68	6.13	12.45	1.34	2.16
CaO	Wt %	11.21	20.29	8.17	2.27	9.12	12.90	5.57	1.97
K ₂ O	Wt %	2.21	2.59	0.83	0.35	2.14	3.22	0.63	0.55
Na ₂ O	Wt %	0.64	2.21	0.04	0.54	1.33	3.14	0.34	0.70
P ₂ O ₅	Wt %	0.18	0.39	0.08	0.10	0.15	0.38	0.05	0.09
Ce	ppm	24.03	54.20	14.20	9.55	36.67	64.50	11.60	16.25
Co	ppm	48	62	31	5	42	68	23	9
Cr	ppm	161	340	90	74	162	960	10	195
Cu	ppm	161	288	32	68	103	257	7	69
Dy	ppm	4.65	7.40	3.70	0.87	4.66	9.78	2.15	1.83
Er	ppm	2.75	4.48	2.20	0.54	2.73	5.30	1.25	0.96
Eu	ppm	1.37	2.12	0.96	0.34	1.25	2.69	0.54	0.53
Gd	ppm	4.47	7.72	3.27	0.98	4.64	10.05	2.30	1.98
Hf	ppm	2.91	6.10	1.64	0.96	3.55	7.60	1.30	1.53
Ho	ppm	0.95	1.52	0.78	0.17	0.96	2.03	0.47	0.37
La	ppm	9.95	23.80	5.60	4.35	16.43	29.20	5.10	7.34
Lu	ppm	0.38	0.60	0.28	0.07	0.38	0.73	0.18	0.13
Nb	ppm	9	19	4	4	9	19	3	5
Nd	ppm	15.56	32.00	9.50	5.64	19.19	38.60	7.20	8.78
Ni	ppm	75	162	41	24	67	336	3	56
Pb	ppm	5	12	2	3	10	58	2	12
Pr	ppm	3	7	2	1	5	9	2	2
Rb	ppm	22	85	0	23	52	127	8	29
Sc	ppm	40	45	28	5	33	43	18	5
Sm	ppm	4.00	7.36	2.74	1.14	4.43	9.86	1.79	2.00
Sr	ppm	198	443	127	77	183	432	90	67
Ta	ppm	0.52	1.00	0.30	0.21	0.63	1.40	0.20	0.35
Tb	ppm	0.73	1.19	0.52	0.14	0.75	1.63	0.36	0.31
Th	ppm	1.14	2.17	0.71	0.36	4.06	8.02	1.22	2.04
Tm	ppm	0.39	0.64	0.32	0.07	0.40	0.83	0.19	0.15
U	ppm	0.31	0.49	0.16	0.09	1.02	1.96	0.28	0.48
V	ppm	343	416	241	50	316	546	83	102
Y	ppm	25	39	21	4	26	51	12	10
Yb	ppm	2.49	3.97	1.95	0.45	2.54	4.85	1.12	0.87
Zr	ppm	101	227	56	37	124	268	44	56

		GS 9 n=11			Std Dev	GS 10 n=4			Std Dev
		Ave.	Max	Min		Ave.	Max	Min	
SiO ₂	Wt %	49.20	60.01	44.54	3.93	52.62	52.70	52.54	0.08
TiO ₂	Wt %	2.77	4.25	1.25	1.19	0.54	0.55	0.52	0.01
Al ₂ O ₃	Wt %	16.55	19.59	14.32	1.55	9.58	10.00	9.12	0.36
FeO	Wt %	14.11	17.46	11.60	1.80	10.06	10.15	9.94	0.10
MnO	Wt %	0.21	0.32	0.04	0.07	0.19	0.19	0.18	0.01
MgO	Wt %	6.04	10.00	0.29	2.40	16.87	18.48	15.70	1.18
CaO	Wt %	5.25	10.05	0.66	3.64	7.95	8.29	7.33	0.44
K ₂ O	Wt %	2.79	4.33	1.72	0.68	1.52	1.66	1.27	0.18
Na ₂ O	Wt %	2.54	5.64	0.20	1.70	0.60	0.71	0.46	0.12
P ₂ O ₅	Wt %	0.55	0.81	0.33	0.18	0.08	0.08	0.07	0.00
Ce	ppm	78.09	174.50	51.10	34.29	22.89	24.37	20.96	1.42
Co	ppm	44	65	6	16	72	76	69	3
Cr	ppm	40	90	10	34	600	600	600	0
Cu	ppm	32	105	2	35	70	74	65	4
Dy	ppm	6.94	13.90	4.38	2.75	2.30	2.47	2.08	0.16
Er	ppm	3.85	7.72	2.52	1.49	1.36	1.44	1.26	0.08
Eu	ppm	2.60	5.37	1.81	1.01	0.66	0.71	0.60	0.05
Gd	ppm	7.94	15.25	4.64	2.95	2.34	2.48	2.14	0.15
Hf	ppm	6.15	14.30	1.10	3.28	1.72	1.80	1.61	0.08
Ho	ppm	1.37	2.86	0.84	0.57	0.46	0.49	0.42	0.03
La	ppm	35.55	79.40	24.50	15.39	11.52	12.27	10.40	0.79
Lu	ppm	0.48	1.10	0.29	0.23	0.19	0.20	0.17	0.01
Nb	ppm	26	67	4	17	3	3	3	0
Nd	ppm	42.03	86.70	27.70	16.56	11.17	11.83	10.19	0.71
Ni	ppm	42	82	1	29	421	474	384	38
Pb	ppm	5	11	2	3	5	6	4	1
Pr	ppm	10	21	7	4	3	3	3	0
Rb	ppm	48	106	2	30	22	25	16	4
Sc	ppm	23	35	12	6	25	26	24	1
Sm	ppm	8.69	17.60	5.63	3.40	2.36	2.53	2.18	0.14
Sr	ppm	318	905	31	273	124	134	105	13
Ta	ppm	1.37	3.30	0.20	0.82	0.23	0.30	0.20	0.05
Tb	ppm	1.16	2.34	0.71	0.46	0.37	0.40	0.33	0.03
Th	ppm	2.86	9.34	0.37	2.31	3.14	3.42	2.81	0.25
Tm	ppm	0.51	1.07	0.32	0.21	0.19	0.21	0.18	0.01
U	ppm	0.61	2.13	0.09	0.53	0.87	0.94	0.78	0.07
V	ppm	184	308	101	69	170	175	164	5
Y	ppm	35	72	23	14	13	14	12	1
Yb	ppm	3.25	6.96	1.92	1.43	1.25	1.33	1.17	0.07
Zr	ppm	236	628	32	149	68	73	62	5

		GS 11 n=14				GS 12 n=43			
		Ave.	Max	Min	Std Dev	Ave.	Max	Min	Std Dev
SiO ₂	Wt %	56.80	66.02	52.50	4.32	51.90	55.26	49.52	1.44
TiO ₂	Wt %	1.22	2.47	0.51	0.60	1.47	2.86	0.68	0.60
Al ₂ O ₃	Wt %	13.42	15.59	11.12	1.51	13.95	16.05	11.53	1.14
FeO	Wt %	11.98	18.26	8.75	2.92	13.06	18.47	8.39	2.36
MnO	Wt %	0.20	0.28	0.14	0.04	0.20	0.27	0.15	0.03
MgO	Wt %	4.34	8.18	0.64	2.79	6.19	8.85	2.92	1.21
CaO	Wt %	8.48	12.15	4.68	2.64	10.06	12.38	5.74	1.32
K ₂ O	Wt %	2.26	2.95	1.40	0.59	2.45	4.54	1.21	0.65
Na ₂ O	Wt %	1.10	3.43	0.40	0.92	0.59	1.16	0.20	0.27
P ₂ O ₅	Wt %	0.20	0.92	0.03	0.25	0.12	0.27	0.05	0.05
Ce	ppm	43.44	115.00	14.10	34.57	20.80	32.60	10.20	6.30
Co	ppm	33	53	11	12	45	65	32	6
Cr	ppm	73	220	10	80	110	370	10	104
Cu	ppm	56	155	9	40	154	428	7	107
Dy	ppm	7.20	19.30	2.51	5.61	4.52	7.88	2.46	1.46
Er	ppm	4.35	11.60	1.57	3.24	2.77	5.17	1.61	0.85
Eu	ppm	1.62	4.34	0.48	1.23	1.14	1.87	0.63	0.36
Gd	ppm	6.85	18.85	2.17	5.65	4.20	7.40	2.46	1.40
Hf	ppm	5.03	17.20	1.30	4.55	2.88	4.90	1.60	0.94
Ho	ppm	1.46	3.85	0.51	1.12	0.93	1.74	0.51	0.29
La	ppm	19.49	48.80	6.30	14.91	8.78	13.40	4.10	2.68
Lu	ppm	0.58	1.55	0.21	0.41	0.37	0.67	0.19	0.11
Nb	ppm	10	31	3	9	6	10	3	2
Nd	ppm	25.11	73.40	7.40	22.09	13.27	21.10	7.00	4.36
Ni	ppm	24	62	1	18	65	131	1	29
Pb	ppm	12	43	3	11	7	14	2	4
Pr	ppm	6	16	2	5	3	4	1	1
Rb	ppm	40	115	5	34	21	51	2	13
Sc	ppm	34	48	18	9	39	52	22	6
Sm	ppm	6.11	18.40	1.62	5.38	3.58	6.02	1.93	1.25
Sr	ppm	127	177	80	29	151	265	60	45
Ta	ppm	0.62	2.00	0.10	0.57	0.38	0.70	0.20	0.15
Tb	ppm	1.13	3.21	0.35	0.94	0.70	1.20	0.38	0.24
Th	ppm	4.56	11.60	1.65	3.43	1.79	3.47	0.57	0.71
Tm	ppm	0.63	1.70	0.18	0.48	0.39	0.77	0.22	0.12
U	ppm	1.25	3.56	0.42	0.99	0.48	1.02	0.12	0.21
V	ppm	260	701	5	209	363	898	92	124
Y	ppm	40	107	13	31	24	44	14	8
Yb	ppm	4.02	10.45	1.42	2.85	2.49	4.49	1.41	0.74
Zr	ppm	174	634	42	169	93	155	49	31

		GS 13 n=10				GS 14 n=2			
		Ave.	Max	Min	Std Dev	Ave.	Max	Min	Std Dev
SiO ₂	Wt %	50.02	51.10	45.69	1.57	49.81	49.94	49.69	0.18
TiO ₂	Wt %	2.17	5.28	1.11	1.25	1.28	1.40	1.17	0.17
Al ₂ O ₃	Wt %	13.20	14.23	11.27	1.07	13.33	13.42	13.25	0.12
FeO	Wt %	14.16	17.61	11.41	2.22	14.00	14.47	13.53	0.67
MnO	Wt %	0.24	0.44	0.20	0.07	0.25	0.26	0.25	0.01
MgO	Wt %	6.54	7.90	4.35	1.15	6.86	7.11	6.62	0.35
CaO	Wt %	10.51	12.26	7.30	1.57	11.70	12.02	11.39	0.44
K ₂ O	Wt %	2.38	3.32	2.03	0.38	2.46	2.59	2.34	0.17
Na ₂ O	Wt %	0.62	1.52	0.21	0.41	0.20	0.24	0.16	0.06
P ₂ O ₅	Wt %	0.16	0.28	0.09	0.06	0.09	0.10	0.07	0.02
Ce	ppm	24.71	41.20	13.61	9.64	9.70	11.10	8.30	1.98
Co	ppm	50	66	43	7	58	58	57	1
Cr	ppm	166	271	90	79	95	110	80	21
Cu	ppm	233	633	9	172	167	171	162	6
Dy	ppm	5.64	9.07	3.63	1.69	4.62	4.94	4.29	0.46
Er	ppm	3.41	6.23	2.22	1.19	2.80	2.99	2.61	0.27
Eu	ppm	1.46	2.54	0.94	0.53	1.10	1.17	1.02	0.11
Gd	ppm	5.42	8.53	3.26	1.74	3.89	4.20	3.58	0.44
Hf	ppm	3.26	5.40	1.70	1.36	2.10	2.30	1.90	0.28
Ho	ppm	1.16	1.84	0.76	0.36	1.02	1.07	0.96	0.08
La	ppm	10.59	18.50	5.65	4.32	3.50	4.10	2.90	0.85
Lu	ppm	0.43	0.72	0.31	0.14	0.41	0.43	0.39	0.03
Nb	ppm	8	12	5	2	2	3	2	0
Nd	ppm	16.65	25.70	9.66	5.78	8.45	9.40	7.50	1.34
Ni	ppm	68	93	9	25	74	79	68	8
Pb	ppm	5	10	1	4	7	7	7	NA
Pr	ppm	4	5	2	1	2	2	1	0
Rb	ppm	23	72	4	20	4	4	3	1
Sc	ppm	43	46	34	4	48	49	46	2
Sm	ppm	4.58	7.17	2.67	1.59	3.00	3.36	2.63	0.52
Sr	ppm	186	374	134	77	101	105	98	5
Ta	ppm	0.49	0.70	0.30	0.14	0.15	0.20	0.10	0.07
Tb	ppm	0.88	1.43	0.55	0.28	0.70	0.75	0.64	0.08
Th	ppm	1.82	3.39	0.81	0.96	0.57	0.68	0.45	0.16
Tm	ppm	0.47	0.80	0.32	0.16	0.43	0.46	0.40	0.04
U	ppm	0.56	1.42	0.21	0.39	0.16	0.19	0.12	0.05
V	ppm	453	904	298	178	395	419	371	34
Y	ppm	31	51	20	10	26	28	24	3
Yb	ppm	3.00	5.11	2.03	0.99	2.69	2.89	2.48	0.29
Zr	ppm	110	190	61	43	68	76	60	11

		GS 15 n=2				GS 16 n=3			
		Ave.	Max	Min	Std Dev	Ave.	Max	Min	Std Dev
SiO ₂	Wt %	50.19	51.06	49.31	1.24	41.82	43.36	40.87	1.35
TiO ₂	Wt %	0.41	0.43	0.39	0.03	0.16	0.20	0.10	0.05
Al ₂ O ₃	Wt %	17.10	17.36	16.84	0.37	1.91	2.16	1.76	0.21
FeO	Wt %	7.88	8.57	7.19	0.98	13.46	14.62	11.80	1.48
MnO	Wt %	0.16	0.16	0.15	0.00	0.10	0.12	0.09	0.02
MgO	Wt %	10.41	11.47	9.35	1.50	42.43	42.62	42.31	0.16
CaO	Wt %	12.18	12.74	11.62	0.79	0.05	0.10	0.02	0.04
K ₂ O	Wt %	1.25	1.30	1.19	0.08	0.02	0.03	0.01	0.01
Na ₂ O	Wt %	0.40	0.43	0.37	0.04	0.01	0.02	0.00	0.01
P ₂ O ₅	Wt %	0.03	0.03	0.02	0.01	0.02	0.03	0.01	0.01
Ce	ppm	7.75	7.90	7.60	0.21	1.30	1.80	1.00	0.44
Co	ppm	45	54	35	13	119	129	114	8
Cr	ppm	600	940	260	481	8750	9790	7710	1471
Cu	ppm	68	77	59	13	5	10	2	5
Dy	ppm	1.57	1.69	1.44	0.18	0.34	0.39	0.30	0.05
Er	ppm	1.10	1.13	1.07	0.04	0.21	0.25	0.19	0.03
Eu	ppm	0.37	0.41	0.33	0.06	0.07	0.09	0.05	0.02
Gd	ppm	1.32	1.36	1.28	0.06	0.26	0.26	0.25	0.01
Hf	ppm	0.90	1.00	0.80	0.14	0.20	0.20	0.20	0.00
Ho	ppm	0.30	0.32	0.28	0.03	0.07	0.07	0.06	0.01
La	ppm	3.60	3.70	3.50	0.14	0.63	0.90	0.50	0.23
Lu	ppm	0.15	0.16	0.13	0.02	0.04	0.04	0.04	0.00
Nb	ppm	2	2	2	0	0	0	0	0
Nd	ppm	4.10	4.40	3.80	0.42	0.63	0.90	0.50	0.23
Ni	ppm	168	232	103	91	2098	2260	1785	271
Pb	ppm	39	39	39	NA	3	3	2	1
Pr	ppm	1	1	1	0	0	0	0	0
Rb	ppm	17	20	13	5	0	0	0	0
Sc	ppm	23	27	19	6	7	8	7	1
Sm	ppm	1.11	1.21	1.00	0.15	0.25	0.28	0.21	0.04
Sr	ppm	85	86	84	1	3	4	1	2
Ta	ppm	0.10	0.10	0.10	0.00	NA	0.00	0.00	NA
Tb	ppm	0.23	0.24	0.22	0.01	0.05	0.05	0.04	0.01
Th	ppm	0.89	0.98	0.79	0.13	0.14	0.19	0.11	0.04
Tm	ppm	0.15	0.15	0.14	0.01	0.04	0.04	0.04	0.00
U	ppm	0.24	0.26	0.22	0.03	0.50	0.92	0.14	0.39
V	ppm	163	171	154	12	63	90	21	37
Y	ppm	9	9	9	0	2	2	2	0
Yb	ppm	1.04	1.12	0.96	0.11	0.24	0.28	0.21	0.04
Zr	ppm	23	24	22	1	9	10	8	1

		GS 17 n=3			Std Dev
		Ave.	Max	Min	
SiO ₂	Wt %	63.25	73.94	55.74	9.51
TiO ₂	Wt %	0.73	1.04	0.27	0.41
Al ₂ O ₃	Wt %	14.90	15.66	13.81	0.97
FeO	Wt %	6.15	8.45	1.91	3.68
MnO	Wt %	0.09	0.12	0.02	0.06
MgO	Wt %	3.16	5.30	0.71	2.31
CaO	Wt %	5.04	7.47	1.53	3.11
K ₂ O	Wt %	3.39	3.65	3.10	0.28
Na ₂ O	Wt %	2.99	4.63	2.05	1.43
P ₂ O ₅	Wt %	0.29	0.43	0.08	0.19
Ce	ppm	104.70	113.00	88.10	14.38
Co	ppm	17	27	3	12
Cr	ppm	93	170	10	80
Cu	ppm	29	46	5	21
Dy	ppm	3.55	4.58	1.71	1.60
Er	ppm	1.81	2.47	0.82	0.88
Eu	ppm	1.55	2.13	0.88	0.63
Gd	ppm	4.86	6.19	2.76	1.84
Hf	ppm	5.73	6.80	4.40	1.22
Ho	ppm	0.67	0.88	0.33	0.30
La	ppm	53.77	56.50	48.70	4.39
Lu	ppm	0.24	0.31	0.12	0.11
Nb	ppm	10	11	9	1
Nd	ppm	46.30	55.30	30.50	13.73
Ni	ppm	45	81	9	36
Pb	ppm	15	26	6	10
Pr	ppm	12	14	9	3
Rb	ppm	98	144	66	40
Sc	ppm	12	17	3	8
Sm	ppm	7.03	8.86	4.43	2.31
Sr	ppm	469	615	355	133
Ta	ppm	0.57	0.80	0.40	0.21
Tb	ppm	0.64	0.83	0.34	0.27
Th	ppm	13.23	20.80	7.83	6.75
Tm	ppm	0.26	0.33	0.14	0.10
U	ppm	2.71	5.77	0.92	2.66
V	ppm	116	166	22	81
Y	ppm	19	25	9	9
Yb	ppm	1.58	2.01	0.76	0.71
Zr	ppm	225	272	171	51

Table 2.2a: Summary table of known published dates of Meso-Proterozoic dykes in western Laurentia. Abbreviations: U-Pb_{Ba} = U-Pb age determination using baddeleyite (ZrO₂), U-Pb_{Zr} = U-Pb age determination using zircons (ZrSiO₄), subscript WR are whole rock age determinations OMA = Sample outside map area; NC = No accurate coordinates could be obtained. The value in the number column location of the dated sample taken from the original reference plotted in Figure 2.1D.

Moyie-Purcell LIP					
Dyke or Sill	Age	Dating Method	Author	Year	Number On Figure 2.1d
Moyie Sills (GS 2-5)	1468 ± 2 Ma	U-Pb _{Zr}	Anderson and Davis	1995	1
Goat Flat Dyke (GS 6)	1471 ± 3 Ma	U-Pb _{Zr} In-Situ	Chamberlain et al. Chamberlain Pers. Com.	2000; 2014	OMA
Diorite Dyke	1378.7 ± 1.2 Ma	U-Pb _{Zr}	Doughty and Chamberlain	1996	2
Amphibolite Dyke	1463 ± 6 Ma	U-Pb _{Zr}	Doughty and Chamberlain	2008	3
Purcell Lava	1447 ± 7 Ma	U-Pb _{Zr}	Evans et al.	2000	4
Dyke (GS 7)	1448 ± 49 Ma	Sm-Nd _{WR}	Harlan et al.	2005	5
Plains Sill (GS 11)	1469 ± 2.5 Ma	U-Pb _{Zr}	Sears et al.	1998	6
Paradise Sill (GS 12)	1457 ± 2 Ma	U-Pb _{Zr}	Sears et al.	1998	7
Crossport Sill	1433 ± 10 Ma	U-Pb _{Zr}	Zartman et al.	1982	8
Dykes, TRM (Group A; GS 7)	1455 ± 125 Ma	Rb-Sr _{WR}	Wooden et al.	1978	9
Dykes, TRM (Group C; GS 8)	1130 ± 130 Ma	Rb-Sr _{WR}	Wooden et al.	1978	10

Table 2.2b: Geochronological summary of Gunbarrel LIP

Gunbarrel LIP					
Dyke or Sill	Age	Dating Method	Author	Year	Number on Figure 2.1d
Sill Tsezotene	779.5 ± 2.5 Ma	U-Pb _{Ba}	Harlan et al.	2003	OMA
Sill, Concajou	779.5 ± 2.5 Ma	U-Pb _{Ba}	Harlan et al.	2003	OMA
Sills, Hottah Sheets	780 ± 1 Ma	U-Pb _{Ba}	Harlan et al.	2003	OMA
Dyke, Muncho (GS 1)	777.3 ± 3 Ma	U-Pb _{Ba}	Harlan et al.	2003	NC
Sill, Holland Lake (GS 1)	777.5 ± 2.5 Ma	U-Pb _{Zr}	Burtis et al.	2007	11
Sill, Wolf Creek (GS 1)	776 ± 5 Ma	U-Pb _{Ba}	Harlan et al.	1997	12
Dykes, TRM (Group B; GS 1)	1120 ± 185 Ma	Rb-Sr _{WR}	Wooden et al.	1978	13
Dykes, TRM (Group B; GS 1)	769 ± 7 Ma	U-Pb _{Zr}	Harlan	1993	14
Dykes, TRM (Group B; GS 1)	782.4 ± 4.9 Ma	⁴⁰ Ar- ³⁹ Ar _{Hbl}	Harlan et al.	2003	15
Dyke, Christmas Lake (GS 1)	750 Ma	Rb-Sr _{WR}	Mueller and Rogers	1973	NC
Dyke, Christmas Lake (GS 1)	774 ± 4 Ma	⁴⁰ Ar- ³⁹ Ar	Harlan et al	1997	NC
Dyke, Christmas Lake (GS 1)	779.5 ± 3 Ma	U-Pb _{Ba}	Harlan et al	2003	16
Dyke, Mount Moran (GS 1)	775 Ma	Rb-Sr _{WR} , K-Ar	Reed and Zartman	1973	OMA
Dyke, Mount Moran (GS 1)	765 ± 5 Ma	⁴⁰ Ar- ³⁹ Ar	Harlan et al.	1997	OMA

Table 2.3: Geochemical signatures and nomenclature synopsis. Legend of symbols and groups.

■	GS 1 - Group B or "780Ma Gunbarrel LIP" dykes and sills (Harlan et al. 2003; Wooden et al. 1978).	■	GS 10 – "Elbow Creek Group dikes" – these are 4 dykes that were only identified near the Stillwater Mine in the Stillwater Complex
○	GS 2 - Top of the Middle Aldrich Fm. "TMA" 1468±2Ma (Anderson and Parrish, 2000, Anderson and Goodfellow 2000).	●	GS 11 - "Paradise Sill Group" - 1457±2 Ma formerly unnamed group not recognized geochemically in this area of western Laurentia (Sears et al., 1998)
△	GS 3 - Middle Aldrich Fm. "MA" 1468±2Ma (Anderson and Parrish, 2000, Anderson and Goodfellow 2000).	●	GS 12 - "Plains Sill Group" - 1469±2.5 Ma formerly unnamed group not recognized geochemically in this area of western Laurentia (Sears et al., 1998)
◇	GS 4 - Top of the Lower Aldrich Fm. "TLA" 1468±2Ma (Anderson and Parrish, 2000, Anderson and Goodfellow 2000).	■	GS 13 - "Nevada City Group" - formerly unnamed group not recognized geochemically or geochronologically in the study area.
▽	GS 5 - Bottom of the Lower Aldrich Fm. "BLA" 1468±2Ma (Anderson and Parrish, 2000, Anderson and Goodfellow 2000).	◇	GS 14 – Unnamed Group; not previously named geochronologically or geochemically recognized in the area of western Laurentia
●	GS 6 - "Goat Flat Dike Group" - based on a 1471±8Ma U-Pb baddeleyite date on the Goat Flat dike (Chamberlain Pers. Comm. 2014)	○	GS 15 - Unnamed Group; not previously named geochronologically or geochemically recognized in the area of western Laurentia
◆	GS 7 - Ramshorn Creek Gp. "Wooden Gp A" (Wooden et al. 1978).	▲	GS 16 - Unnamed Group; not previously named geochronologically or geochemically recognized in the area of western Laurentia
▲	GS 8 - Mammoth Dyke Group "Wooden Gp C" (Wooden et al. 1978).	●	GS 17 - Unnamed Group; not previously named geochronologically or geochemically recognized in the area of western Laurentia
■	GS 9 – "Highland Mountain Group", predominately confined to the Highland Range Mountains, have not been previously described or precisely dated		

Table 2.4: Summary of REE and Ti/V slopes for each geochemical signature in western Laurentia. Abbreviations are defined as follows: n = number of samples used for calculations, R = Range of values, A=Average values, R^2 = Goodness of fit of the slope, YI = Y-intercept (Vanadium), SI = Slope. Regression lines were calculated using the tightest clustering of samples, outliers were removed from the calculations. The degree of partial melt is estimated based on approach in Rollinson (1993) and White (2013).

Group	REE Slope (La/Yb) _{PM}	Light REE Slope (La/Sm) _{PM}	Heavy REE Slope (Gd/Yb) _{PM}	Ti/V Averages	Regression of Ti/V	Magnetic Susceptibility
GS 1 n=21	R=2.45-4.43 A=3.36	R=1.39-2.31 A=1.70	R=1.43-1.82 A=1.65	R=.029-0.042 A=0.033	SI = 20.0 YI = 167 R^2 = 0.69 n=16	R=0.04-2.98 A=1.51 n=11
GS 2 n=15	R=1.82-2.63 A=2.32	R=1.36-1.73 A=1.36	R=1.34-1.49 A=1.41	R=0.012-0.022 A=0.018	SI = 40.3 YI = 79.4 R^2 = 0.94 n=9	No Measurements
GS 3 n=39	R=2.15-3.89 A=2.61	R=1.51-2.80 A=1.82	R=1.21-1.47 A=1.35	R=0.010-0.022 A=0.019	SI = 38.9 YI = 87.3 R^2 = 0.84 n=35	R=0.03-0.05 A=0.04 n=1
GS 4 n=15	R=2.24-5.54 A=3.47	R=1.62-3.12 A=2.37	R=1.03-1.44 A=1.29	R=0.013-0.109 A=0.035	SI = 25.1 YI = 156 R^2 = 0.62 n=12	R=0.04-0.86 A=0.11 n=2
GS 5 n=38	R=2.15-5.43 A=3.25	R=1.34-3.13 A=2.25	R=1.10-1.78 A=1.29	R=0.011-0.060 A=0.019 n=38	SI = 36.8 YI = 113 R^2 = 0.83 n=33	R=0.03-0.45 A=0.07 n=4
GS 6 n=7	R=1.90-3.96 A=8.85	R=1.22-2.19 A=1.78	R=1.27-1.77 A=1.47	R=0.017-0.021 A=0.020 n=7	SI = 51.9 YI = 2.70 R^2 = 0.86 n=8	No Measurements
GS 7 n=18	R=1.88-5.62 A=2.88	R=1.23-2.09 A=1.56	R=1.18-1.96 A=1.50	R=0.020-0.053 A=0.030 n=18	SI = 19.5 YI = 171 R^2 = 0.94 n=16	R=0.06-1.50 A=0.66 n=3
GS 8 n=21	R=2.76-8.26 A=4.58	R=1.73-3.39 A=2.41	R=1.27-1.97 A=1.46	R=0.014-0.041 A=0.024 N=21	SI = 21.0 YI = 152 R^2 = 0.80 n=26	R=0.03-0.05 A=0.04 n=3
GS 9 n=7	R=5.73-10.47 A=8.03	R=2.16-3.28 A=2.66	R=1.81-2.55 A=2.05	R=0.024-0.191 A=0.103 n=7	SI = 14.6 YI = -4.85 R^2 = 0.88 n=5	R=0.03-5.76 A=1.17 n=6
GS 10 n=4	R=6.41-6.73 A=6.60	R=3.08-3.20 A=3.15	R=1.52-1.57 A=1.54	R=0.018-0.019 A=0.018	SI = 33.4 YI = 62.2 R^2 = 0.42 n=4	R=0.50-2.82 A=1.49 n=4
GS 11 n=14	R=3.92-8.12 A=3.92	R=1.66-2.83 A=2.36	R=1.12-2.12 A=1.38	R=0.013-1.440 A=0.218 n=14	No Regression Possible	R=0.03-7.02 A=0.37 n=3
GS 12 n=40	R=1.73-4.74 A=2.55	R=1.21-2.29 A=1.61	R=1.14-1.79 A=1.39	R=0.010-0.171 A=0.027	SI = 20.2 YI = 193 R^2 = 0.75 n=38	R=0.02-5.73 A=0.56 n=27
GS 13 n=10	R=1.98-3.68 A=2.50	R=1.35-1.74 A=1.47	R=1.32-1.74 A=1.50	R=0.021-0.035 A=0.026 n=9	SI = 20.8 YI = 175 R^2 = 0.91 n=10	R= A=
GS 14 n=2	R=0.84-1.02 A=0.93	R=0.71-0.75 A=0.75	R=1.19-1.20 A=1.20		No Regression Possible	R= A=
GS 15 n=2	R=2.24-2.77 A=2.50	R=1.98-2.26 A=2.12	R=0.95-1.17 A=1.06		No Regression Possible	R= A=

Group	REE Slope (La/Yb) _{PM}	Light REE Slope (La/Sm) _{PM}	Heavy REE Slope (Gd/Yb) _{PM}	Ti/V Averages	Regression of Ti/V	Magnetic Susceptibility
GS 16 n=3	R=1.28-3.08 A=2.00	R=1.15-2.77 A=1.74	R=0.77-0.98 A=0.91		No Regression Possible	R= A=
GS 17 n=2	R= A=	R=4.12-4.65 A=4.38	R=2.31-2.59 A=2.45		No Regression Possible	R= A=

Table 2.5: Average mineralogy of each GS unit within the study area. Gp=Group; Pg=plagioclase; Px=Pyroxene; Ol=olivine; NO=Not Observed

Gp	Pg	Px	Ol	Oxides	Biotite	Local Dyke Trends	Textures
GS 1	50-60%	25-50%	NO	3-8% 1-2mm	Trace	NW to WNW	Relatively fresh crystallography; Skeletal growths of magnetite and ilmenite
GS 4	30-50% 1-3mm	50-70% 1-5mm	NO	Trace	Trace	NA	Some samples have prismatic amphibole overgrowing pyroxene.
GS 5	10-30% 1-15mm	30-90% 1-4mm	NO	Trace	Trace	NA	Porphyritic to fine grained rocks. Bladed plagioclase forms porphyritic variety.
GS 6	20-30% 0.5-1mm	70-80% 0.5-1mm	NO	Trace	Trace	WNW	Eu-Sh; Minor Ser of Plag; Oxides are blebby and interstitial to plag and px.
GS 7	30-50% 1-3mm	50-70% 1-3mm	NO	Trace	Trace	WNW	Equigranular, massive.
GS 8	30-50% 1-3mm	50-70% 1-3mm	NO	Trace	Trace	WNW to NW	Equigranular, massive.
GS 9	20-40% 0.5- 1.5mm	60-80% 0.5-1mm	NO	<1% <0.5mm	Trace	NW	Fresh with only minor limonite and iron oxide developing around ol; qtz crystals have been stressed post crystallization; rare blade like iron oxides, normally interstitial to plag and px
GS 10	30-50% <1mm	40-50% 1-3mm	1-2% 0.5- 1mm	1-2% 1-2mm	Trace <0.5mm	NW	Bladed plag crystals that show warping; ol and px are breaking down into iron oxides possibly limonite
GS 11	60-80% 1-3mm	20-40% 1-2mm	NO	Trace	Trace	NW	Plag almost completely replaced by ser; bt is replacing px along the edges; qtz interstitial to px and plag <0.5 mm; post crystallization stress caused fanning extinction of qtz crystals.
GS 12	10-30%	70-90%	NO	Trace	Trace	NW to WNW	Blocky oxides, interstitial to plag and px

**Chapter 3: Phosphorous and Potassium Metasomatic
Enrichment in the Mantle Source of the ca. 1450-1425 Ma
Michael-Shabogamo Gabbro of Eastern Laurentia.**

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3.2 RECOMMENDED CITATION

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3.3 ABSTRACT

A ca. 1450 Ma, east-west oriented suite of Proterozoic mafic intrusions in eastern Canada located between Labrador City and coastal Labrador near Rigolet, have been divided into two groups: the Shabogamo Gabbro that outcrops west of Churchill Falls and the Michael Gabbro that outcrops east of Churchill Falls. These gabbros are subalkaline basalts to basaltic-andesites that are plate-margin tholeiites enriched in P_2O_5 and K_2O . In this study the Michael-Shabogamo Gabbro (MSG) is shown to represent a single event with geochemically distinct groups with ages of 1450-1425 Ma based on new U-Pb ID-TIMS baddeleyite ages of 1449 ± 3 Ma, 1437 ± 4 Ma and 1435 ± 10 Ma, along with previously published ages.

Each group is defined by a distinct geochemistry and is characterized by $[P_2O_5 \cdot 1000]/Zr$ (P/Zr) ratios within the MSG: 1) the high P/Zr group - ca. 1425-1435 Ma; 2) intermediate-amphibolite P/Zr group; and 3) the low P/Zr group with sub pulses at 1435 Ma and 1450 Ma. The positive slope of the $[P_2O_5 \cdot 1000]$ vs. Zr data arrays for each group indicates that melting of apatite was pivotal during the generation of the MSG magmas and their secular changes in geochemistry. K_2O is also enriched relative to EMORB in the MSG and is correlated with P_2O_5 , Ba and Rb.

Enrichment of P_2O_5 and K_2O in the MSG is argued to be due to melting of a metasomatized subcontinental lithospheric mantle (M-SCLM) source interpreted to be derived from subduction of a late Paleo- to early Mesoproterozoic phosphate-rich sediment, possibly the Menihek shale during the

closing of the basin that existed between the Molson Lake and Lac Joseph terranes at some time after ca. 1650 Ma. A slab window facilitated melting at ca. 1450-1425 Ma as the terminal end of a flat-subducting slab was dragged underneath the craton by slab-pull.

Mafic intrusions of the younger ca. 1290-1280 Ma Nain-HP and LP intrusions show geochemical characteristics similar to the MSG. The poorly dated ca. 1100 Ma Aillik intrusions show comparable enrichment of P/Zr ratios relative to EMORB. Thus, the high P/Zr ratios indicate that a metasomatized P₂O₅-rich lithospheric mantle persisted beneath Eastern Laurentia for at least ca. 350 Ma from ca. 1450 Ma to ca. 1100 Ma and was tapped by multiple mantle melting events.

3.4 INTRODUCTION

The Michael-Shabogamo Gabbro (MSG) is one of a number of prominent Proterozoic mafic, magmatic suites in eastern Laurentia, that range in age from ca. 1650 Ma through ca. 1100 Ma. They include the ca. 1650 Ma Ossokmanuan Mountain Intrusive Suite, 1290 Ma Nain-HP and 1280 Ma Nain-LP dykes, 1275 Ma Harp dykes, 1250 Ma Mealy dykes, and 1250 Ma and 1224 Ma Seal Lake Group sills and volcanic rocks (Gower *et al.*, 1990, Buchan & Ernst, 2004; Details in Table 3.1). The mafic suites occur as dykes and sills except for the Seal Lake Group, which also includes lava flows. Most of the suites are subalkaline, tholeiitic transitional to alkaline, and petrogenetically classified as within-plate basalts (Gower *et al.*, 1990).

The MSG was originally mapped as the Michael Gabbro east of Churchill Falls to coastal Labrador near Rigolet and as the Shabogamo Gabbro west of Churchill Falls to Labrador City (Figure 3.1a; Fahrig & Larochelle, 1972, Fahrig *et al.*, 1974, Fahrig & Loveridge, 1981, Gower, 1986, Gower *et al.*, 1986, Fahrig, 1987, Gower & Erdmer, 1988, Gower *et al.*, 1990, Gower & Krogh, 2002). The Michael Gabbro intrudes the Groswater Bay terrane as parallel-sided to boudinaged bodies and span an area of approximately 350 km by 50 km (Gower & Owen, 1984). The Shabogamo Gabbro extends approximately 350 km by 50 km on an east-northeast orientation and then south-southwest from Labrador City for approximately 50 km into the province of Quebec. The Shabogamo Gabbro predominately intrudes the Gagnon, Molson Lake and Churchill Falls terranes (Figure 3.1; James, 1994a). Based on sparse geochronological data (Table 3.1) and matching geochemistry and petrography, Gower *et al.* (1990) suggested that the Shabogamo Gabbro and Michael Gabbro be combined into the MSG event, an interpretation also adopted in the compilation by Ernst and Buchan (2001). Based on three new U-Pb baddeleyite ages, augmenting two previous U-Pb ages (Schärer *et al.*, 1986, James, 1994a), and whole rock and trace element geochemical analysis of 181 samples from across the magmatic intrusions we further test Gower's hypothesis of a single MSG magmatic event.

In western Labrador the MSG intrudes volcanic and volcanoclastic rocks of the Blueberry Lake Group and Trans-Labrador Batholith (e.g., James, 1994a) in the Molson Lake and Lac Joseph terranes (Brooks *et al.*, 1981). The Michael Gabbro was intruded into granitoid orthogneiss (Brooks *et al.*, 1981) dominantly

of the Groswater Bay terrane. The MSG intrudes rocks of the Churchill Province deformed during the New Quebec and Torngat Orogens ca. 1800 Ma, and within the Grenville Province have been variably affected by Grenvillian deformation and metamorphism (ca. 1000 Ma; Brooks *et al.*, 1981; C. Gower pers. comm. 2017).

3.5 FIELD OBSERVATIONS AND PETROGRAPHY

Progressive metamorphism up to granulite facies is observed in the Michael-Shabogamo Gabbro as a function of increasing distance to the Grenville front. The mineralogy of the least deformed rocks east of Churchill Falls consists of clinopyroxene, olivine, plagioclase and Fe (Ti) oxides, with accessory apatite, biotite and potassium feldspar (Gower *et al.*, 1990). A similar mineralogy exists within the intrusions west of Churchill Falls. Macroscopic potassium feldspar was not observed in the rocks. However, petrographic analysis indicates that potassium feldspar is present in most samples from less than 0.5 mm to trace amounts to 2 modal %, with the exception of samples that show cumulate textures. The southernmost MSG bodies are more intensely deformed and appear to be folded, most likely due to Grenvillian deformation (Gower *et al.*, 1990). Samples close to or within the Labrador Trough include metamorphic amphibole and biotite replaced pyroxene as the major mafic phases.

Throughout the study area mineral preservation is variable, ranging from complete metamorphic replacement to nearly complete preservation of primary igneous textures, often within the same outcrop. Like the difference between

eastern and western portions in potassium feldspar modal abundance, coronas within the MSG west of Churchill Falls are not as distinct as those to the east. It is possible that subsequent retro-grade metamorphic events have modified the texture and mineralogy of the corona rims in the western area making them less distinct compared to those found east of Churchill Falls. Metamorphic coronas are ubiquitous in nearly all MSG samples. Rocks in the northernmost MSG localities contain narrow double coronas separating olivine from plagioclase, bounded by colourless orthopyroxene with elongation perpendicular to olivine margins (Emslie, 1983). In the southernmost samples olivine is no longer present, and orthopyroxene have grown inward to constitute a complete inner core, commonly surrounded by a green clinopyroxene rim. This core is commonly followed by a rim of sodic-plagioclase followed by a wide rim of coarse garnets (Emslie, 1983). Such coronas are common in all greenschist to amphibolite grade rocks as previously documented (Brooks *et al.*, 1981, Emslie, 1983, James, 1994a) where low-grade retrogression also occurs (James, 1994a). Coronas are not as common in samples located near the banded iron formations within the Labrador Trough. Here, most of the MSG is metamorphosed to amphibolites.

I found that igneous layering is common in the MSG west of Churchill Falls, with layering in approximately 30% of outcrops, unlike statements in previous reports (Brown, 1981). Similar layering has been recognized east of Churchill Falls (C. Gower pers. comm., 2017) Igneous layering is due either to alignment of plagioclase laths or, more commonly, to grain size variation between individual layers of the rock forming minerals. The layering can be distinct to indistinct,

appear graded, or form parallel to undulating units (Figure 3.2 a-d). The layering is not observed in the amphibolites, however metamorphic banding is observed.

In outcrop that displays primary igneous textures it is not possible to distinguish between a unit of MSG or ca. 1650 Ma Ossokmanuan Mountain Intrusive Suite (James, 1994; C. Rogers unpublished data). However, geochemically both suites display distinct REE patterns normalized to primitive mantle (James, 1994; C. Rogers unpublished data).

3.6 METHODOLOGY AND ANALYTICAL PROCEDURES

3.6.1 Analytical Protocol for U-Pb ID-TIMS Geochronology

Separation of baddeleyite for dating was performed using the water-based separation technique of Söderlund and Johansson (2002). Each sample yielded approximately 40 dark brown baddeleyite grains of good quality without any trace alteration (i.e. frosty zircon alteration rims), which would have complicated the ID-TIMS dating (Söderlund et al. 2013). The best quality baddeleyite grains were transferred to Teflon® dissolution capsules and rinsed repeatedly in ultrapure 7M HNO₃ and water to decrease the Pb blank. An ultrapure HF-HNO₃ mixture was then added to the dissolution capsules together with a ²⁰⁵Pb-²³³⁻²³⁶U tracer solution. Capsules were then placed in an oven at 190°C for 3 days until the grains were completely dissolved. After dissolution, the samples were dried down on a hotplate and re-dissolved in ultrapure 6 M HCl with the addition of ultrapure 0.25 M H₃PO₄ before being dried down on the hot plate. The samples were then dissolved in 2 µL of silica gel and loaded on outgassed Re filaments.

The U and Pb isotopic compositions were measured at the Department of Geosciences at the Swedish Museum of Natural History in Stockholm using a Thermo Finnigan Triton Mass Spectrometer equipped with Faraday Cups and a Secondary Electron Multiplier (SEM). Pb isotope analyses were measured in dynamic (peak-jumping) mode using the secondary electron multiplier. After completion of the ²⁰⁴Pb, ²⁰⁵Pb, ²⁰⁶Pb and ²⁰⁷Pb and ²⁰⁸Pb isotopic measurements (typically in the 1220-1240°C filament temperature range) for between 50 and 100 cycles, the ²³³U, ²³⁶U and ²³⁸U isotopic measurements were made in

dynamic mode at filament temperatures greater than 1350°C. Procedural blanks were measured at 0.6 pg Pb and 0.06 pg U at the time these analyses were run. Mass fractionation is 0.1% per mass unit for Pb, determined by replicate analyses of NBS standards SRM 981 and SRM 983. U fractionation was determined from the deviation between the measured $^{233}\text{U}/^{236}\text{U}$ isotopic ratio of the sample and the spike ratio. Initial Pb isotopic compositions were taken from the model common Pb evolution curve (Stacey and Kramers, 1975). The listed uncertainties in Pb/U ratios were calculated by propagating the within-run error for measured isotopic ratios, and the uncertainties in fractionation (± 0.04 for Pb, absolute uncertainties), Pb and U blank concentration ($\pm 50\%$), and Pb blank composition (2% for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.2% for $^{207}\text{Pb}/^{204}\text{Pb}$; Table 3.2).

3.6.2 Analytical Methods for Geochemistry

Seventy-six samples were collected in the field for geochemistry and an additional 102 previously processed powders were obtained from the Newfoundland and Labrador Geological Survey, Geological Survey of Canada and the Iron Ore Company (Rio Tinto, Iron Ore Group). These geochemical analyses cover the geographical area between coastal Labrador near Rigolet to 50 km southwest of Labrador City (Figure 3.1a-b).

The sample suite of the present study covers the Michael and Shabogamo Gabbro, as well as the older and intermixed ca. 1647 Ma Ossokmanuan Mountain Intrusive Suite (which is the focus of a companion paper, Rogers et al., in prep.).

Samples were collected from rock outcrop and weathered portions were removed in the field. Maps of dyke and sill exposures obtained from the Newfoundland and Labrador provincial government were compiled in an ArcGIS environment (Figure 3.1a-b)(Wardle, 1981, Wardle, 1982a, Wardle, 1982b, Wardle, 1984a, Wardle, 1984b, Rivers, 1985a, Rivers, 1985c, Rivers, 1985b, Rivers & Massey, 1985, Wardle *et al.*, 1985, James, 1991, James, 1993, Wardle, 1993, James, 1994b, James, 1994c, James, 1997, Gower, 2010f, Gower, 2010d, Gower, 2010g, Gower, 2010e, Gower, 2010a, Gower, 2010b, Gower, 2010c, Gower, 2010h, Gower & Erdmer, 2010).

In the laboratory, samples were cut into multiple 1 cm thick slabs and any remaining weathering surface removed. A single representative slab was selected and flat surfaces were polished with 120-grit carborundum powder to remove any metal contamination introduced during the cutting process. Some of the slab material was repeatedly crushed in a Chipmunk jaw crusher and sieved, until all crushed material was less than 2 mm before being milled to less than 200 mesh in an agate ring mill. A pre-contamination aliquot was processed prior to the crushing and milling stages. Tools and working surfaces of the crusher and mill were cleaned with ethyl alcohol between each sample. These steps were used to reduce risk of cross-contamination of trace elements and isotopes between samples.

Pre-powdered samples obtained from the Newfoundland and Labrador Geological Survey, Geological Survey of Canada, and the Iron Ore Company were processed in a steel ring mill. To avoid any potential contamination issues of

Ni or Cr neither element from these samples was used in geochemical plots. The processing procedure for those samples from the Newfoundland and Labrador Geological Survey is described in Applied Research Laboratories, Ultrasonic Nebulization document II 170796 (Finch, 1998).

Approximately 20g of <200 mesh powder from each sample were then sent to ALS Laboratories (North Vancouver Canada: <http://www.alsglobal.com/>) for major, minor and trace element analysis. Sample powders were sintered with lithium metaborate flux, before being analyzed for 55 major oxide and minor to trace elements via ICP-AES and ICP-MS. The sample analyses were normalized to 100% dry weight before plotting. The precision of repeat analyses of a blind internal standard and blind duplicate samples and average of two BVHO-2 samples with USGS certified values are listed in Appendix 2.1.

Nd isotopic analyses were performed on the crushed powders at Carleton University's Isotope Geochemistry and Geochronology Research Centre (IGGRC). According to standard procedure between 100 and 300 mg of sample powder are weighed into a screw-cap Teflon vial, to which a mixed ^{148}Nd - ^{149}Sm spike is added. The powder-spike mixture is dissolved in HNO_3 -HF, then further attacked with HNO_3 and HCl until no residue is visible. Sr and the bulk REE are separated sequentially by cation chromatography (Dowex 50-X8) using 2.5N HCl and 6N HCl , respectively. The REE-bearing residue is dissolved in 0.26N HCl and loaded into an Eichrom chromatographic column containing Teflon powder coated with HDEHP [di(2-ethylhexyl) orthophosphoric acid, Richard et al., 1976]. Nd is eluted using 0.26N HCl , followed by Sm in 0.5N HCl .

Sr residues is dissolved in 0.3N H₃PO₄ and loaded onto a single Ta filament and run at 1350-1400°C in a 9-cup Thermo-Finnigan Triton T1 thermal ionization mass spectrometer (TIMS). Sr isotope ratios are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.11940$. Total procedural blanks are < 200 pg Sr. Isotope ratios are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.1194$. Forty-seven runs of the NBS987 Sr-standard average $^{86}\text{Sr}/^{88}\text{Sr} = 0.710251 \pm 0.000023$ (2 σ ; Feb 2012 - July 2014), the certified value for NBS987 is 0.71034. All analytical uncertainties are 2-sigma standard deviations of the mean of 100 scans.

Nd and Sm residues are loaded with 0.3N H₃PO₄ on one side of a Re double filament assembly, and run at temperatures of 1750-1800°C in the Triton mass spectrometer. Isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. Total procedural blanks for Nd are < 100 picograms. $^{147}\text{Sm}/^{144}\text{Nd}$ ratios are reproducible to 0.5%. Analyses of the USGS standard BCR-1 yield Nd = 29.02 ppm, Sm = 6.68 ppm, and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512668 \pm 20$ (n=4). Isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. Twenty-two runs of the in-house metal Nd-standard average $^{143}\text{Nd}/^{144}\text{Nd} = 0.511831 \pm 0.000011$ (2 σ ; May 2014 - August 2016), equivalent to a La Jolla standard value of 0.511861 based on comparative runs. Epsilon values at time T are calculated using the following relation:

$$\epsilon_{\text{Nd}}^T = \left(\left[\frac{^{143}\text{Nd}}{^{144}\text{Nd}_{\text{sample}} T} / \frac{^{143}\text{Nd}}{^{144}\text{Nd}_{\text{CHUR}} T} \right] - 1 \right) * 10000$$

where CHUR is the Chondrite Uniform Reservoir and T is generally the time the rock was formed. Depleted mantle model ages are calculated assuming a modern upper mantle with $^{147}\text{Sm}/^{144}\text{Nd} = 0.214$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.51315$.

The 2σ uncertainty in the initial ϵNd values is ± 0.5 epsilon units, based on the duplicate analysis of samples. Initial ϵNd_T values for volcanic rocks are calculated at 1550 Ma, or 1590 Ma. The isotopic data and corrected ages are listed in Table 4.3a.

3.7 RESULTS

3.7.1 Description of U-Pb Dating Samples

13-CR-08-03b and CG83-006 are coarse-grained gabbros from the western and eastern parts of the study area, respectively (Figure 3.1a). Sample FA71-04 is also a coarse grained gabbro from the northeastern part of the study area.

3.7.2 Geochronology Results

Three baddeleyite fractions of sample FA71-04 plot normally discordant ($\leq 1.5\%$) whereas one fraction plots slightly above the Concordia curve (Figure 3.3a). Regression yields upper intercept of 1449 ± 3 Ma (MSWD = 2.8). The 1449 ± 3 Ma intercept age is interpreted to date crystallization of this sample.

Three of the four baddeleyite fractions of sample CG83-006 plot concordantly, yielding a $^{207}\text{Pb}/^{206}\text{Pb}$ age of 1437 ± 4 Ma (MSWD = 0.32; Figure 3.3b). One fraction is discordant by ca. 4 %. Regression comprising all four analyses yields an upper intercept of 1435 ± 8 Ma (MSWD = 0.30). We favor the $^{207}\text{Pb}/^{206}\text{Pb}$ age as the best estimate for this sample.

For sample 13-CR-08-03b, three baddeleyite fractions plot almost concordantly and one fraction is discordant by 3.5% (Figure 3.3c). The upper intercept is 1435 ± 10 Ma and is interpreted to date the crystallization of this sample.

The U/Th ratio was estimated for the majority of fractions (calculated from the recorded $^{206}\text{Pb}/^{208}\text{Pb}$ ratio). These ratios are very high for FA71-04 and CG83-006 (112-320), and high for 13-CR-08-03b (21-60).

3.7.3 Geochemistry of the MSG

The data for the 163 samples are outlined in Figures 3.4-3.29. The MSG is a subalkaline basalt to basaltic andesite (Figure 3.4) as shown in the trace element diagram Zr/Ti vs. Nb/Y (Pearce, 1996). However, some of these samples plot within the trachybasalt to basalt fields in a total-alkalis diagram (TAS; Figure 3.5; Le Bas *et al.*, 1986), indicating that other geological processes, such as alteration, may have affected the alkali elements, particularly K_2O . In some classification diagrams (i.e. Figure 3.6) the rocks show characteristics that trend from plate margin basalts through to within-plate basalts. In other classification diagrams they show distinct subduction-related plate margin affinity (Figure 3.7 and Figure 3.8; (Condie, 2005)) or within-plate affinity (Figure 3.9). Using the diagram FeO_7/MgO vs. SiO_2 by Miyashiro (1974) shows that the MSG are tholeiitic and not calc-alkaline (Figure 3.9).

In a MORB-OIB array diagram (Figure 3.10; the most-parental samples outlined in red), the MSG samples plot above the EMORB field indicating that these were produced from an enriched mantle source and are affected by either

metasomatized lithospheric mantle or crustal contamination during their evolution (Pearce (2008). In a Ti/1000 vs. V diagram (Figure 3.11), the MSG samples show two trends. One trend can be related to a single geochemical group, whereas the other two geochemical groups form the second trend with the flatter trend representing more alkalic-like magmas and the upper trend representing more tholeiitic-like magmas. Different trends in a TiO_2 vs. V diagram are interpreted by Shervais (1982) to indicate changing magmatic oxygen fugacity and could represent either changing conditions within the same magma chamber or different magma chambers for the sample suites belonging to each trend.

Several of the major and trace elements show anomalous patterns. In particular P_2O_5 and K_2O are correlated (Figure 3.12) and are enriched compared to typical EMORB values (Sun & McDonough, 1989), with values up to 1.78 wt.% and 4.08 wt.%, respectively. Middle rare-earth elements (Gd, Nd, and Sm) and P_2O_5 follow similar trends when plotted against incompatible elements like Zr, Yb and Y. Rb, Ba and K_2O follow P_2O_5 and incompatible elements. Additionally, the MSG show groups of high and low TiO_2 magmas, particularly when plotted against Mg# (Figure 3.13).

The MSG have Mg#'s that range from 30-65, representing somewhat evolved magmas, whereas a primary mantle magma has Mg#'s greater than 65. In order to identify mantle source characteristics, samples that represent the parental or most-primitive (least-evolved) melts of the MSG needs to be identified. To do so the geochemical suite was filtered by selecting rocks that have a SiO_2 <52 wt.% and MgO from 4 to 9 wt.% to represent mantle melts that experienced

minimal assimilation or fractional crystallization (AFC; labeled as parental in Appendix 3.1). Any sample having a europium anomaly (Eu^*) value less than 0.9 or greater than 1.1 is considered to have fractionated or accumulated plagioclase, respectively, and is removed from further consideration.

In addition, we utilize an unpublished ternary diagram with $\text{Co-Sc-Al}_2\text{O}_3^*4$ at the apices (J.A. Pearce, written com. 2016, Figure 3.14), in which any sample that falls outside the main sample cluster is an indicator of crystal accumulation or crystal fractionation that draws the magma composition away from the main cluster. Specifically, trends away from Co indicate excess olivine fractionation, trends away from Sc indicate excess pyroxene fractionation, and trends away from Al_2O_3 indicate excess plagioclase fractionation. Trends towards the apices indicate corresponding crystal accumulation in the melt. As noted in Figure 3.14, most of the data plot as a central group (outlined in red) and the outliers were removed from further consideration.

As a result of the filtering, 39 samples were identified as reflecting most-primitive magma compositions. Multi-element plots for the most-primitive magmas of the MSG shows positive anomalies for P, K and Ti, negative anomalies for Nb-Ta, Sr, and some samples exhibit negative anomalies for P and Ti (Figure 3.15e-h). Although the most-evolved samples are removed and a main cluster of most-primitive samples has been identified, it should be noted that these most-primitive samples have still undergone some olivine and plagioclase fractionation with respect to melts in equilibrium with a mantle source (Figure 3.14 and 3.15 outlined in red).

The most-primitive magmas show a strong enrichment of P_2O_5 and K_2O relative to EMORB, and split into groups of high and low TiO_2 magmas (Figure 3.13). Fenner diagrams (Mg# vs. major element) provide basic geochemical trends and are located in Appendix 3.2. Any trend in the Fenner diagram for a particular geochemical group would represent a liquid line of descent. When plotted against incompatible elements (e.g., Zr, Yb and Y), the middle rare-earth elements (e.g., Nd, Sm and Gd) follow trends similar to P_2O_5 vs. Zr. When plotted against incompatible elements large-ion lithophile elements like Ba and Rb follow trends similar to K_2O vs. Zr.

3.8 DISCUSSION

The discussion will address splitting the MSG into high, intermediate-amphibolite, and low P/Zr geochemical groups, how the P_2O_5 and K_2O was stored in the mantle and why there is a geochemical difference between the 3 P/Zr groups. I will also provide a tectonic model that can explain the aforementioned topics.

3.8.1 Division into P/Zr groups

Plotting P_2O_5 vs. Zr (Figure 3.17) produces 3 trends, which are used to separate the MSG into 3 geochemical groups: the highest P/Zr values (>2.77) the intermediate-amphibolite P/Zr groups (between 2.77 and 2.10) and the other group shows the lowest P/Zr values (<2.10). Additionally, there is an inverse relationship between K_2O and P_2O_5 where a higher K_2O/P_2O_5 ratio is found in the

low P/Zr group and a lower K_2O/P_2O_5 ratio in the high P/Zr group. Below, we examine the geochemical and chronological relationships, the P_2O_5 and K_2O enrichment, the storage of P_2O_5 and K_2O in the mantle, the melting conditions, and propose a tectonic model to explain these observations.

3.8.2 Assessing Geochemical Uncertainty

Because the P_2O_5 and K_2O values are high (1.78 and 4.08 wt.%, respectively) relative to most basaltic magmas (0.14 and 0.25 wt.%, respectively for EMORB) it is prudent to determine whether the values could be anomalously high due to laboratory analytical error or metasomatism. To assess the precision of the laboratory where the samples were analyzed, an internal blind standard was submitted with each batch of major and trace element chemistry. For both P_2O_5 and K_2O the standard deviation for the internal blind standard is ± 0.01 wt.% demonstrating good precision for the analytical laboratory (the multiple analyses of the blind standard are reported in Appendix 2.1). To further scrutinize these data, select samples were analyzed at two geochemical laboratories, the Newfoundland and Labrador Geological Survey in-house laboratory and ALS Laboratories, North Vancouver, Canada. With one exception, the analytical results were within ± 0.05 wt.%, which is a typical 2-sigma analytical precision for P_2O_5 and K_2O analyses by ICP-AES or X-ray fluorescence spectroscopy (See Table 3.4 for selected analysis). The internal blind standard analyses are within analytical error of the accepted value and two analysis of BVHO-2 are within analytical error of the USGS certified values. In addition, samples were collected

in different years by different individuals (1979, 1980, 1982, 1983, 1984 by C. Gower; 1969, 1970 by W. Fahrig; 2005 by A. Kerr; and 2013 by C. Rogers) with no sampling bias detected. Each subset (collected by different individuals) includes representative samples that plot on the two geochemical trends of the MSG. If a laboratory or sampling bias were present, then it is likely some of the geochemical trends would be shifted based on the analytical laboratory or the individual collecting the samples, but this is not observed in the geochemical data.

Plots of large ion lithophile elements against a less mobile incompatible elements (i.e. Ba, K₂O vs. Zr, Yb) show that metamorphism or other secondary geological processes have not affected the more mobile elements despite some of these samples reaching granulite facies (Figure 3.16). If the MSG was affected by metamorphism then it is expected that Figure 3.16 would show more scatter in the data. This observation applies but with one caveat; a subset of the low P/Zr group, herein called the intermediate-amphibolite P/Zr group, displays a slightly different trend in the [P₂O₅*1000] vs. Zr diagram, with a y-intercept at 0.13 instead of near the origin as the other two groups (Figure 3.17). Because P₂O₅ and Zr are incompatible elements it is expected in any melt system that both elements enter the melt at a consistent rate relative to each other. Therefore, any primary trend-line should project back near the origin in any [P₂O₅*1000] vs. Zr plot. Ten out of 16 samples from this anomalous group were collected from the Labrador Trough and are in close proximity to the banded iron formation deposits; these 10 samples are amphibolites ± garnet and no longer have primary igneous textures and are referred to as the amphibolite P/Zr group. The

6 samples outside the Labrador Trough do produce a line of best fit through the origin in a $P_2O_5 \cdot 1000$ vs. Zr diagram and are referred to as the intermediate group (Figure 3.17). The intermediate and amphibolite P/Zr groups geochemically overlap and are collectively called the intermediate-amphibolite P/Zr group. Most REEs (Figure 3.15) and high field strength elements like TiO_2 and V in the intermediate-amphibolite P/Zr group do not appear to be affected (i.e. Figure 3.11) by metamorphism and plot closer to the high P/Zr group. In other diagrams the intermediate-amphibolite P/Zr group plots between the high and low P/Zr groups (Figure 3.17). It is possible that the more mobile elements (i.e. P_2O_5 , K_2O , Pb) in the intermediate-amphibolite P/Zr group samples from the Labrador Trough may be perturbed during subsequent metamorphic or alteration events. Although the samples from the Labrador Trough fall within the criteria for selecting most-primitive samples, it is possible that these 10 samples from amphibolite P/Zr group in the Labrador Trough have not remained a closed system. It is possible the attributes of the metamorphic fluids permeating the banded-iron formations were modified to mobilize P_2O_5 and K_2O easier than the REE. It is also possible that these amphibolite P/Zr group samples are not part of the MSG and belong to another magmatic pulse. However, the geochemical REE similarity of the amphibolite P/Zr group with the low P/Zr groups suggests otherwise. The amphibolite samples are identified with a separate symbol on geochemical diagrams.

3.8.3 Chronology of the P/Zr Suites

Identification of the 3 P/Zr groups for the entire geochemical data set was influential in selecting the samples for U-Pb geochronology. The high P/Zr group was already dated, and the focus was on the low P/Zr group and intermediate-amphibolite P/Zr group. Each new geochronology sample was selected from near the mid-length position of each P/Zr trend for intermediate-amphibolite and low P/Zr groups. These samples are from positions where the geochemical trends are distinctive, and ensured selection of a sample that is part of the correct group. Samples from the upper end of the trends that are more differentiated and possibly crustally contaminated (i.e. AFC processes) were also avoided.

Geochronological results show that the high P/Zr group has an age of 1426 ± 6 Ma by Schärer *et al.* (1986) and the geochemically similar intermediate P/Zr group has an age of 1437 ± 4 Ma (Figure 3.3c). The low P/Zr group has 3 U-Pb baddeleyite age determinations of 1435 ± 8 Ma for sample CG83-006 and 1449 ± 3 Ma for sample FA71-04 (Figure 3.3a), and a U-Pb zircon age determination of 1452^{+15}_{-13} Ma for DJ-90-2303 (Connelly, 1992). [Note that the sample number for the geochemistry may be mislabeled in Connelly (1992), as DJ-90-2302 and DJ-90-2303 are listed with the same UTM coordinates, and no geochemical data are reported for DJ-90-2303 (C. Saunders, written comm. 2014)].

Connelly and Heaman, (1993) reported another U-Pb zircon age of 1459^{+23}_{-22} , for a Shabogamo Gabbro in the Molson Lake terrane. However, no

geochemical data could be obtained for this sample. Additionally Connelly and Heaman combined the 1459^{+23}_{-22} Ma age with the Schärer *et al.* (1986) 1426 ± 6 Ma age to define a concordia line with an age 1431 ± 7 Ma for the MSG crystallization age. The mixed concordia line age may reflect the average age of the MSG with distinct geochemical pulses at ca. 1450-1435 Ma (low P/Zr group) and ca. 1435-1425 Ma (high P/Zr group) (Table 3.5).

It is possible the low P/Zr group has two pulses of magma: one at ca. 1450 and a younger pulse at ca. 1435 Ma, however it is not possible to geochemically distinguish either pulse. The low, intermediate-amphibolite, and high P/Zr groups have ages that are almost within error (Table 3.5) but are geochemically distinct on the $P_2O_5 \cdot 1000$ vs. Zr diagram (Figure 3.17). Therefore the ages suggest that the low P/Zr group has two pulses, one at ca. 1450 Ma and a second at ca. 1435 Ma. The second pulse overlaps in time with the 1435-1425 Ma pulse of the high and intermediate-amphibolite P/Zr groups but are geochemically distinct from the high P/Zr group.

3.8.4 Sources of MSG Magmas

With the exception of isotope plots, the remainder of the discussion continues using only the most-primitive MSG with chemistry best representing source characteristics ($SiO_2 < 52\%$ and MgO 4 to 9 wt.%). There are only minor differences in rare earth-element (REE) geochemistry between the high, intermediate-amphibolite and low P/Zr groups (Figure 3.15). Especially notable is the similarity of intermediate-amphibolite P/Zr group samples collected inside

(amphibolite rocks) and outside (primary igneous textures preserved) of the Labrador Trough (Figure 3.15B and E). The strong negative Sr anomaly (Figure 3.15) suggests that, even in the most-primitive magmas, there has been some plagioclase fractionation.

The ratio $(\text{La}/\text{Sm})_{\text{PM}}$ can be used as a proxy to represent either assimilation of lithosphere (mantle or crust) or the degree of partial melting, where PM represents the ratio normalized to primitive mantle (Sun and McDonough, 1989). Either a higher crustal contribution or a lower degree of partial melting increases the concentration of La more than Sm in a melt. At low degrees of partial melt La is released from crystal structures preferentially over Sm. As the degree of partial melting increases the difference in incompatibility between La and Sm is less important, causing the La/Sm ratio to decrease. Varying degrees of partial melt will show a fanning of the light-REEs in a multi-element plot (Rollinson, 1993). Generally, crustal rocks have a higher ratio of La/Sm than the mantle and any magma produced from melting of the crust will have a high La/Sm ratio compared to mantle melts. In REE plots, samples considered part of the same group will tend to have the same La/Sm slope and REE pattern.

The ratio $(\text{Gd}/\text{Yb})_{\text{PM}}$ can be used as a proxy for depth of melting (Figure 3.19), since garnet retains Yb preferentially over Gd, and ratios over ~2 indicate melting within the garnet stability field of the mantle (e.g., Pearce, 2008, Álvaro *et al.*, 2014). On the basis of light/middle ($\text{La}/\text{Sm}_{\text{PM}}=1.20$ to 4.22) and middle/heavy ($\text{Gd}/\text{Yb}_{\text{PM}}=1.21$ to 2.09) REE slopes it can be inferred that the MSG magmas

experienced minor assimilation of lithosphere or were derived by low degrees of partial melting and that melts were generated primarily within the spinel field of the mantle.

Neodymium isotopes are useful to distinguish between mantle melts (undepleted, depleted, and enriched melts) and crustal melts (upper, middle and lower). The MSG have a limited range of $\epsilon\text{Nd}_{(t)}$ values of -6 to -4 over a large range of Mg numbers (30-75). If crustal contamination were a major influence there should be a larger variation of $\epsilon\text{Nd}_{(t)}$ due to mixing between low, negative $\epsilon\text{Nd}_{(t)}$ values of crustally contaminated melts with the high positive $\epsilon\text{Nd}_{(t)}$ values of the mantle melts. The limited range of $\epsilon\text{Nd}_{(t)}$ values (-6 to -4) with no correlation with SiO_2 or MgO indicates that the mantle source of the MSG was enriched with fluids (e.g., silicate, hydrous) with the isotopic characteristics of old crust (Figure 3.20). Additionally, we can project the values of $\epsilon\text{Nd}_{(t)}$ back to the depleted-mantle model age of ca. 2870-2300 Ma (DePaolo, 1988). Figure 3.21 also supports a mantle enriched with an early Proterozoic sediment signature produced the MSG.

High $\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ isotope values (0.70354 to 0.70615) supports a mantle source that was enriched with an old sediment component, possibly Achaean or early Proterozoic. The $\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ values indicate that the source was either variably enriched in Rb, which would need time to decay to Sr or had high and variable Sr. In general, sediments like the shale rich Menihek Fm. are enriched in the REEs, especially in the light REEs compared to the heavy-REEs. Therefore, higher sediment input produces higher REE values and higher La/Sm when normalized

to chondrites. REE multi-element plots do not indicate a high sediment contribution, as the enrichment of light-REEs is only 11 to 20 when normalized to chondrite. However, if the source was highly enriched in Sr donated from a mineral(s) with a high partition coefficient for Sr then that enriched source also produces a variable $\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ component in the MSG. A potential source for highly enriched Sr is the phosphate-bearing shales of the Menihek Fm. (Bell & Thorpe, 1986, Pufahl *et al.*, 2006). A modern analogue is subcontinental lithospheric mantle-derived melts in the Great Basin, Nevada, that are a mixture of Achaean lithosphere and a highly Sr-enriched, ancient sediment component (Farmer *et al.*, 1989).

3.8.5 Origin of Excess P₂O₅ and K₂O

It is clear from the geochemistry of the high and low P/Zr groups that MSG magmas have had a complex petrogenetic history. It is challenging to produce basaltic magmas from anything other than an ultramafic mantle source, as melts of basaltic crust generally produce higher-silica magmas (e.g., Peacock *et al.*, 1994). P₂O₅ and K₂O values in a typical EMORB are around 0.14 wt.% and 0.25 wt.% (Sun & McDonough, 1989), respectively, whereas the majority of the most-primitive magmas of the MSG have values up to 1.00 wt.% and 2.00 wt.%, respectively. Processes that could enhance the P₂O₅ and K₂O enrichment relative to EMORB seen in the MSG include crustal assimilation (which has been addressed in the previous section), fractionation with or without continuous recharge, and melting of a metasomatized fluid-enriched mantle. Fractionation

would raise all incompatible element concentrations, not just P_2O_5 and K_2O . Additionally it is difficult to fractionate P from K as seen in the MSG samples. Therefore it is improbable that fractionation is process that produced the difference in the low P/Zr and high P/Zr melts.

3.8.5.1 Fractionation With or Without Continuous Recharge

In a magma chamber where there is no or minimal recharge, incompatible REEs can be enriched as the more compatible elements are removed by fractionation. As plagioclase crystallizes, the crystals incorporate Eu^{2+} , and leave P_2O_5 and other REEs, Y, and Zr in the remaining liquid (Figure 3.15e-h), thus giving the cumulate rocks positive Eu anomalies and the residual liquids negative Eu anomalies after cumulate removal (Philpotts & Schnetzler, 1968). The observed five to ten times enrichment of P_2O_5 or K_2O in MSG units compared to typical E-MORB values (Sun & McDonough, 1989) requires more than 80% fractionation of olivine, plagioclase and pyroxene from a parental magma. This fractionation estimate, based on the Rayleigh equation (Shaw, 1970), an average E-MORB source, and assuming perfect incompatibility for P_2O_5 , results in a residual liquid with only 0.70 wt.% P_2O_5 . That much fractionation produces high silica melts and not the mafic magmas that formed the MSG. As P_2O_5 increases, the REEs should increase at the same rate such that the REEs should be enriched relative to EMORB, which is not observed. Finally, significant Eu anomalies are not observed in the most primitive magmas. Therefore, fractional crystallization alone cannot explain the P_2O_5 and K_2O enrichment in the MSG.

3.8.5.2 Metasomatized Fluid-Enriched Mantle

A plausible scenario to explain the enrichment in P_2O_5 and K_2O is subduction of phosphate-bearing sediments beneath Laurentia that added fluids to the subcontinental lithospheric mantle (SCLM), which subsequently melted to produce P and K rich parental basaltic magmas for the MSG. A possible sedimentary source is the ca. 1700 Ma early Proterozoic Menihek formation, which contains phosphatic beds (Bell & Thorpe, 1986, Pufahl *et al.*, 2006). It is thought that these phosphatic beds formed in an organic-rich near-shore environment (Bell & Thorpe, 1986, Pufahl *et al.*, 2006), which makes these sediments an ideal candidate to be subducted, and subsequently enrich the mantle wedge or the SCLM. In addition to phosphate, these sediments have to have a significant felsic rock component to provide the high K_2O component. Fluids being driven off the subducting slab are the source of the P_2O_5 and K_2O enrichment that metasomatized the SCLM.

The timing of mantle metasomatism that produced the MSG is important to link with candidate subduction events. There are two possible timings for the subduction events that may be the source of metasomatism of the mantle source rocks that produced the MSG magmas. The first possibility for a subduction and metasomatic event is when an unnamed oceanic plate was subducted beneath the Lac Joseph terrane. The timing of earliest subduction is constrained by the ca. 1650 Ma Ossokmanuan Mountain Intrusive Suite, which does not show an enrichment of P_2O_5 (0.01-0.55 wt.%) or K_2O (0.16-4.16 wt.%) compared to

EMORB (0.14 and 0.25 wt.%, respectively; Sun & McDonough, 1989, James, 1994a, Rogers, 2016 unpublished data). Therefore, the metasomatic event had to occur after arc magmatism of the ca. 1650 Ma Ossokmanuan Mountain Intrusive Suite ceased. The next possible metasomatic event occurred during subduction in the middle to late Elsonian, before the MSG were emplaced. At this time in the evolution of eastern Laurentia, Gower and Krogh (2002) proposed a flat slab subduction model, which could transport P_2O_5 and K_2O rich sediments into the mantle. The model requires that the subducting oceanic plate was quite young, because a hot and buoyant subducting slab will have a shallow dip into the mantle and may underplate the overriding plate instead of sinking into the mantle. By remaining close to the base of the SCLM, there may not be a mantle wedge per se and wedge melting may not occur. In addition, the subducting slab acts as an insulator between the hot asthenosphere beneath the slab and fluids introduced into the thin mantle wedge and SCLM above the slab, thereby preventing fluid-induced melting of the SCLM or mantle wedge at that time. There are modern examples of metasomatized lithospheric mantle sources for mafic lavas in the Sierra Nevada Mountains margins of Great Basin in the western United (Cousens *et al.*, 2011, Farmer *et al.*, 2013). This study shows that although the Great Basin magmatism is recent, the metasomatism occurred in the Precambrian. The Great Basin analog could be comparable to the MSG, except in this case the melting of the Precambrian metasomatised mantle also took place in the Precambrian.

3.8.5.3 Mantle Storage of P_2O_5 and K_2O

To store the P_2O_5 and K_2O in the mantle a mineral phase for each element is required. Two phosphate minerals that are stable in the mantle are monazite and apatite (Rudnick *et al.*, 1992, Frost, 2006, Konzett *et al.*, 2012). If monazite were contributing P_2O_5 to the melt, then in addition to a correlation between P and the middle rare earth elements, which have a high partition coefficient in both apatite and monazite, there would be a correlation between P and the light REE that have a high partition coefficient in monazite (Stepanov *et al.*, 2012). In order to distinguish between apatite and monazite contributing P_2O_5 to the melt it is necessary to use a geochemical proxy for both minerals. Apatite has a high partition coefficient for P_2O_5 and Nd; therefore Nd is released into the melt by apatite at a rate consistent with P_2O_5 abundances. Monazite has high partition coefficients for La and Th (Stepanov *et al.*, 2012), therefore, Th is released into the melt by monazite at a rate comparable to La. When $(La/Th)_{PM}$ is plotted versus $(P_2O_5/Nd)_{PM}$ (Figure 3.22), a sub-horizontal trend (x-axis parallel) represents melting of an apatite-bearing source and a subvertical trend (y-axis parallel) represents melting of a monazite-bearing source. Figure 3.22 shows that most samples plot on a near horizontal trend indicating that apatite is more likely to be the dominant mineral storing the P_2O_5 in the mantle source for MSG magmas.

In addition to P_2O_5 enrichment in the MSG magmas there is also an enrichment of K_2O relative to typical EMORB values (Sun & McDonough, 1989). During metasomatism K_2O is often enriched with P_2O_5 , and as a result phlogopite

is commonly associated with apatite (Frost, 2006, Konzett *et al.*, 2012 and references therein). As with apatite, Ba has a high partition coefficient in phlogopite and when plotted with K₂O in a binary plot forms a linear trend. Therefore $((K_2O \cdot 10)/Ba)_{PM}$ can be used as a proxy for phlogopite. In the MSG data there is a near horizontal trend of $(La/Sm)_{PM}$ with K₂O (Figure 3.23), indicating that K₂O enrichment (as with P₂O₅ enrichment) did not originate from crustal assimilation, which increases $(La/Sm)_{PM}$ in the contaminated magma, but rather is the result of the melting of phlogopite. Additionally, high phlogopite content could explain the transition from alkaline to sub alkaline rocks in a TAS diagram (Figure 3.5) and not in the corresponding Zr/Ti vs. Nb/Ti diagram (Pearce, 1996; Figure 3.4). If the M-SCLM is enriched in phlogopite and primary melting releases anomalously high concentrations of K₂O then the alkaline to sub-alkaline trend in the TAS diagram is a reflection of high alkali-elements (K₂O) in the source and not a reflection of either low degree partial melts or post-emplacement enrichment during metamorphism or late alteration.

3.8.6 Melting of Metasomatized Lithosphere

The P₂O₅ and K₂O enrichments in the MSG were produced from melting of apatite and phlogopite in a M-SCLM. The low P/Zr group has lower concentrations of P₂O₅ than the intermediate-amphibolite P/Zr group, which has less than the high P/Zr group. Because apatite is normally unstable in the mantle and melts at low degrees of partial melting, it is expected that the low P/Zr group should contain higher concentrations of P₂O₅. Another unexpected observation is

the inverse relationship of higher K_2O/P_2O_5 ratio in the low P/Zr group while there is a lower K_2O/P_2O_5 ratio in the high P/Zr group in the MSG.

The P_2O_5 and K_2O anomalies in the partial melts of lithospheric mantle are a result of any of three processes: 1) different degrees of partial melting leading to different amounts of apatite and phlogopite melting in the metasomatised mantle for each group; 2) distinct sources acquiring different amounts of apatite and phlogopite; and, 3) sensitivity of apatite to melting in the presence of a fluid (released during melting of phlogopite).

3.8.6.1 Anomalies Generated by Different Degrees of Partial Melting?

If the magmas were derived by different degrees of partial melting, then the multi-element plots should show a fan-like pattern in the more incompatible element patterns of REE-multi-element plots (Rollinson, 1993, Pearce, 2008). This relationship is not observed (La to Sm, and Ba to P; Figure 3.15). Instead, the multi element plots show a tight parallel clustering of the data. Additionally, a La/Sm vs. La diagram should distinguish between crystal fractionalization and degree of partial melting (Figure 3.24). The crystallization process creates a near horizontal trend in a La/Sm vs. La binary diagram, since La and Sm are both incompatible in plagioclase, olivine and pyroxene. Lower degrees of partial melting increases both the La/Sm and La concentration in the melt compared to higher degrees of melting. The La/Sm vs. La diagram for the MSG (Figure 3.24) supports minimal changes in degree of partial melting as most of the data plot on a near-horizontal-crystallization trend.

3.8.6.2 Anomalies Generated by Distinct Melting Sources?

The second possibility for generating anomalies in the MSG is melting distinct sources where one source is apatite poor-mica rich and another is apatite rich-mica poor. For this scenario to work the mantle composition (proportions of olivine, pyroxenes) has to be nearly identical for both batches of melt to vary only in the amount of apatite and phlogopite. Otherwise the REE plots would have more variation in their patterns.

3.8.6.3 Anomalies Generated by Apatite Sensitivity

Studies have shown that apatite is stable in peridotite mantle when hydrous phases are present (Watson, 1980, Frost, 2006, Konzett et al., 2012). If the first increments of melt generation in the SCLM included H₂O (micas or other hydrous minerals) or chlorine, then apatite remains stable and will not melt (Watson, 1980). Initial melting includes peridotite mantle and phlogopite or other less stable hydrous minerals, releasing H₂O into the melt phase. Once the mantle has been sufficiently dehydrated, the residual apatite becomes unstable and will melt in the SCLM.

Initial melting of hydrous minerals followed by the destabilization and ultimately the melting of apatite can explain the secular changes in geochemistry of the MSG from low P/Zr to high P/Zr. It is for these reasons that production of P₂O₅ rich magmas belonging to the low P/Zr group was slow at first because of the presence of H₂O released by the melting of hydrous minerals. This

relationship is demonstrated in Figure 3.12 where K_2O vs. P_2O_5 shows that the high P/Zr group has a lower ratio of K_2O/P_2O_5 , and the relationship is reversed for the low P/Zr group. The ratio of K_2O/P_2O_5 is consistently higher in the high P/Zr group compared to low P/Zr group. As the mantle source becomes dehydrated as phlogopite is melted, apatite is no longer stable and melts more readily. The phlogopite-apatite relationship can explain the overlap in age with the high and low P/Zr groups. It can be assumed that melting was heterogeneous and parts of the mantle were depleted in phlogopite faster than others. The area to become dehydrated first also produced melts higher in P_2O_5 sooner than mantle that was still hydrated. Therefore, progressive dehydration beginning with melting of phlogopite and later to melting of apatite in the metasomatized SCLM appears to be the best model for generating the variations in K_2O and P_2O_5 the MSG.

Apatite and phlogopite contain approximately 19 wt. % and 11 wt. % P_2O_5 and K_2O in their respective crystal structures. Assuming that the release of a fluid from the melting of phlogopite stabilized apatite, preventing melting, then partial melts between 5-10% produce similar trace element values as those seen in the low P/Zr group (Table 3.6a). The melting of the residual mantle to approximately 20-25% produces trace element concentrations similar to those observed in the high P/Zr groups (Table 3.6b).

3.8.7 Tectonic Models for Emplacement of the MSG

To generate melting in the mantle there needs to be an increase in temperature, a decrease in pressure, or an introduction of fluids into the locus of melting (e.g., Winter, 2010). As demonstrated above, the geochemistry and Sm-Nd isotopes indicate that the MSG magmas were produced from a M-SCLM.

There are several possibilities to generate melting of the M-SCLM to produce the melts of the MSG. The most plausible models include: 1) subduction with melting of the mantle wedge, 2) introduction of a plume with or without the presence of the subducting slab, 3) decompression melting of thinned lithosphere as a result of rifting, or 4) slab break-off followed by slab-pull creating a “slab-window” that allows rapid up flow of hot asthenosphere.

3.8.7.1 Subduction Model

Previous research in the area of the MSG has proposed a subduction margin at the time of their emplacement but which was initiated much earlier (James, 1994a, Gower & Krogh, 2002), sometime <1650 Ma which is the time of the proposed metasomatic enrichment of the lithospheric mantle (as discussed earlier). If the MSG magmas were produced during melting of the mantle wedge, then the MSG should have a calc-alkaline component to them. Given the absence of such a chemistry (Section 3.73), a model that invokes melting of the mantle wedge in a typical subduction zone can be rejected.

An alternative mechanism for melting in a subduction zone concerns slab rollback. As the oceanic crust of the subducting slab is converted to eclogite, its

density increases and results in slab rollback (Collins, 1994, Ganguly *et al.*, 2009). As the slab rolls back, hotter asthenosphere can upwell into the migrating and growing mantle wedge that causes heating of the SCLM. Given the narrow window for emplacement (1425-1450 Ma) of the MSG intrusions, the slab has to roll back at a rapid and consistent rate over the full width (~50 km) of the MSG distribution. A present-day analog for rapid slab rollback with such a minimal longitudinal variation of geochemistry along strike has not been reported in the literature. If the slab rollback occurred at a different rate in different portions of the MSG magmas then there should be geochemical and temporal variation between the eastern and western portions of this magmatic event but this is not observed. Furthermore, the MSG is restricted to a geographic width of approximately 50 km not including 50-100 km of Grenvillian shortening (see Gool *et al.*, 2008 for details) and do not show wider - 100's of km width - extent over a protracted period of time as seen in rollback-related volcanic belts such as the Great Basin of the western USA (Farmer *et al.*, 2002, Farmer *et al.*, 2013).

3.8.7.2 Plume Model

Some authors (Gower *et al.*, 1990, Buchan & Ernst, 2004) have suggested that the MSG has an intra-plate signature characteristic of a mantle plume. Some geochemical diagrams show an intraplate signature (e.g., Figure 3.9), however diagrams showing magmas that are transitional from plate margin to intra-plate (e.g., Figure 3.6) and arc chemistry are more common (e.g., Figure 3.7 and Figure 3.8). Neither do the MSG show isotopic characteristics of typical oceanic-

island basalts. The typical ϵ_{Nd} for modern day plumes range from +10 to -4 (e.g., White, 2010) where the MSG have ϵ_{Nd} values between -4 to -6. Modern day plume $\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ ratios range from 0.702 to 0.708 (e.g., White, 2010), whereas the MSG $\frac{^{87}\text{Sr}}{^{86}\text{Sr}}$ ratio ranges from 0.702 to 0.716. Because of the metasomatic activity in the SCLM prior to melting of the MSG it is difficult to convincingly characterize the MSG as either intra-plate or plate margin basalts.

If a plume was involved in generating the magmas for the MSG then it has to either 1) heat the insulating subducting slab (that earlier metasomatized the SCLM), sufficiently to raise the temperature enough to melt the M-SCLM, 2) break through the subducting slab to heat and melt the M-SCLM 3) arrive at the base of the lithosphere after the subducting slab was removed.

If a plume arrived beneath a flat-subducting slab (as proposed by Gower and Krogh (2002)) in eastern Laurentia, the plume has to heat the cold down going slab sufficiently to generate melting in the M-SCLM above the slab. If the ascending plume contained that much heat or melting was facilitated through adiabatic decompression - ca. 250 °C greater than ambient upper mantle (Watson & McKenzie, 1991) - it is highly likely that the plume would melt the sediments on the slab, the oceanic component of the slab and the plume itself. This process would require the plume completely eroding through the slab. Modern day examples like the Hawaiian plume have mechanically thinned the lithosphere by only 50 km lithosphere in 65 Ma (McNutt, 1984, McNutt & Shure, 1986).

In a scenario where the subducting slab is removed before the arrival of a mantle plume, removal of the slab has to postdate metasomatism of the SCLM, and the timing of metasomatism is critical to evaluating this model. If the metasomatism occurred soon after the Ossokmanuan suite at ca. 1650 Ma then there would be nearly 200 Ma before the MSG magmatism is generated (Figure 3.25 B). To remove the subducting slab, a process like slab rollback or delamination has to occur. If the oceanic component of the subducting slab converted to eclogite and became denser, as the leading edge of the slab starts to sink it allows the influx of hot asthenosphere. The influx of hot asthenosphere is able to generate melting similar to processes in the Great Basin of the western United States (Farmer *et al.*, 1989, Ormerod *et al.*, 1991, Farmer *et al.*, 2002, Farmer *et al.*, 2013). Thus, removal of the eclogitic slab and the influx of hot asthenosphere reduces the need for a plume to provide heat to generate melting.

Plume chemistry is commonly a mixture of EMORB and OIB melts (White, 2010). Because the MSG plot directly over EMORB on the MORB-OIB array (Figure 3.10: Pearce 2008) geochemical concentrations from Sun and McDonough (1989) were used as a plume proxy for comparison. Nd-isotopes are helpful for distinguishing an EMORB source. At ca. 1450 Ma EMORB $\epsilon\text{Nd}_{(t)}$ should be positive, between +3 to +7. However, the MSG possess a consistent ϵNd signature around -5. A source can be further evaluated when $\epsilon\text{Nd}_{(t)}$ is plotted against a proxy for slab melts, $(\text{Nb}/\text{La})_{\text{PM}}$. Figure 3.26 shows that the MSG melts have low $\text{Nb}/\text{La}_{\text{PM}}$ values indicative of a volcanic arc-like mantle source without an upper mantle (EMORB) involvement. If either of the latter two sources were

involved, then the $\epsilon\text{Nd}_{(t)}$ vs. $\text{Nb}/\text{La}_{\text{PM}}$ values should plot primarily in the upper right quadrant, or if mixing were a factor then the data would form an array between the upper right and lower left quadrants (Figure 3.26). On the other hand, some LIP events (e.g., CAMP; Callegaro *et al.* (2014)) include enriched lithospheric mantle melts without melting of the plume that is proposed to drive the LIP event. Another possibility is for the plume to penetrate the subducting slab and melt the metasomatized SCLM to generate the MSG magmas. There are proposed examples of a plume breaking through a slab (e.g., Murphy *et al.*, 1999) while others question the mechanical strength of a plume to pierce the slab (Camp *et al.*, 2015). Currently there are no known studies of thermal modeling, geochemical modeling or length of time this process would require.

3.8.7.2.1 Correlation of ca. 1450 Ma Mafic Events in Amazonia and Fennoscandia

Mafic magmatism of similar age to the MSG exists in Fennoscandia, in Sweden and Russia as the Trond-Gotta and Lake Ladoga dykes, respectively, and in Amazonia (Brazil) as the Salto do Ceu Sill and associated dykes (Söderlund, 2006, Lubnina *et al.*, 2010, Teixeira *et al.*, 2011, Teixeira *et al.*, 2016). Determining whether these mafic intrusions from these different crustal blocks are related to the MSG requires a continental reconstruction at this time in the Proterozoic (Figure 3.27). Paleomagnetic-based reconstructions show that Laurentia and Baltica (Fennoscandia) were attached during this time (Gower & Owen, 1984, Söderlund, 2006, Lubnina *et al.*, 2010, Buchan, 2014), and so a

genetic link between the Baltic units and MSG units is plausible. In the latest reconstruction by Buchan (2014), the trend of the intrusions from Fennoscandia forms approximately a 30° to 45° junction with the elongated trend of the MSG (a linear distribution of intrusions approximately 750 km long and 50 km wide) and the convergence point could potentially define a plume centre for the age correlated events. However, there remains debate on the reconstruction of Amazonia with respect to eastern Laurentia at this time (Teixeira *et al.*, 2011, Teixeira *et al.*, 2016). Also, the proposed correlations between these different ca. 1460 Ma units remain to be tested using geochemistry.

3.8.7.3 Rifting Model

Gower (1996) proposed rifting along a 1710 Ma zone of weakness, parallel to the trend of MSG starting around ca. 1450 Ma. Although rifting was successful further west, in Labrador rifting is only expressed by the MSG magmatism (Gower, 1996). In a rifting model the heating caused by lithospheric extension (e.g., decompression melting) could produce MSG melts. Continental rift magmas tend to be alkaline to tholeiitic and both maybe contaminated by continental crust (e.g., Winter, 2010). The MSG magmas are tholeiitic but, as discussed above, are not contaminated by continental crust and their alkaline nature is due to phlogopite in the mantle source, not low degree of partial melting. Rifting itself is not enough to generate large continental flood basalts; in many cases a plume is needed to generate the volume of magma required for a LIP (e.g., Winter, 2010). If rifting was continental, then it is expected to see more

alkaline magmatism that has not been identified at the time of emplacement of the MSG. Rifting may have aided in the production of the magma for the MSG but was not the driving tectonic influence.

3.8.7.4 Slab-Window Model

A final option that we consider is opening of a slab window that allows ascent of hot asthenosphere from below causing melting of the M-SCLM (e.g., Thorkelson and Taylor, 1989, Thorkelson, 1996). One way to open a slab window is to continue subducting a down-going slab after terminal continent-continent collision. Considering that terminal collision does not occur until the beginning of the Grenvillian Orogeny (ca. 1000 Ma) this is not an option for the MSG. However, Gower and Krogh (2002), suggested that the Laurentian craton overrode a spreading centre that resulted in the termination of a continuous down-going slab (Figure 3.25 a). There are two orientations of the spreading centre that could accommodate this model: 1) the ridge is orthogonal or at a high angle to the subduction zone, or 2) the ridge is parallel or sub-parallel to the subduction zone.

If the ridge is orthogonal to the subduction zone and continues to spread as the ridge subducts then magmatism should get progressively younger on either side of the subducting ridge over time. If the ridge is at a high angle to the subduction zone then as the slab window migrates as the ridge migrates, relative to the subduction zone, the magmas should get progressively younger in the

direction of migration (cf. Thorkelson, 1996). The MSG does not show either of these age related trends.

However if the ridge is parallel or sub-parallel to the subduction zone as the slab continues to be drawn into the mantle via slab pull, the trailing edge associated with the former spreading centre separates from the plate being formed on the other side of the spreading centre, forming a slab window, and allows hot asthenosphere to well up and start melting the base of the M-SCLM (Figure 3.25 b). As the slab continues to migrate northward with time, the influx of hot asthenosphere at its trailing edge could provide a heat source that moves progressively northward over a broad region of the overlying M-SCLM (Figure 3.25 c; Thorkelson and Taylor 1989; Thorkelson 1996; Breitsprecher and Thorkelson 2009).

This model may explain why there is an absence of MSG east of Churchill Falls. If a section of plate bounded by two transform faults with a "normal" dip angle, compared to the sections of plate that are "flat" may give you a section of the arc that was much narrower than the arc above the flat slabs. Therefore that part of the ridge never subducted a slab window would never have opened to produce magma east of Churchill Falls. A similar scenario exists today if Nevada vs. Washington and Oregon parts of the Ancestral Cascades are compared (Cousens et al. 2008). Additionally subduction of the ridge may cause rifting which contributes (via decompression melting) to the heat provided by the asthenosphere. As the flat subducting slab is pulled northward by slab pull beneath the lithosphere, it causes drag, pulling the lithosphere with it (Figure

3.25 c). This process causes extensional stresses in the lithosphere, leading to weak rifting perpendicular to the slab pull direction. Both the thinning of the lithospheric mantle and the influx of hot asthenosphere below the lithosphere are able to produce basaltic magmas and produce the large volumes of basaltic magma of the MSG.

3.8.8 Duration of M-SCLM

A metasomatized SCLM may have persisted beneath Labrador for approximately 325 Ma after the MSG was emplaced (Figure 3.25 d). Like the MSG, the ca. 1290 Ma Nain-HP (Cadman *et al.*, 1993) and ca. 1280 Ma Nain-LP dykes (Buchan *et al.*, 1996) are enriched in P_2O_5 compared to EMORB, as are the imprecisely dated (K-Ar whole rock method) ca. 1100 Ma Aillik dykes (Fahrig & Larochelle, 1972). Therefore, it is possible that all of these different dyke events sampled a metasomatized SCLM similar to the source of the MSG (Figure 31 depth-lithospheric contamination proxy). P/Zr patterns for the Nain LP, Seal Lake and Harp groups are similar to the intermediate-amphibolite P/Zr group of the MSG, and the Aillik and Nain HP dykes have P/Zr trends even higher than the high P/Zr group of the MSG (Figure 3.29). The four younger mafic intrusive events have chemical characteristics that indicate they were produced from slab fluid-modified mantle source and therefore were produced by melting of M-SCLM comparable to that of the MSG (Figure 33).

Assuming that the zone of melting was near the southernmost points of both the MSG units and the Seal Lake dykes at time of each event, there is 200

Ma between melting events. Allowing $\pm 20\%$ for Mesoproterozoic shortening or extension events yields a rate of approximately 9-13 cm/yr of the migration of the zone of melting. Assuming that the migration of the zone of melting is equivalent to the original subduction rate, the rate at which the slab is moving is equivalent to the subduction of the Farallon plate at 7-11 cm/yr, which coincidentally has also metasomatized its overlying SCLM (Farmer *et al.*, 2013).

3.9 CONCLUSIONS

Originally considered as separate events, the Michael-Shabogamo Gabbro are sub-alkaline, arc-like mafic magmatism that is part of a single multi-pulse event. New U-Pb baddeleyite ages of 1449 ± 3 Ma, 1437 ± 4 Ma, and 1435 ± 8 Ma presented here augment older ages of 1426 ± 6 Ma by Schärer *et al.* (1986), and 1452^{+15}_{-13} Ma (Connelly, 1992). Detailed U-Pb geochronology and geochemical analysis of the MSG has seven implications.

1. The MSG can be divided into two major geochemical groups on the basis of P/Zr ratios. The amphibolite rocks from the amphibolite P/Zr group may possibly be from a different magmatic suite but share REE geochemical characteristics with non-metamorphosed rocks of the intermediate and high P/Zr groups.
2. The P/Zr groups have the following age constraints: 1) the high P/Zr group - ca. 1425-1435 Ma; and 2) the low P/Zr group with sub pulses at 1435 Ma and 1450 Ma. The source for the parental magmas of the MSG were elevated in P_2O_5 and K_2O that could only

have come from a metasomatized subcontinental lithospheric mantle;

3. Some of the parental magmas of the MSG evolved to form rocks that were generated from accumulation of fractionating crystals, and others that were produced from the filter pressing of cumulate material;
4. Excess P_2O_5 and K_2O were stored in apatite and phlogopite in the M-SCLM;
5. Higher P/Zr ratios, may correlate with dehydration of the mantle - depletion of phlogopite - and an increase of apatite melting;
6. The melts to produce the MSG were produced from the opening of a slab window allowing the influx of asthenospheric mantle and lithospheric extension to partially melt the M-SCLM;
7. The M-SCLM may have persisted for at least 325 Ma years after the MSG because younger mafic intrusions, as young as approximately 1100 Ma, are also enriched in P_2O_5 .

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Figure 3.1a. Map of the study area showing the location of the MSG least evolved samples and geochronology locations. GT=Gagnon Terrane, MLT=Molson Lake terrane, CFT=Churchill Falls terrane, WLT=Wilson Lake terrane, MMT=Mealy Mountains Bay terrane, LMT=Lake Melville terrane, HRT-Hawke River terrane, ETB=Exterior Thrust Belt, IMB=Interior Magmatic Belt. Terrane boundaries modified from Gower (1996).

Figure 3.1b Topographic map of the study area showing only the locations of evolved samples. GT=Gagnon Terrane, MLT=Molson Lake terrane, CFT=Churchill Falls terrane, WLT=Wilson Lake terrane, MMT=Mealy Mountains terrane, GBT=Groswater Bay terrane, LMT=Lake Melville terrane, HRT-Hawke River terrane, ETB=Exterior Thrust Belt, IMB=Interior Magmatic Belt. Terrane boundaries modified from Gower (1996).

Figure 3.2 Field Photos of Michael-Shabogamo units: (a) Photo of parallel layering based on grain-size of rock forming minerals. Layers contain approximately the same modal percentages of minerals. (b) Photo of undulating layering. Layers are irregular but contain similar modal percentages of minerals with variation in grain-size. FGN=Fine-grained mineralogy layer, CGN=coarse-grained mineralogy layer

Figure 3.2 Field Photos of Michael-Shabogamo units: (c) Photo of parallel layering with similar grain-size but different concentrations of magnetic minerals. Magnetic layers were strongly attracted to a magnet. Non-magnetic layers were weakly or not attracted to a magnet.(d) Photo of aligned pyroxene crystals in coarse and fine grained parallel-layered MSG.

a)

b)

Figure 3.3 Concordia diagram of (a) FA71-04 (b) CG83-006 and (c) 13-CR-8-3b

Figure 3.4 Nb/Y vs. Zr/Ti diagram showing the basalt-like nature of the high, amphibolite and low P-Zr groups. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.5 Total Alkalis vs. Silica plot shows the alkaline nature of the MSG. The high $\text{K}_2\text{O} + \text{Na}_2\text{O}$ value is due to higher than normal K_2O values in the primary melts and not subsequent alteration. Amp_M P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.6 Ti/Y vs. Zr/Y shows the transitional nature of the MSG from within plate basalts to plate margin basalts (arc). Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.7 Nb/Th vs. Zr/Nb plot showing arc-like nature of MSG. Amp_M P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.8 Nb vs. Ba plot of the MSG showing arc-like nature. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.9 SiO_2 vs. FeO/MgO plot showing tholeiite nature of the MSG. Amp_M P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.10 A2- 8 Nb/Yb vs. Th/Yb plot of the MSG on the MORB-OIB array (base diagram after Pearce, 2008), shows the cluster of most primitive magmas from the high, intermediate and low P/Zr groups clustering just above the MORB-OIB array, indicating minimal lithospheric contribution. Whereas the samples from the Churchill Falls Group lot significantly higher indicating they have had significantly more lithospheric contribution and/or AFC. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.11 Ti vs. V showing the different oxidation states of the magma for the two groups of MSG. Oversize symbols represent the most parental samples. Red fields represent the most parental samples for the high P-Zr and low P-Zr groups. Amp_M P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.12 K_2O vs. P_2O_5 showing increasing abundance of each element in the MSG. Red fields represent most the parental samples for the high P-Zr and low P-Zr groups. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.13 Mg number vs. TiO₂ showing the high TiO₂ and low TiO₂ basalts of the MSG. The Mg# is calculated as: $Mg\# = 100 * \left(\frac{Mg^{2+}}{(Mg^{2+} + Fe_{tot}^{2+})} \right)$ Red fields represent most the parental samples for the high P-Zr and low P-Zr groups. Note: low and high P-Zr groups are present in both the high and low Ti groups. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.14 Ternary plot of Sc-Co-Al₂O₃ showing least evolved samples. Red fields represent most parental samples for the high P-Zr and low P-Zr groups. (central cluster) and evolved samples are outside main cluster. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.15 REE plots of the least-evolved magmas of the MSG. Plots a, b and c are of La-Lu for the high P/Zr group, amphibolite P/Zr group and the low P/Zr group respectively. Plots d, e and f are of extended REEs for the high P/Zr group, amphibolite P/Zr group and the low P/Zr group respectively. Plots do not show much variation between the high, intermediate and low P-Zr Groups. All samples show positive Eu and Sr anomalies and negative Nb-Ta anomalies. Samples with >150 ppm Zr have been omitted to ensure proper P/Zr group relationship. Solid black line in A and D is sample CG-84-172E (1426 ± 6 Ma; Schärer et al. 1986), solid black line in B and E is sample 13-CR-08-03b (1435 ± 8 Ma), solid black line in C and F is sample CG-83-006 (1437 ± 4 Ma), solid grey line in C and F is sample FA-71-004-02 (1449 ± 3 Ma), dashed grey line in C and F is sample DJ-90-2302 (1452^{+15}_{-13} Ma; Connolly, 1992).

Figure 3.16 Plot of Ba vs. Zr showing a nearly linear array of all samples from the Michael-Shabogamo Gabbro, indicating that the chemistry has not been severely altered during subsequent metamorphic events. Red fields represent most parental samples for the high P-Zr and low P-Zr groups. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.17 Plot of ($P_2O_5 \times 1000$) vs. Zr showing the 4 groups of Michael-Shabogamo Gabbro. The 1425 Ma high P-Zr group, 1435 Ma intermediate P-Zr group, 1435 Ma intermediate (metamorphosed) P-Zr group, 1430-1450 Ma low P-Zr group. Amp. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.18 $(La/Sm)_{PM}$ vs. $(P_2O_5/Nd)_{PM}$ plot of the proxy for lithospheric contribution and/or degree of partial melt. The diagram show that the lithospheric contribution and/or degree of partial melt is low and independent of the proxy for apatite melting. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.19 $(La/Sm)_{PM}$ vs. $(Gd/Yb)_{PM}$ plot of the proxy for lithospheric contribution and/or degree of partial melt vs. depth of melting. The diagram show that the lithospheric contribution and/or degree of partial melt is low and apparently increases with depth of melting. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.20 Plot of $\epsilon_{Nd(t)}$ vs. $\frac{^{87}Sr}{^{86}Sr}$ showing the uniform mantle contribution with differing metasomatic contribution. Epsilon values at time T are calculated using the following relation $\epsilon_{Nd}^T = \left(\left[\frac{^{143}Nd}{^{144}Nd_{sample}} \right] / \left[\frac{^{143}Nd}{^{144}Nd_{CHUR}} \right] - 1 \right) * 10000$ where CHUR is the Chondrite Uniform Reservoir and T is the time the rock was formed. The 2σ uncertainty in the initial ϵ_{Nd} values is ± 0.5 epsilon unit, based on the duplicate analysis of samples. Amp. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.21 $\epsilon_{Nd(t)}$ vs. time showing the dePaolo mantle evolution curve. The samples for the MSG plot on the model age curve. Epsilon values at time T are calculated using the following relation

$$\epsilon_{Nd}^T = \left(\left[\frac{{}^{143}Nd}{{}^{144}Nd_{Sample}} \right] / \left[\frac{{}^{143}Nd}{{}^{144}Nd_{CHUR}} \right] - 1 \right) * 10000$$
 where CHUR is the Chondrite Uniform Reservoir and T is the time the rock was formed. The 2σ uncertainty in the initial ϵ_{Nd} values is ± 0.5 epsilon unit, based on the duplicate analysis of samples. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.22 Plot of $(\text{La/Th})_{\text{PM}}$ vs. $(\text{P}_2\text{O}_5/\text{Nd})_{\text{PM}}$ the proxies for monazite and apatite respectively. The plot shows that apatite was the dominant mineral holding P_2O_5 in the mantle. Amp_{M} . P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.23 $(La/Sm)_{PM}$ vs. K_2O plot of the proxy for lithospheric contribution and/or degree of partial melt. The diagram shows that the lithospheric contribution and/or degree of partial melt is low and independent of the proxy for apatite melting. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group, E-MORB, (Enriched Mid Ocean Ridge Basalt) N-MORB (Normal Mid Ocean Ridge Basalt), OIB (Ocean Island Basalt), PM (Primitive Mantle), LC (Lower Crust), MC (Middle Crust), UC (Upper Crust) points represent average analyses.

Figure 3.24 Plot of La/Sm vs. La showing that fractionation and partial melt approximately equal influence in the evolving magmas that produced the MSG. Amp_M P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.25 (A) Schematic representing the oceanic slab subducting under Laurentia after ca. 1620 extension between the Molson Lake and Lac Joseph terranes in Labrador (James, 1994). As the slab is subducting, phosphatic rich sediments are enriching the lithosphere and the subducting slab acts as a thermal barrier preventing the fluids from melting the subcontinental lithospheric mantle. (B) Between ca. 1620-1450 Ma as flat-slab subduction continues the phosphatic fluids continues to enrich the mantle beneath the future location for the Michael-Shabogamo Gabbro and starts enriching the lithospheric mantle beneath the Harp dykes. During this time Laurentia is approaching the spreading centre that is located between Laurentia and Amazonia(?). (C) Around 1450 Ma Laurentia has overridden the spreading centre. As the spreading center is subducted beneath Laurentia it opens a slab-window between the two oceanic plates to allow hotter asthenosphere to start melting the magma for the Michael-Shabogamo Gabbro. As the subducting plate continues to be dragged along under the SCLM by slab pull, the fluids from the slab continue to enrich the SCLM on its journey northward (present day). (D) The continued subduction of the oceanic plate closer to Amazonia(?) continues to subduct beneath Laurentia. It is unknown if that subducting oceanic plate begins normal angled subduction or continues with flat-slab subduction. If the Amazonian(?) oceanic plate continues with flat-slab subduction then that slab would start acting as an second thermal barrier preventing any more melting after the Michael-Shabogamo Gabbro.

Figure 3.26 Nb/La vs. $\epsilon\text{Nd}(i)$ plot showing the $\epsilon\text{Nd}(i)$ values (-5 to 0) for the MSG is lower than a atypical EMORB, which is normally positive $\epsilon\text{Nd}(i)$. Additionally the Nb/La trend is away from EMORB not towards the field indicating that the magmas for the Michael-Shabogamo Gabbro are not related to a plume. Epsilon values at time T are calculated using the following relation $\epsilon_{Nd}^T = \left(\left[\frac{{}^{143}\text{Nd}}{{}^{144}\text{Nd}}_{\text{sample}} / \frac{{}^{143}\text{Nd}}{{}^{144}\text{Nd}}_{\text{CHUR}} \right] - 1 \right) * 10000$ where CHUR is the Chondrite Uniform Reservoir and T is the time the rock was formed. The 2σ uncertainty in the initial ϵNd values is ± 0.5 epsilon unit, based on the duplicate analysis of samples. Amp_M. P/Zr Gp.=amphibolite P/Zr group, Int. P/Zr Gp.=intermediate P/Zr group.

Figure 3.27 Paleomagnetic reconstruction of Laurentia ca. 1450 Ma after Hamilton and Buchan, (2010). Dyke trends in eastern Laurentia, Fennoscandia and Amazonia have been placed in their reconstructed positions. Amazonia has been placed in both of its two possible positions in the northern and southern hemispheres.

Figure 3.28 Plot of $(La/Sm)_{PM}$ vs. $(Gd/Yb)_{PM}$ showing that the Aillik, Harp, Nain and Seal Lake groups obtained their P_2O_5 from the mantle and not the lithosphere same as the Michael-Shabogamo Gabbro. Green outline represents extent of low P/Zr Group, Magenta outline represents extent of high P/Zr Group, including the amphibolite and intermediate groups.

Figure 3.29 Plot of P_2O_5 vs. Zr for the Aillik, Harp, Nain and Seal Lake groups showing similar trends as the Michael-Shabogamo Gabbro, in particular for the Nain-HP and Nain-LP groups. Arrows represent trends of low P/Zr Group (1435-1450 Ma), intermediate-amphibolite P/Zr group and high P/Zr Group (1435-1425 Ma)

Table 3.1 Summary of mafic geochronological data from ca. 1650 to 1100 Ma in Labrador. Table modified from (Gower et al. 1990).

Age (Ma)	Method	Material	Reference
<u>Ossokmanuan Mountain Intrusive Suite</u>			
1639 ± 2	U-Pb	Zircon, Rutile	(James 1994)
1623 ⁺⁷ ₋₅	U-Pb	Zircon	(Connelly and Heaman 1993)
<u>Mealy dykes</u>			
1380 ± 54	Rb-Sr	Whole-rock	(Emslie et al. 1984)
1250 ± 2	U-Pb	Baddeleyite	(Hamilton and Emslie 1997)
<u>Shabogamo Gabbro intrusions</u>			
1379 ± 65	Sm-Nd	Whole-rock, minerals	(Zindler et al. 1981)
1365 ± 170	Rb-Sr	Whole-rock	(Brooks et al. 1981)
1353 ± 17	Ar-Ar	Biotite	(Dallmeyer 1982)
1423 ⁺²³ ₋₂₂	U-Pb	Zircon	(Connelly and Heaman 1993)
1452 ⁺¹⁵ ₋₁₃	U-Pb	Baddeleyite	(James 1994)
1445 ± 4	U-Pb	Zircon	(Krogh 1993)
<u>Michael Gabbro intrusions</u>			
1461 ± 96	Rb-Sr	Whole-rock	(Fahrig and Loveridge 1981)
1472 ⁺²⁷ ₋₂₁	U-Pb	Zircon	(Corrigan et al. 2000)
1426 ± 6	U-Pb	Zircon	(Schärer et al. 1986)
1383 ± 56	Rb-Sr	Whole-rock	(Brooks et al. 1981)
1348 ± 120	K-Ar	Whole-rock	(Wanless et al. 1972)
1323 ± 53	K-Ar	Whole-rock	(Wanless et al. 1973)
<u>Seal Lake Group sills and volcanics</u>			
1323 ± 92	Rb-Sr	Whole-rock	(Wanless and Loveridge 1978)
1250 ⁺¹⁴ ₋₇	U-Pb	Baddeleyite	(Romer et al. 1995)
1224 ⁺⁷ ₋₅	U-Pb	Zircon	(Romer et al. 1995)
<u>Harp dykes</u>			
1350 ± 280	Sm-Nd	Whole-rock	(Ashwal et al. 1986)
1206 ± 122	Rb-Sr	Whole-rock	(Grant et al. 1983)
1316 ± 94	K-Ar	Whole-rock	(Wanless et al. 1978)
1273 ± 1	U-Pb	Baddeleyite-Zircon	(Cadman et al. 1993)
<u>Nain dykes</u>			
1385 ± 143	Sm-Nd	Whole-rock, minerals	(Gower et al. 1990)
1276 ± 23	Rb-Sr	Whole-rock, minerals	(Carlson et al. 1993)
1277	U-Pb	Baddeleyite	(Buchan et al. 1996)
1280 ± 2.5	U-Pb	Baddeleyite	(Buchan et al. 1996)
1293 ^{+1.7} _{-2.7}	U-Pb	Baddeleyite	(Cadman et al. 1993)
<u>Aillik dykes</u>			
~1100	K-Ar	Whole-rock	(Fahrig and Larochelle 1972)

Table 3.2 U-Pb TIMS data

Analysis no. (Number of Grains)	U/Th	Pbc/ Pbtot ¹	²⁰⁶ Pb/ ²⁰⁴ Pb	raw ²			corr ³			[age, Ma]		
				²⁰⁷ Pb/ ²³⁵ U	± 2s % err	²⁰⁶ Pb/ ²³⁸ U	± 2s % err	²⁰⁷ Pb/ ²³⁸ U	²⁰⁶ Pb/ ²³⁸ U	²⁰⁷ Pb/ ²⁰⁶ Pb	± 2s	Concordance
FA71-04												
Bd-1 (2 grains)	112.2	0.016	4283.9	3.0786	0.29	0.24612	0.25	1427.4	1418.4	1440.7	2.7	0.985
Bd-2 (2 grains)	152.4	0.027	2428.7	3.1323	0.38	0.24927	0.30	1440.6	1434.7	1449.4	4.2	0.990
Bd-3 (2 grains)	121.1	0.013	5270.9	3.2002	0.37	0.25441	0.32	1457.2	1461.2	1451.4	3.6	1.007
Bd-4 (3 grains)	135.9	0.039	1730.2	3.1227	0.61	0.24947	0.57	1438.3	1435.7	1442.1	4.9	0.996
CG83-006												
Bd-1 (1 grain)	321.1	0.138	498.5	3.1016	1.80	0.24885	1.78	1433.1	1432.5	1433.9	11.1	0.999
Bd-2 (1 grain)	150.6	0.136	492.7	3.1122	1.52	0.24907	1.49	1435.7	1433.7	1438.7	9.9	0.996
Bd-3 (2 grains)	n.m.	0.046	1415.7	3.1233	0.64	0.25035	0.60	1438.4	1440.3	1435.7	5.2	1.003
Bd-4 (2 grains)	n.m.	0.093	645.4	2.7814	0.66	0.22857	0.62	1350.6	1327.0	1388.1	5.3	0.956
13-CR-8-3b												
Bd-1 (3 grains)	36.0	0.134	462.8	3.0529	0.93	0.24546	0.90	1421.0	1415.0	1429.9	6.5	0.990
Bd-2 (4 grains)	20.8	0.185	329.4	3.0325	1.54	0.24360	1.45	1415.8	1405.4	1431.6	11.8	0.982
Bd-3 (4 grains)	n.m.	0.041	1605.4	2.8917	0.92	0.23478	0.89	1379.7	1359.5	1408.8	6.1	0.965
Bd-4 (5 grains)	57.8	0.058	1163.8	3.0277	0.90	0.24424	0.86	1414.6	1408.7	1423.5	6.3	0.990

1) Pbc = common Pb; Pbtot = total Pb (radiogenic + blank + initial).

2) measured ratio, corrected for fractionation and spike.

3) isotopic ratios corrected for fractionation (0.1% per amu for Pb), spike contribution, blank (0.6 pg Pb and 0.06 pg U), and initial common Pb. Initial common Pb corrected with isotopic compositions from the model of Stacey and Kramers (1975) at the age of the sample. n.m. = not measured.

Table 3.3a Sm-Nd isotope results

Table 3.3a Nd-isotopic results

Sample	Nd(Calc)	Sm(Calc)	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$	$\text{eNd}_{(i)}$	$\text{TDM}_{(\text{Nd})}$
<u>Low P/Zr - 1449Ma</u>							
13-CR-09-01b	13.6	2.99	0.512313	0.1333	0.510572	-3.93	2405
13-CR-05-05	35.3	8.23	0.512215	0.1411	0.510516	-4.87	2610
CG82-029B	41.0	8.95	0.512180	0.1321	0.510519	-4.97	2487
13-CR-10-04	23.8	5.29	0.512262	0.1341	0.510567	-4.04	2424
CG83-239	25.3	5.50	0.512159	0.1314	0.510527	-4.89	2469
13-CR-01-02	21.9	4.85	0.512288	0.1337	0.510556	-4.25	2439
13-CR-13-01	15.6	3.54	0.512111	0.1373	0.510576	-3.85	2447
FA71-029-01	30.9	6.91	0.511789	0.1353	0.510501	-5.18	2555
13-CR-09-01a	8.9	1.99	0.512311	0.1359	0.510534	-4.67	2510
13-CR-07-06A	11.9	2.66	0.512206	0.1354	0.510552	-4.32	2468
13-CR-09-06	5.8	1.26	0.511864	0.1388	0.510543	-4.42	2522
13-CR-03-01b	5.6	1.38	0.511915	0.1506	0.510562	-5.56	2866
<u>Int. P/Zr - 1435</u>							
W3-11-71-25	50.4	10.52	0.511766	0.1262	0.510576	-4.05	2331
13-CR-14-01	54.6	11.29	0.511764	0.1250	0.510585	-3.88	2304
13-CR-08-03b	41.9	8.79	0.511731	0.1613	0.510340	-4.88	2412
SW10-65-55	39.3	8.09	0.511738	0.1244	0.510561	-4.26	2359
AK-05-047	67.9	13.74	0.511683	0.1224	0.510529	-4.98	2372
<u>High P/Zr - 1426</u>							
CG84-172E	43.7	9.10	0.512205	0.1258	0.510523	-4.89	2407
CG83-234	22.9	4.66	0.512093	0.1234	0.510558	-4.64	2346
FA68-008-05	22.6	4.65	0.512103	0.1243	0.510526	-5.27	2410
CG80-694C	45.5	9.55	0.512118	0.1269	0.510524	-5.31	2443
AK-05-018B	37.2	7.74	0.512184	0.1257	0.510565	-4.51	2359

Table 3.3b Sr-isotopic results

<u>Low P/Zr - 1449Ma</u>					
Sample	Rb	Sr	87Rb/86Sr	87Sr/86Sr	87Sr/86Sr CHUR
13-CR-01-02	17.6	17.6	0.167519	0.704482	0.702971
13-CR-03-01b	1.0	1.0	0.045061	0.704857	0.702971
13-CR-07-06A	6.4	6.4	0.047227	0.704043	0.702971
13-CR-09-01a	6.9	6.9	0.055135	0.703688	0.702971
13-CR-09-01b	13.2	13.2	0.079717	0.703664	0.702971
13-CR-09-06	2.6	2.6	0.022720	0.703813	0.702983
13-CR-10-04	15.2	15.2	0.142318	0.703842	0.702971
13-CR-13-01	11.1	11.1	0.097011	0.703567	0.702971
CG83-239	21.6	21.6	0.191122	0.703542	0.702971
<u>Int. P/Zr - 1435</u>					
13-CR-08-03b	25.7	25.7	0.226042	0.703971	0.702989
13-CR-14-01	42.8	42.8	0.450579	0.704247	0.702989
<u>High P/Zr - 1426</u>					
AK-05-018B	59.7	59.7	0.640336	0.703668	0.703000
CG80-694C	23.1	23.1	0.262156	0.704109	0.703000
CG83-234	9.5	9.5	0.069398	0.704128	0.703000
CG84-172E	20.9	20.9	0.202937	0.703967	0.703000
FA68-008-05	9.6	9.6	0.069082	0.704073	0.703000

Table 3.4. Comparison of samples analyzed at the Newfoundland and Labrador Geological Survey (NLS) and ALS Laboratories (North Vancouver Canada (ALS)). Major elements for all samples have been normalized to 100% dry weight.

Sample Group	CG82-029A			AK-05-36			CG79-400B			AK-05-81			CG84-172E			AK-05-33		
	ALS	NLS	Low P/Zr Gp.	ALS	NLS	Low P/Zr Gp.	ALS	NLS	Int. P/Zr Gp.	ALS	NLS	Int. P/Zr Gp.	ALS	NLS	High P/Zr Gp.	ALS	NLS	High P/Zr Gp.
Al2O3	15.98	16.12		16.76	16.07		17.76	16.08		15.93	15.64		15.86	16.64		13.25	12.84	
CaO	8.71	8.6		2.18	2.14		8.06	8.36		5.92	5.80		8.77	9.2		10.68	10.66	
FeO	14.05	12.34		7.19	6.73		11.94	12.74		13.63	13.35		14.44	10.23		14.03	13.78	
K2O	1.24	1.23		3.91	3.84		1.31	1.23		4.07	4.08		1.13	1.18		1.30	1.27	
MgO	5.85	6.34		3.36	3.41		6.26	6.35		6.11	6.11		5.29	5.55		5.71	5.76	
MnO	0.21	0.22		0.08	0.08		0.17	0.23		0.22	0.22		0.20	0.21		0.21	0.20	
Na2O	3.06	3.06		1.85	1.82		3.19	3.04		2.35	2.36		3.13	3.28		2.89	2.88	
P2O5	0.44	0.44		0.25	0.26		0.62	0.5		0.73	0.72		0.90	0.95		0.63	0.62	
SiO2	47.88	49.14		63.71	64.93		48.69	48.56		48.38	49.12		46.71	49.01		46.88	47.61	
TiO2	2.58	2.51		0.70	0.71		2.01	2.9		2.65	2.61		3.57	3.74		4.41	4.37	
LOI	0.57	0.04		2.83	5.57		0.33	0.38		3.30	0.55		0.01	0.01		1.01	0.67	
Ba	538	529		554	527		596	558		1271	1585		638	592		631	627	
Ce	70	63.8		90	89.5		68	61.2		78	94.6		78	71.7		69	64.6	
La	29	28.4		46	45.1		30	28.1		36	43.2		35	32.3		29	28.7	
Nb	2	8.5		12	12.6		3	8.8		13	13		6	12.8		13	9.6	
Ni	63	95		46	45		85	114		63	65		49	59		26	26	
Rb	19	26		130	144.5		20	25		91	107		21	20.9		39	25.2	
Sr	283	284		227	208		375	362		310	348		305	298		285	279	
V	239	255		112	112		142	152		148	203		220	219		348	363	
Y	36	37.9		30	27		25	30.1		39	39.7		37	40.6		41	36	
Zn	159	170		82	84		128	131		330	365		154	165		142	157	
Zr	250	244		141	137		196	218		239	285		258	260		235	219	

Table 3.5 Table of ages for the Michael-Shabogamo Gabbro

Group	Age	Author
High P/Zr	1426 ± 6 Ma	Schärer et al. (1986)
Low P/Zr	1435 ± 8 Ma	This study
Intermediate P/Zr	1437 ± 4 Ma	This study
Low P/Zr	1449 ± 3 Ma	This study
Low P/Zr	1452 ⁺¹⁵ ₋₁₃	Connelly, 1992
Unknown	1459 ⁺²² ₋₂₃	Connelly and Heaman (1993)

Table 3.6a: Bulk melting calculations for 5% and 10% of partial melting of a peridotite mantle to produce the Low P/Zr group and 20-25 degrees of partial melting of the residue to produce the high P/Zr group. The peridotite analysis was obtained from (Stewart, 2002). The peridotite is a sample from the Cape Smith belt in Labrador Canada. Mineralogy was estimated from sample description, except P and K values were calculated using 11% P₂O₅ and 19% K₂O in the crystal structures and assuming 10% apatite and 15% mica in the M-SCLM. Abbreviations: Ol = olivine, Opx = orthopyroxene, Cpx = clinopyroxene, Sp = spinel, Pl = plagioclase, Mic = Fe-mica, Ap = apatite, Kd = partition coefficient, % Diff. = percent difference between measured concentration and calculated concentration, IC = initial concentration, Bulk Kd = Bulk partition coefficient for the melt, MC = Melt concentration, RC = residual concentration, F = degree of partial melting. The residue mineral assemblage and residual concentration were used as initial mineral assemblage and initial concentrations for the low P/Zr pulse were. Bulk partition coefficients were obtained from: *Paster et al., 1974*, Rollinson, 1993, *LaTourrette et al., 1995*, *Prowatke & Klemme, 2006* **Bold**; **bold/italicized**; **italicized**; and normal citations are linked to bold; **bold/italicized**; **italicized**; and normal values in the table. Calculations for melt concentrations and residue concentrations used the bulk melting formulas from Shaw, 1970, the % Diff. values were calculated using:

$$\% \text{ Diff.} = \left| \frac{\text{Sample Conc.} - \text{Calc Conc.}}{\text{Sample Conc.}} \right|$$

Table 3.6a

Low P/Zr Pulse

Ol	Opx	Cpx	Sp	Mic	Ap							
Initial Mineral Assemblage												
0.60	0.03	0.11	0.01	0.15	0.10							
Mineral Proportions Entering Melt												
0.02	0.02	0.66	0.10	0.15	0.05							
Residue Mineral Assemblage												
0.63	0.03	0.08	0.01	0.15	0.10							
						F = 0.05			F = 0.10			
Element	CG83-628a ppm	IC ppm	Bulk Kd	Melt D	MC ppm	RC ppm	% Diff.	Bulk Kd	Melt D	MC ppm	RC ppm	% Diff.
Rb	15.20	5.34	0.3798	0.379	13.00	4.94	0.14	0.3798	0.379	12.09	4.59	0.20
Ba	399.00	46	0.5691	0.558	77.81	44.33	0.80	0.5691	0.558	75.01	42.78	0.81
Nb	6.70	6.12	0.1436	0.141	32.81	4.72	3.90	0.1436	0.141	26.67	3.84	2.98
La	17.90	3.67	0.8723	0.471	4.08	3.65	0.77	0.8723	0.471	3.97	3.64	0.78
Ce	39.20	4.61	0.9371	0.523	4.80	4.60	0.88	0.9371	0.523	4.68	4.60	0.88
Sr	309.00	11.28	0.3386	0.256	30.01	10.29	0.90	0.3386	0.256	27.31	9.50	0.91
Nd	21.80	3.2	1.4234	0.827	2.23	3.25	0.90	1.4234	0.827	2.22	3.31	0.90
Sm	4.95	0.92	1.2999	0.825	0.70	0.93	0.86	1.2999	0.825	0.70	0.94	0.86
Zr	168.00	23.77	0.0364	0.143	300.04	9.23	0.79	0.0364	0.143	194.68	4.78	0.16
Eu	2.52	0.39	1.0048	0.716	0.38	0.39	0.85	1.0048	0.716	0.38	0.39	0.85
Ti	12573.00	3087	0.1944	0.410	13786.7	2523.85	0.10	0.1944	0.410	12181.3	2076.52	0.03
Y	25.10	7.49	0.5420	0.573	13.30	7.18	0.47	0.5420	0.573	12.81	6.90	0.49
Yb	2.48	0.79	0.8726	0.699	0.89	0.78	0.64	0.8726	0.699	0.88	0.78	0.65
Lu	3.48	0.11	0.2740	0.473	0.37	0.10	0.89	0.2740	0.473	0.34	0.08	0.90
Gd	4.48	1.19	1.1310	0.934	1.05	1.20	0.77	1.1310	0.934	1.05	1.21	0.77
Sc	5.48	22.73	0.3470	1.160	67.05	20.40	11.24	0.3470	1.160	68.68	17.62	11.53
K	7138.00	16000	2.9553	2.605	5565.14	16549.2	0.22	2.2553	2.255	7512.53	16943.0	0.05
P	1327.00	1000	0.7664	0.386	1254.52	986.60	0.05	0.7664	0.386	1207.96	436.00	0.09

High P/Zr Pulse

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Element	Ol Kd	Opx Kd	Cpx Kd	Sp Kd	Ap Kd	Mic Kd
Rb	0.010	0.022	0.010	0.001	0.001	2.480
Ba	0.010	0.013	0.001	0.001	0.107	3.680
Nb	0.010	0.150	0.008		0.002	0.880
La	0.001	0.001	0.054	0.001	8.615	0.028
Ce	0.001	0.002	0.086	0.002	9.219	0.034
Sr	0.010	0.020	0.128	0.001	2.941	0.159
Nd	0.001	0.003	0.190	0.001	14.000	0.012
Sm	0.001	0.005	0.290	0.001	12.670	0.002
Zr	0.010	0.030	0.200	0.050	0.044	0.017
Eu	0.002	0.020	0.350		9.600	0.030
Ti	0.020	0.100	0.390	0.150		0.900
Y	0.010	0.050	0.500	0.010	4.767	0.018
Yb	0.005	0.200	0.430	0.001	8.100	0.042
Lu	0.016	0.420	0.560	0.000	1.902	0.000
Gd	0.008	0.090	0.610		10.542	0.016
Sc	0.170	1.200	1.700		0.220	0.000
K	0.007	0.014	0.007	0.001		15.000
P	0.100	0.030	0.050	0.000	7.000	0.000

Chapter 4: The Newly Discovered ca. 1590 Ma Mammoth-Western Channel LIP in Western Laurentia, and Links with the South Australian craton, Australia

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4.2 RECOMMENDED CITATION

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4.3 ABSTRACT

A new 1590 Ma Mammoth-Western Channel Large Igneous Province (LIP) event is proposed for Western Laurentia. It comprises a previously unrecognized node of 1590 mafic magmatism in the Tobacco Root Mountains of the Wyoming craton and is linked with previously recognized 1590 Ma magmatism in NW Laurentia (Western Channel Diabase and Wernecke breccias). In addition, a second pulse of 1550 Ma magmatism was discovered in the Tobacco Root Mountains.

New U-Pb dates of 1590 ± 5 and 1550.6 ± 5.2 Ma reported here confirm previous geochemical evidence of Rogers et al. (2016) for additional magmatic pulses besides the previously recognized ca. 1460 Ma Moyie-Purcell and ca. 780 Ma Gunbarrel mafic intrusions along the western margin of Laurentia. The expected felsic components of the 1590 and 1550 Ma events would provide a potential detrital zircon source ending the requirement of an off craton source for detrital zircon peaks that lie within the 1610-1490 Ma "North American Magmatic Gap".

A third U-Pb age of 1592.4 ± 2.5 Ma for the Western Channel Diabase of NW Laurentia supplements the two existing ca. 1590 Ma ages showing the two geochemical groups of the Western Channel are both the same age as the 1590 ± 5 Ma Mammoth group ~2000 km south. Magmatism in both of these locations in Laurentia (NW and W) is geochronologically and geochemically similar to contemporaneous volcanic rocks within the Gawler and Curnamona cratons in the Southern Australian craton. This study proposes a shared ca. 1590 Ma plume

between the Laurentian, Gawler and Curnamona cratons that fed the Tobacco Root Mountains dykes, Western Channel Diabase and Gawler Range Volcanics, and whose centre is located by converging dyke swarms. The younger 1552 Ma age in the Tobacco Root Mountains may represent a stage of rifting that pre-dates the ca. 1470 Ma Belt-Purcell Basin extension

4.4 INTRODUCTION

Large Igneous Provinces (LIPs) have become an important focus for study in recent years due to their potential as a tool for paleocontinental reconstruction and as an economic exploration tool (Ernst and Jowitt 2013 and references therein). LIPs were originally defined by Coffin and Eldholm (1991; 1992) as mafic magmatism with a large aerial extent ($>0.1 \text{ Mkm}^2$) represented “massive crustal emplacement of predominately mafic (Mg and Fe rich) extrusive and intrusive rock and originated other than ‘normal’ seafloor spreading”. This definition has been revised by Bryan and Ernst (2008), Ernst (2014), and Ernst and Youbi (2017): LIPs represent large volume ($>0.1 \text{ Mkm}^3$; frequently above 1 Mkm^3), mainly mafic (-ultramafic) magmatic events of intraplate affinity (based on tectonic setting and/or geochemistry), occur in both continental and oceanic settings, and are typically of short duration ($<5 \text{ Ma}$) or consist of multiple short pulses over a maximum of a few 10s of Ma. They comprise volcanic successions (flood basalts) and a plumbing system of dyke swarms, sill complexes, layered intrusions, and a crustal magmatic underplate. LIPs can also be associated with silicic magmatism including dominantly silicic events termed Silicic LIPs (SLIPs),

and also carbonatites and kimberlites. LIPs occur at a variable rate that averages approximately every 20–30 Ma but with possible peaks associated with supercontinent breakup, back at least to 2.5 Ga. The rate of LIP occurrence in the Archaean is less certain due to its poorer preservation (Ernst, 2014).

The LIP record can be displayed and compared as a range of ages resembling a supermarket barcode for different crustal blocks. Those blocks with multiple matches in LIP age (i.e., matching barcodes; e.g., Bleeker and Ernst, 2006), are inferred to be formerly adjacent and the matched LIP units to represent reconstructed fragments of more widespread individual LIPs.

4.5 WESTERN LAURENTIA LIP MAGMATISM

Western Laurentia hosts major Proterozoic intraplate magmatic events. Two major events have long been recognized in this region: the ca. 1460 Ma Moyie-Purcell LIP and the ca. 780 Ma Gunbarrel LIP (Park et al. 1995; Anderson and Goodfellow 2000; Ernst and Buchan 2001; Harlan et al. 2003; Harlan et al. 2005; Ernst et al. 2008; Harlan et al. 2008). However, a recent detailed geochemical study of the region (Rogers et al. 2016; Chapter 2) identified 17 geochemical groups and suggested some of these groups were not part of either the Moyie-Purcell or Gunbarrel events and therefore could represent previously unknown events (Figure 4.1A). Here we report new U-Pb baddeleyite ages of 1590 and 1550 Ma for two of the new geochemical groups identified in Rogers et al. (2016), the Mammoth and Ramshorn Creek dyke swarms, respectively, in the Tobacco Root Mountains of the Wyoming craton.

These 1590 and 1550 Ma swarms are geochemically compared with similar aged mafic dykes and sills of the Western Channel Diabase of NW Laurentia and mafic units of the Gawler Range LIP of South Australian craton, and the corresponding geochemistry is integrated.

4.5.1 Wyoming Craton

The Wyoming craton is one of the oldest on Earth with plutonic rocks as old as 3.5 Ga and sedimentary rocks contain detrital zircons as old as 3.8 Ga (Figure 1A; detailed in Chamberlain and Mueller 2007). Numerous mafic dyke swarms of Archaean to Proterozoic age with differing trends crop out in the basement rocks of the Wyoming craton, which are exposed in Laramide-age (Late Cretaceous-Early Eocene) basement-cored uplifts of the Wyoming foreland province (Snyder et al. 1989; Harlan et al. 1996; Kilian et al. 2015). These swarms and related intrusions range from 2500-780 Ma and represent major intraplate magmatic events (including LIPs) that have implications for the reconstruction with other cratons such as the Superior craton (e.g., Bleeker and Ernst, 2006; Killian et al. 2015, 2016). These swarms include the Gunbarrel LIP (ca. 780 Ma U-Pb zircon; Harlan et al. 2003), Tobacco Root Mountains dykes (ca. 1455 Ma Sm-Nd isochron; Harlan et al. 2005), Sourdough mafic dyke swarm (ca. 1899 Ma U-Pb zircon; Kilian et al. 2016), Rabbit Creek swarm (ca. 2161-2152 Ma U-Pb zircon; Kilian et al. 2015), and unnamed dykes near the ca. 2.7 Ga Stillwater mafic-ultramafic intrusion (ca. 2480 Ma U-Pb baddeleyite; C. Rogers, unpublished data).

4.5.2 Dykes of the Northwestern Wyoming Craton

Herein we focus on the dykes of the southern Tobacco Root Mountains, where Neo- and Mesoproterozoic mafic dykes strike 290° NW, are subvertical, and cut the NE-striking foliation of Achaean crystalline basement at a high angle (Figure 4.1B; Koehler 1976; Wooden et al. 1978; Harlan et al. 2005; Harlan et al. 2008). Geochemical analyses of these NW-trending mafic dykes from the southern Tobacco Root Mountains and the Ruby Range by Wooden et al. (1978) identified three distinct geochemical groups based only on major element data. Subsequent paleomagnetic and a U-Pb and Sm-Nd geochronologic study of the mafic dykes from the southern Tobacco Root Mountains (Harlan et al. 2003; Harlan et al. 2005; Harlan et al. 2008) identified two events, the ca. 780 Ma Gunbarrel LIP (Harlan et al. 2003) and the ca. 1460 Ma Moyie-Purcell LIP (Harlan et al. 2005).

The ca. 780 Ma Gunbarrel LIP which extends 2000 km from Wyoming to the Northwest Territories of Canada, has been extensively studied (e.g., Harlan et al. 2003; Mackinder 2014; Sandeman et al. 2014) and precisely dated to 780.3 ± 1.4 Ma by U-Pb zircon methods (Harlan et al. 2003).

The recognition of the ca. 1460 Ma event was based on a Sm-Nd mineral isochron of 1448 ± 49 Ma from a single dyke of reversed magnetic polarity. Also, paleomagnetic results from other Mesoproterozoic dykes in the Tobacco Root Mountains yielded dual polarity magnetizations of similar orientation that are supported by both normal and reverse polarity baked contact tests. The paleomagnetic pole from these dykes is broadly consistent with poles from ca.

1.5-1.4 Ga intrusions from elsewhere in North America. The similarity between paleomagnetic data from two of the three geochemical groups of dykes originally identified by Wooden et al. (1978) led Harlan et al. (2008) to suggest they were both 1.45 Ga in age, and linked to the ca.1460 Ma sills in the Belt Basin (Anderson and Goodfellow 2000; Anderson and Davis 1995; Sears et al. 1998; Anderson and Parrish 2000; Chamberlain et al. 2000) and which are collectively termed the Moyie-Purcell LIP (Ernst and Buchan 2001; Rogers et al. 2016).

However, the trace element geochemical study of Rogers et al. (2016; Chapter 2) identified additional geochemical groups of dykes within the Tobacco Root Mountains that do not belong in either the ca. 780 Ma Gunbarrel or the ca. 1460 Ma Moyie-Purcell LIPs. This study aims to test the hypothesis that these additional dyke groups are related to other dyke events in Laurentia (and other cratons?). U-Pb ages of 1590 Ma and 1550 Ma, were obtained and we present the implications for regional reconstruction models involving Australia.

4.6 NORTHWESTERN LAURENTIA AND AUSTRALIA LIP MAGMATISM AT CA. 1590 MA

4.6.1 Western Channel Diabase

Mafic sheets and dykes of the Western Channel Diabase near eastern Great Bear Lake, NWT Canada (Figure 4.1C) The Western Channel Diabase intrudes Proterozoic volcanic and sedimentary basement rocks of the Cameron Bay and Echo Bay Groups, which are unconformably overlain by sandstones and

dolostones of the Hornby Bay Group of the Wopmay orogen (Irving et al. 1972; Hildebrand et al. 1982; Irving et al. 2004). Both the sheets and dykes strike EW to ENE (Irving et al. 1972) and ages of 1592 ± 3 and 1590 ± 4 were previously reported using the U-Pb baddeleyite method by Hamilton and Buchan (2010). Approximately 1000 km east of the Western Channel Diabase in the Thelon Basin, northern Canada there are 1540 ± 30 Ma (U-Pb baddeleyite SIMS) potassic lavas that have not been geochemically analyzed (Chamberlain et al. 2010) but their age suggests they could also be related to the 1590-1550Ma Tobacco Root Mountains and Western Channel Diabase magmatism.

4.6.2 Wernecke Breccias

Hamilton and Buchan (2010) have linked the ca. 1590 Ma Western Channel Diabase with the Wernecke Breccias of the Wernecke and Ogilvie Mountains of the northern Yukon via a slightly older U–Pb titanite age of 1598.8 ± 1 Ma reported by Furlanetto et al. (2013). The ages from the Western Channel Diabase and Wernecke Breccias are similar to the ca. 1.6 Ga age of magmatism from inherited zircons in a granite clast from the Coates Lake diatreme in the Mackenzie Mountains (Jefferson and Parrish 1989). These precise U-Pb ages demonstrate there is a substantial component of magmatism associated with the 1599 Ma Wernecke “event” (Thorkelson et al. 2001; Furlanetto et al. 2013).

Thorkelson et al. (2001; 2005) proposed that the Wernecke Breccias and Olympic Dam breccias of the Gawler and Curnamona cratons of southern

Australia, which have a similar U–Pb zircon age of 1593 ± 7 Ma (Johnson and Cross 1991), formed a single large (approximately 1000 km diameter) hydrothermal province that may have developed over a mantle plume.

4.6.3 Olympic Dam Breccias and Gawler Range Volcanics-Hiltaba Suite

The Olympic Dam breccias are coeval with widespread ca. 1590-1575 Ma bimodal, felsic and minor mafic, Gawler Range Volcanics-Hiltaba suite of the Gawler craton (Fanning et al. 1988; Hand et al. 2007). The bimodal volcanic component at ca. 1595 Ma and the granitoid Hiltaba suite at 1590-1575 Ma represents one of the largest felsic volcanic systems in the world (Hand et al. 2007). The Gawler Range Volcanics have a maximum thickness of ~1.5 km and extend $>25,000 \text{ km}^2$ across the central Gawler craton (Hand et al. 2007). Gawler Range Volcanics can be subdivided into the lower Gawler Range Volcanics which are moderately to vertically dipping and contain sequences of basalt, andesite, dacite, rhyodacite, and rhyolite, and the upper Gawler Range Volcanics which consist of dominantly felsic volcanic rocks (dacite-rhyodacite-rhyolite) that are flat lying and relatively undeformed. ID-TIMS U-Pb zircon ages from the lower (1591 ± 3 Ma) and upper (1592 ± 3 Ma) parts of the system are geochronologically indistinguishable (Fanning et al. 1988; Blissett et al. 1993).

Coeval (to slightly younger) with the Gawler Range Volcanics is the Hiltaba Suite, which is comprised of highly fractionated granite to granodiorite ($>70 \text{ wt } \% \text{ SiO}_2$) with minor but widespread mafic rocks (e.g., Hand et al. 2007).

The Hiltaba suite intrudes the 1620-1610 Ma St. Peter granites and Archaean

basement rocks (Hand et al. 2007). Compilation of U-Pb crystallization ages from Hiltaba Suite-Gawler Range Volcanics samples suggests there may be two phases of felsic Hiltaba magmatism, one at ca. 1590 Ma and a slightly younger event at ca. 1575 Ma (Hand et al. 2007).

The Hiltaba Suite magmatism has widely been considered to have developed in an anorogenic or extensional setting (e.g., Hand et al. 2007). These interpretations were largely based on the volume of magmatism associated with the Hiltaba Suite and the lack of obvious compressional deformation within the co-magmatic Gawler Range Volcanics, rather than on direct evidence of extensional structures. However, the Hiltaba Suite magmatism in part coincides with the northwest-southeast compressional ca. 1620–1585 Ma Olarian orogeny in the Curnamona province, suggesting magmatism occurred in an overall compressional regime (e.g., Hand et al. 2007).

4.6.4 Benagerie Volcanic Suite

Within the Curnamona province that is adjacent to the Gawler craton (and separated by a younger rifting event) occurs a sequence of slightly younger, flat-lying felsic volcanic rocks called the Benagerie Volcanic Suite (1587–1581 Ma), which are dominantly felsic volcanic rocks but contain mafic volcanic flows that are correlated to the Gawler Range Volcanics (Fanning et al. 1988; Howard et al. 2011; Wade 2011). They are also approximately coeval with the Hiltaba granites of the Gawler craton, with U-Pb ages between ca. 1598 and 1583 Ma (Flint et al. 1993).

The southern Curnamona Province was affected by the Olarian Orogeny and includes voluminous quantities of S- and I-type granites and A-type volcanic rocks (Fricke 2006; Wade 2011). The Benagerie Volcanic Suite is the lowest suite of the Ninnerie supersuite, which also contains three suites of felsic intrusive and volcanic rocks, which are exposed at the surface. The Benagerie Volcanic Suite is a thick package of bimodal volcanic rocks where the mafic volcanic rocks are only found in drill core around the Benagerie Ridge region and are near the bottom of the section. An older limit for extrusion of the basalts is provided by a maximum depositional age of 1591 ± 6 Ma for underlying white sandstone and 1550 ± 6 Ma for an overlying red sandstone suggesting the basalts were simultaneously emplaced with the felsic volcanic rocks (Wade et al. 2012).

4.7 METHODS

4.7.1 Sample Analysis

A subset of 43 geochemical analyses from the Tobacco Root Mountains dykes from Rogers et al. (2016; Chapter 2) was used in this study. Two samples from this subset were selected for geochronological analysis. An additional 4 geochemical analyses were obtained from Ernst and Buchan (2010) as well as the pre-processed powders for further Nd-isotopic analysis of the Western Channel Diabase. The sample analyses were normalized to 100% dry weight before plotting.

Nd isotopic analyses were performed on the crushed powders at Carleton University's Isotope Geochemistry and Geochronology Research Centre (IGGRC). Per standard procedure between 100 and 300 mg of sample powder are weighed into a screw-cap Teflon vial, to which a mixed ^{148}Nd - ^{149}Sm spike is added. The powder-spike mixture is dissolved in HNO_3 -HF, then further attacked with HNO_3 and HCl until no residue is visible. Sr and the bulk REE are separated sequentially by cation chromatography (Dowex 50-X8) using 2.5N HCl and 6N HCl , respectively. The REE-bearing residue is dissolved in 0.26N HCl and loaded into an Eichrom chromatographic column containing Teflon powder coated with HDEHP [di(2-ethylhexyl) orthophosphoric acid, Richard et al., 1976]. Nd is eluted using 0.26N HCl , followed by Sm in 0.5N HCl .

Sr residues are dissolved in 0.3N H_3PO_4 and loaded onto a single Ta filament and run at 1350-1400°C in a 9-cup Thermo-Finnigan Triton T1 thermal ionization mass spectrometer (TIMS). Sr isotope ratios are normalized to $^{86}\text{Sr}/^{88}\text{Sr} = 0.11940$. Total procedural blanks are < 200 pg Sr. Two Sr standards are run at Carleton University, NIST SRM987 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.710253 \pm 19$, $n=53$, Jan. 2016 - March 2017) and the Eimer and Amend (E&A) SrCO_3 ($^{87}\text{Sr}/^{86}\text{Sr} = 0.708012 \pm 15$, $n=18$, Sept. 2008-July 2014). The value obtained for the NBS987 standard for this study is 0.710253 ± 18 . All analytical uncertainties are 2-sigma standard deviations of the mean of 100 scans.

Nd and Sm residues are loaded with 0.3N H_3PO_4 on one side of a Re double filament assembly, and run at temperatures of 1750-1800°C in the Triton mass spectrometer. Isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} =$

0.72190. Total procedural blanks for Nd are < 100 picograms. $^{147}\text{Sm}/^{144}\text{Nd}$ ratios are reproducible to 0.5%. Analyses of the USGS standard BCR-1 yield Nd = 29.02 ppm, Sm = 6.68 ppm, and $^{143}\text{Nd}/^{144}\text{Nd} = 0.512668 \pm 20$ (n=4). Isotope ratios are normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. Twenty-two runs of the in-house metal Nd-standard average $^{143}\text{Nd}/^{144}\text{Nd} = 0.511831 \pm 0.000011$ (2 σ ; May 2014 - August 2016), equivalent to a La Jolla standard value of 0.511861 based on comparative runs. Epsilon values at time T are calculated using the following relation:

$$\epsilon_{\text{Nd}}^T = \left(\left[\frac{^{143}\text{Nd}}{^{144}\text{Nd}_{\text{Sample } T}} / \frac{^{143}\text{Nd}}{^{144}\text{Nd}_{\text{CHUR } T}} \right] - 1 \right) * 10000$$

where CHUR is the Chondrite Uniform Reservoir and T is generally the time the rock was formed. Depleted mantle model ages are calculated assuming a modern upper mantle with $^{147}\text{Sm}/^{144}\text{Nd} = 0.214$ and $^{143}\text{Nd}/^{144}\text{Nd} = 0.51315$. The 2 σ uncertainty in the initial ϵ_{Nd} values is ± 0.5 epsilon units, based on the duplicate analysis of samples. Initial ϵ_{Nd_T} values for volcanic rocks are calculated at 1550 Ma, or 1590 Ma. The isotopic data and corrected ages are listed in Table 4.3a.

4.7.1.1 U-Pb Geochronology

Approximately 150 g of sample was processed using conventional separation protocols that included a modified version of the Söderlund and Johansson (2002) Wilfley table heavy mineral concentration technique. Separations for TR-05 and 14-CR-1-1 were done at the Lund University

Geochronology Laboratory (Lund Sweden) and FA66-045 was separated at the Jack Satterly Geochronology Laboratory at the University of Toronto. Weight estimates were made from a digital measurement of grain dimensions and the density of baddeleyite. Selected baddeleyite grains were photographed and transferred to Teflon® dissolution capsules. The grains were rinsed repeatedly in ultrapure 7 M HNO₃ and water to decrease the Pb blank. An ultrapure HF-HNO₃ mixture was then added to the dissolution capsules together with a ²⁰⁵Pb-²³³⁻²³⁶U tracer solution. Capsules were placed in an oven at 190°C for 3-4 days until the grains were completely dissolved. After dissolution, the samples were dried down on a hotplate with phosphoric acid and re-dissolved in ultrapure 6 M HCl with the addition of ultrapure 0.25 M H₃PO₄ before being dried down. The samples were then dissolved in 2 µL of silica gel and loaded on outgassed Re filaments.

U-Pb geochronology for sample 14-CR-1-1 was done at the Department of Geosciences, Swedish Museum of Natural History in Stockholm on a Triton Finnigan thermal mass spectrometer, samples TR-05 and FA66-045 were carried out at the Jack Satterly Geochronology Laboratory at the University of Toronto on a Daly collector with a pulse counting detector on a solid source VG354 mass spectrometer. Pb and U isotope analyses were analyzed in peak-switching mode using the SEM (Secondary Electron Multiplier). After completion of the ²⁰⁴Pb, ²⁰⁵Pb, ²⁰⁶Pb and ²⁰⁷Pb isotopic measurements in the 1210-1230°C filament temperature range, the ²³³U, ²³⁶U and ²³⁸U were measured at filament temperatures greater than 1320°C. Procedural blanks were estimated to 0.8 pg Pb and 0.08 pg U. Mass fractionation is 0.1% per mass unit for Pb, determined

by replicate analyses of NBS standards SRM 981 and SRM 983. U fractionation was determined from the deviation between the measured $^{233}\text{U}/^{236}\text{U}$ isotopic ratio of the sample and the spike ratio. Initial Pb compositions were taken from the model common Pb evolution curve (Stacey and Kramers 1975). The listed uncertainties in Pb/U ratios were calculated by propagating the within-run error for measured isotopic ratios, and the uncertainties in fractionation (± 0.04 for Pb, absolute uncertainties), Pb and U blank concentration ($\pm 50\%$), and Pb blank composition (2% for $^{206}\text{Pb}/^{204}\text{Pb}$ and 0.2% for $^{207}\text{Pb}/^{204}\text{Pb}$).

Initial corrections were made using an in-house data reduction program. Uncertainties for the ID-TIMS data are given at the 95% (2σ) confidence level. Decay constants used in age calculations are those of Jaffey et al. (1971). Graphical data presentation and quoted ages were generated using the Microsoft Excel Add-in Isoplot/Ex v. 3.00 of Ludwig (2003).

4.7.2 Description of Dykes Sampled for U-Pb geochronology

4.7.2.1 Dykes of the Tobacco Root Mountains

Two samples were dated from NW-trending dykes in the Tobacco Root Mountains and these are located in Figure 4.1B. Sample TR-05 (Lat. 45.52, Long. -112.15) is composed of massive dolerite from a near vertical 10-20 m thick dyke that strikes 290° NW and is intermittently exposed for approximately 1.5-2 km and presumably extended further before the dyke crossed into a working aggregate quarry and could not be followed further. Sample 14-CR-1-1 (Lat.

45.71, Long -112.07) was collected from a highly brittle outcrop in a dyke that is up to 250 m wide and intermittently exposed for approximately 5-6 km and trends approximately 315° NW.

In outcrop, the dykes from which TR-05 and 14-CR-01-01 were sampled are massive and weather tan to slightly rusty tan in colour, and on fresh surfaces are greenish grey. Mineralogy is typical of the dykes in the Tobacco Root Mountains and consists of fine- to medium-grained holocrystalline dolerite with subophitic texture; 60-80% subhedral clinopyroxene and 20-40% plagioclase feldspar with minor (1-2%) biotite crystals. Accessory phases include opaque oxides, and minor biotite. Small patches of micrographic quartz-feldspar intergrowths are locally present. Crystal size ranges from 0.5-2 mm. Locally within outcrop there are felsic rich pods that range in size from 2-30 cm. Contacts with the country rock are sharp with minimal to no contact alteration within the country rock. Fragments of country rock were not seen within the dyke.

4.7.2.3 Western Channel Diabase

A sample (FA66-045; Lat. 66.6, Long. -117.7) from the Western Channel Diabase sill near Great Bear Lake was obtained from the paleomagnetic core archives of Walter Fahrig of the Geological Survey of Canada. This sample is a medium-grained, holocrystalline dolerite with subophitic texture consisting of slightly altered well-formed plagioclase with subhedral augite, and trace orthopyroxene. Accessory phases include apatite and opaque oxides, minor

brown biotite, lesser quartz. Small patches of micrographic quartz-feldspar intergrowths are locally present.

4.8 RESULTS

4.8.1 U-Pb Geochronology of Dykes of the Tobacco Root Mountains

4.8.1.1 Sample TR-05, Tobacco Root Mountains, Wyoming Craton

Baddeleyite recovery from this sample was challenging due to its low abundance. Approximately, 500 g of rock powder yielded only a small amount (~0.1 microgram total) of baddeleyite. The grains were divided into three fractions of clear brown platy baddeleyite, which had approximately 2-8 picograms of radiogenic Pb in each fraction. To obtain meaningful ages from small amounts of Pb* requires background Pb levels to be low. In these analyses, the total amount of common Pb was 0.2-0.6 picograms, permitting reasonably robust dates despite the small sample sizes.

The three analyzed baddeleyite fractions gave overlapping data, two of which plot just below the Concordia curve (Figure 4.2). If minor Pb loss occurred at the time of voluminous Cretaceous magmatism in the Wyoming craton at ca. 100 Ma (e.g. Foster et al. 2006), a line through the 3 data points would give an age of 1551.8 ± 5.5 Ma (MSWD=0.34). A minimum age estimate is obtained from the weighted mean of the three $^{207}\text{Pb}/^{206}\text{Pb}$ ages, which is 1550.6 ± 5.2 Ma (2s, here and throughout; N=3; MSWD=0.43). This minimum age estimate assumes

minor Pb loss occurred in the recent past and is considered the best estimate for the age of emplacement of the dyke.

4.8.1.2 Sample 14-CR-1-1 Tobacco Root Mountains, Wyoming craton

Approximately 50 grains of dark brown baddeleyite of good quality were recovered. The grains are crystalline though some grains appear dull possibly due to accumulation of radiation damage. The optically freshest grains were combined into fractions comprising 2-4 grains.

The three fractions analyzed plot between 4 and 18% below the Concordia (Figure 4.3, Table 2). Intercept dates are 1590 ± 3 Ma and 81 ± 100 Ma for the upper and lower intercepts, respectively (Figure 4.3). Although the MSWD value of 3 signals minor scatter, we interpret the 1590 ± 3 Ma date to represent the emplacement age of the dyke.

4.8.2 Petrology and geochemistry of 1590 and 1550 Ma dykes of the Tobacco Root Mountains, Wyoming craton

Our new 1590 ± 5 Ma and 1550.6 ± 5.2 Ma ages on the Mammoth and Ramshorn Creek geochemical groups, respectively, as defined in Rogers et al. (2016) confirm they are not coeval with the ca. 1460 Ma Moyie-Purcell LIP. Geochemically the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups in Tobacco Root Mountains are subalkaline basalt to basaltic andesite (Figure 4.4) and are transitional from plate margin to within-plate basalts (Figure 4.5; Rogers

et al. 2016). REE patterns for both the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups show enrichment in light-REEs (LREE), with a positive Pb anomaly, a negative P anomaly, and relatively flat heavy-REE slope (Figure 4.6a-d, Figure 4.7a-d; Rogers et al. 2016). These mafic rocks show a distinct bimodal geochemical difference in the REE patterns. The 1550 Ma Ramshorn Creek group shows a fanning in the LREE (La-Sm) with minimal change in the heavy-REE (Gd-Lu), and according to Rollinson (1993), such a pattern represents different degrees of partial melting. Whereas the older 1590 Ma Mammoth group shows a parallel pattern in the full suite of REE indicating that a process other than differing degrees of partial melt caused the range in LREE slopes (Rogers et al. 2016).

4.8.3 U-Pb Geochronology and Geochemistry of the Western Channel Diabase

Currently, the Western Channel Diabase of NW Laurentia has four geochemical analyses (Ernst and Buchan 2010); three samples consistently plot with the 1590 Ma Mammoth group and the fourth sample plots with the 1550 Ma Ramshorn Creek group, herein referred to as WC-2 and WC-1, respectively. [Note the name of these Western Channel groups are numbered based on geochemical evidence for relative enrichment in crustal components, least enriched (WC-1) to more enriched (WC-2; e.g., Figure 4.10.)]

The Western Channel Diabase intrusions are subalkaline basalt to basaltic andesites that plot mostly within the plate margin field (Figure 4.5). REE data for

the WC-2 and WC-1 also show geochemical similarity to the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek dykes, respectively, with similar positive Pb and negative P anomalies and relatively flat HREEs. WC-2 and the 1590 Ma Mammoth group also share a similar negative Nb-Ta anomaly (Figure 4.6e-f).

4.8.3.1 Geochronology of the Western Channel - Sample FA66045, NW Laurentia

The 1590 Ma WC-2 group of the Western Channel Diabase is a geochemical and geochronological match to the 1590 Ma Mammoth group located 2000 km south in the Tobacco Root Mountains. However, the undated WC-1 sample is a geochemical match to the ca. 1550 Ma Ramshorn Creek group. A U-Pb age for this Western Channel diabase (WC-1) was acquired to test for a possible 1550 Ma age. However, a 1590 Ma age was unexpectedly obtained, as detailed below.

Approximately 25 pale to medium brown, striated blades and blade fragments of baddeleyite were recovered. Grains appeared to be free of zircon overgrowths, and discrete grains of magmatic zircon were absent in the heavy mineral concentrate.

Uranium-lead isotopic data for four fractions of baddeleyite are presented in Table 2, and shown graphically in Figure 4.8. Calculated Th/U ratios are low (0.04-0.07), consistent with optical microscope observations that the grains lacked any noteworthy zircon overgrowth. U-Pb results are clustered in two overlapping pairs, below Concordia with ~1.0 and 1.3% discordance, all of which

are essentially collinear. Free regression of the data results in a high probability of fit and an upper intercept age of 1592.4 ± 2.5 Ma, which we interpret as a primary age of emplacement and crystallization. This age is within analytical error of previous U-Pb age determinations by Hamilton and Buchan (2010), and confirms that sample FA66-045 represents a component of the Western Channel Diabase and all the samples belong to a single 1590 Ma pulse, comprising two geochemical types – that are similar to the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek swarms of the Tobacco Root Mountains.

4.9 DISCUSSION

4.9.1 New 1590 Ma Event in Western Laurentia

Until the geochemical study of Mesoproterozoic dykes in western Laurentia by Rogers et al. (2016) it had been assumed all the dolerite intrusions in the Tobacco Root Mountains were associated with either the ca. 1460 Ma Moyie-Purcell LIP or the 780 Ma Gunbarrel LIP (Ernst and Buchan 2001; Harlan et al. 2008; Rogers et al. 2016). The new U-Pb dates of 1590 ± 5 Ma for the Mammoth group and 1550.6 ± 5.2 Ma for the Ramshorn Creek group reported here are significantly older and replace the imprecise Rb-Sr whole rock isochron age of 1455 ± 125 Ma of Wooden et al. (1978) and the Sm-Nd mineral isochron age of 1448 ± 49 Ma reported by Harlan et al. (2005). The precise U-Pb baddeleyite geochronology from the present study has shown these intrusions are not related to the ca. 1460 Ma Moyie-Purcell LIP (consistent with the

prediction based on geochemistry by Rogers et al. (2016)) and are approximately 90-130 Ma older.

The following discussion will focus on the provenance, evolution and tectonic implications of the newly recognized 1590 and 1550 Ma magmas in the Wyoming craton, which was attached to western Laurentia by 1715 Ma (Dahl et al. 1999).

4.9.1.1 Potential 1590-1550 Ma Source of Detrital Zircons in

Mesoproterozoic Sedimentary Rocks of the Belt-Purcell Supergroup

Recognition of precise dates for the Ramshorn Creek (1550.6 ± 5.2 Ma) and Mammoth (1590 ± 5 Ma) dykes has a significant implication for the interpretations of detrital zircon studies within the Belt Basin. There are numerous ca. 1550 Ma and ca. 1590 Ma detrital zircons concentrated in the lower Prichard Formation (Figure 4.9) and the Wallace Formation of the Belt Basin. Other units such as the: Hoodoo Quartzite, Swaguer Quartzite, Revett Formation within the Belt Basin in Idaho and Montana also contain major peaks at ca. 1590 Ma and minor detrital zircon peaks on probability-age plots of ca. 1550 Ma (Link et al. 2007). Detrital zircon studies in east-central Idaho and the Belt Supergroup reveal a ca. 1550 Ma and ca. 1590 Ma peaks that had been linked with a non-North American source, possibly northeastern Australia formerly to the west (Ross et al. 1992; Ross and Villeneuve 2003; Link et al. 2007). Although one study of paleocurrent direction in central Idaho, suggests sediment transport was bidirectional from the northeast and the southwest (Tysdal et al. 2003).

This newly recognized ca. 1550 Ma Ramshorn Creek and 1590 Ma Mammoth events would represent a potentially closer provenance for these sediments and their detrital zircons. The presence of 1550 and 1590 Ma North American zircons would be consistent with a significant felsic component to the Mammoth-Western Channel magmatic event. Most LIPs are associated with a significant felsic component (Bryan 2007; Bryan and Ferrari 2013; Ernst 2014). However, such felsic rocks have not been identified in Western Laurentia, but most of western Laurentia is under younger cover. One known felsic intrusion in Idaho known as the Leclède orthogneiss does have an U-Pb zircon age of 1576 ± 13 Ma that has been interpreted to be a sliver of Australia that remained attached to western Laurentia during Rodinian rifting (Doughty et al. 1998), but could also represent an example of a felsic intrusion associated with the 1590 Ma Mammoth-Western Channel LIP.

Additionally, because there is a significant ca. 1590 Ma felsic component to the South Australian craton (e.g., Fanning et al. 1988; Wade et al. 2012; section 1.3) we could predict the erosion of these units could also have contributed to the detrital zircon population of the Belt-Purcell Basin stratigraphy.

4.9.2 Geochemistry of 1590 Ma Mammoth and 1550 Ma Ramshorn Creek Groups Dykes

The new geochronological data from the Tobacco Root Mountains dykes allow more sophisticated interpretations of melt generation and melt evolution than was previously considered in Rogers et al. (2016). The most diagnostic

diagram to separate the two dated groups (1590 Ma Mammoth and 1550 Ma Ramshorn Creek) is the Th/Yb vs. Nb/Yb diagram by Pearce (2008; Rogers et al. 2016). In this diagram, most of the dolerite samples plot above the MORB-OIB array. The 1550 Ma Ramshorn Creek group plots close to the array and the 1590 Ma Mammoth group plot further above the array indicating the 1590 Mammoth group is more enriched in crustal components than the 1550 Ramshorn Creek group (Figure 4.10; Rogers et al. 2016)

4.9.3 Geochemistry of the Western Channel Diabase

The age and geochemistry of the 1590 ± 5 Ma Mammoth group matches the reported ages of ca. 1590 Ma (Hamilton and Buchan 2010) and geochemistry of WC-2 (Figure 4.10). The geochemical and geochronological similarity of both 1590 Ma groups suggest that despite being emplaced 2000 km apart they were produced from similar processes and sources.

The geochemistry of WC-1 is a match to the 1550.6 ± 5.2 Ma Ramshorn Creek group; however, WC-1 yields an age 40 Ma older of 1590 ± 5 Ma. The significance of the age difference but compositional match between Ramshorn Creek and WC-1 units will be further discussed in section 4.9.5.

4.9.4 Magma Sources

For the duration of this discussion the term “enriched source” refers to an ultramafic source (e.g., asthenosphere or lithospheric mantle) that has been

enriched in crustal components (e.g., large ion lithophile elements like Th, La, Ba, or enriched Sr and Nd isotopes etc.). Addition of minor volumes of enriched magmas or fluids would be enough to control the REE signature of most mantle melts while not affecting major oxide elements (e.g., Halls et al. 2008). Such components can be transported or transferred to the lithospheric mantle by metasomatism or transfer from a subducting slab.

Magmas for the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek group dykes are derived from partial melts generated within the spinel stability zone of the mantle. The ratio $(\text{Gd/Yb})_{\text{PM}}$ can be used as a proxy for depth of melting, where a value greater than two suggests melts were generated within the garnet stability zone of a peridotitic mantle as garnet would preferentially retain Yb over Gd (PM=Primitive Mantle normalized; Pearce 2008; Álvaro et al. 2014). Values between one and two indicate polybaric melting with some portion of the magma being generated in the garnet stability field and some generated in the spinel field, and resulting mixing of magmas generated at different depths. $(\text{Gd/Yb})_{\text{PM}}$ values between 1.2 and 2.0 demonstrate parental melts of the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups were generated by partial melting over a similar depth range possibly starting within the garnet stability field, but mostly within the spinel stability zone of the mantle (Figure 4.11).

The ratio $(\text{La/Sm})_{\text{PM}}$ can be used as a proxy to represent either assimilation of lithosphere (mantle or crust) or the degree of partial melting, where PM represents the ratio normalized to primitive mantle values of Sun and McDonough (1989). Either a higher crustal contribution or a lower degree of

partial melting increases the concentration of La relative to Sm in a melt. At low degrees of partial melting La is released from crystal structures preferentially over Sm. As the degree of partial melting increases the difference in incompatibility between La and Sm is less important, causing the La/Sm ratio to decrease. Varying degrees of partial melting will show a fanning of the light-REEs in a multi-element plot (Rollinson 1993). In REE plots, samples considered part of the same group will tend to have the same La/Sm slope and REE pattern.

The 1590 Ma Mammoth group has a higher $(\text{La/Sm})_{\text{PM}}$ ratio than the 1550 Ma Ramshorn Creek group (Figure 4.12). The 1590 Ma Mammoth group also plots further above the MORB-OIB array (Figure 4.10), and thus the large variation and parallel trends in REE ratios suggests the earlier 1590 Ma Mammoth group has undergone more lithospheric interaction as opposed to varying degrees of partial melting (Figure 4.12). Variable mixing between EMORB mantle and enriched components would also explain the wide spread in REE patterns in Figure 4.6a-f for the 1590 Ma Mammoth group. The REE plots for the younger 1550 Ma Ramshorn Creek group, however, shows fanning of the light-REE (La to Sm) likely reflects differing degrees of partial melting, and much less crustal enrichment for the Ramshorn Creek mantle source (Rollinson 1993).

4.9.4.1 Potential Mixing Components in the Tobacco Root Mountains

Th/Nb vs. TiO_2/Yb (Pearce et al. 2015) show the mantle source for the ca. 1590 Ma Mammoth group was more enriched in incompatible elements compared to the ca. 1550 Ma Ramshorn Creek group (Figure 4.13). This

diagram uses Th/Nb as a proxy for crustal input (i.e. lithospheric metasomatism) and TiO_2/Yb as a proxy for melting depth. If crustal assimilation were responsible then it would be expected to increase the SiO_2 values and move the classification of the rocks to andesite to rhyolite. The Th/Nb ratio, along the y-axis represents the arc array because during arc metasomatism Th is more incompatible than Nb, and as fluids are removed from the subducting slab, the Th/Nb ratio increases (Pearce et al. 2015). The TiO_2/Yb ratio represents the MORB-OIB array because as melting becomes shallower Yb is released as garnet is no longer stable and the ratio decreases (Pearce et al. 2015).

Neodymium isotopes are useful to distinguish different mantle melts including undepleted, depleted, and enriched types from mantle and crustal sources. If the melts for the ca. 1590 Ma Mammoth group were more evolved than the melts for the ca. 1550 Ma Ramshorn Creek group, but both shared a common mantle source, then ϵNd values in rocks from the two groups would be indistinguishable, as Nd isotopes do not fractionate during fractional crystallization. Magmas for the 1590 Ma Mammoth group were produced from mixing of an EMORB-like depleted mantle source ($\epsilon\text{Nd}_{(i)} +5$) with a metasomatized (upper crust-like REE) lithospheric mantle source ($\epsilon\text{Nd}_{(i)} -6$; Figure 4.12), while the 1550 Ma Ramshorn Creek group was produced from a mildly depleted mantle source ($\epsilon\text{Nd}_{(i)} +3$ to $+4$). If the 1590 Ma Mammoth group resulted from mixing of mantle and crustal melts one would expect to see a negative trend because as $\epsilon\text{Nd}_{(i)}$ decreases SiO_2 increases (Figure 4.12 inset). Additionally, mixing of magmas produces linear trends between two end-

members. Neither is observed in the 1550 Ma Ramshorn Creek group or 1590 Ma Mammoth group. Therefore, the only other source of enriched components that does not add SiO_2 is metasomatized lithospheric mantle. The 1590 Ma Mammoth group ($\epsilon\text{Nd}_{(t)}$ 0 to +5) has a greater range in ϵNd than the Ramshorn Creek group ($\epsilon\text{Nd}_{(t)}$ +3 to +4), indicating the sources for Mammoth group magmas was a similar depleted source but some assimilation of an enriched source (Figure 4.12).

The REE chemistry and ϵNd values suggest that the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups were derived from EMORB-like mantle sources that mixed with a variably REE-enriched metasomatized lithospheric. At least three possible crust-like, metasomatic components (elemental concentrations from Rudnick and Gao 2007) with different Nd isotope ratios can be modeled to be present in the the lithospheric mantle: (1) an upper crustal, old (Archaean (?)) component ($\epsilon\text{Nd} \sim -9$; ML-1), (2) an upper crustal, younger (Paleoproterozoic (?)) component ($\epsilon\text{Nd} \sim -5$; ML-2). (3) a middle crustal, more depleted component ($\epsilon\text{Nd} \sim 0$; ML-3). A plot of Th/Y vs. ϵNd shows that mixing of the three possible metasomatic lithospheric components with an EMORB source could form the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups. Figure 4.14 shows there is a range of mixing between EMORB and two enriched upper crust sources, with $\epsilon\text{Nd}_{(t)}$ values of -9 and -5 making up the end-members. The EMORB and middle crust enriched mixing components are dominant in the 1550 Ma Ramshorn Creek geochemical group. It is unlikely the 1550 Ma Ramshorn Creek group mixed with either the ML-1 or ML-2 end-members.

The DePaolo (1988) Nd model age diagrams show that the 1550 Ma Ramshorn Creek group shows a tight clustering, with depleted mantle (TDM) model ages from 2138-1825 Ma, indicating they were all derived from a source that had a variably depleted Nd source (Figure 4.15a). Note that there are only ca. 275-590 Ma between the Nd model ages and the crystallization age of the Ramshorn Creek group, which is consistent with a general lack of enriched components in this magma group. In contrast, the 1590 Ma Mammoth and similar WC-2 geochemical group were derived from a source that included an old and variably enriched component (TDM = ca. 1890 Ma), possibly of early Proterozoic or late Archaean age (Figure 4.15b). However, the geochemically similar 1592 Ma WC-1 and CUR-1 samples have TDM ages of 1970 Ma and 2899, indicating although these samples crystallized ~40 Ma earlier they still sampled mantle similar to that of the ca. 1550 Ma Ramshorn Creek group. It is notable that the TDM ages for WC-1 and CUR-1 are clearly older than Ramshorn Creek Group, so the WC-1 and CUR-1 do include more crustal-type components than Ramshorn Creek Group.

4.9.4.2 Integration of the Gawler and Curnamona Cratons Geochemistry

Previous studies suggested the Southern Australian craton was connected to NW Laurentia during at least parts of the middle Proterozoic, supporting a link between the 1590-1595 Ma Western Channel Diabase and ca. 1600 Ma Wernecke Breccias of NW Laurentia with the Gawler Range bimodal LIP and associated Olympic Dam deposits of the Southern Australian craton (Bell and

Jefferson 1987; Moores 1991; Thorkelson et al. 2001; Betts et al. 2007; Hamilton and Buchan 2010; Furlanetto et al. 2013; Medig et al. 2014; Betts et al. 2016; et al. 2016; Medig et al. 2016; Thorkelson and Laughton 2016).

To further test this hypothesis, geochemical analyses of Gawler Range mafic volcanic rocks were obtained through Marie Wade at the South Australian government (M. Wade, written comm., 2016) and the OZCHEM database (Budd et al. 2002 and references therein). Filtering of these samples for use in this study was done through a multi-step process. First, only samples from the Gawler and Curnamona cratons, which form the Gawler Range bimodal LIP, with ages between 1590-1600 Ma, were selected. Second, the samples were filtered for SiO₂ between 45 and 56 wt.% and MgO > 5%. Finally, only samples with a complete or near complete trace element suite were retained, and this filtering process left 14 samples for comparison with the geochemistry data from W and NW Laurentia. The samples from the OZCHEM database used in this study and their assigned unit are listed in Appendix 4.1. Note, the geochemical groups in the Gawler and Curnamona cratons are numbered from least (GR-1; CUR-1) to most contaminated (GR-3; CUR-3), as are those associated with the Western Channel Diabase (e.g., Figure 4.10).

Approximately half of the Gawler Range mafic volcanic rocks, herein called GR-2, plot within the 1590 Ma Mammoth group on the Th/Nb vs. TiO₂/Yb diagram. The remaining samples from the Gawler cratons form a third, more evolved, geochemical group, herein called GR-3, plotting above the 1590 Ma Mammoth group (Figure 4.13). The Curnamona craton shows similar

geochemical characteristics to the Gawler Range Volcanics and Western Channel Diabase with samples plotting in three groups, labelled CUR-1, CUR-2, and CUR-3, overlapping with the 1550 Ma Ramshorn Creek, 1590 Ma Mammoth, and GR-3, respectively. One note to make is although GR-1 and CUR-1 geochemically plot within the 1550 Ma Ramshorn Creek group their ages are ca. 40 Ma older at ca. 1590 Ma.

The further the samples plot above the MORB-OIB array, the more contaminated (with crustal components) they are. Therefore, the location of these GR-3 and CUR-3 data indicate magmas from Australia are more contaminated than magmas from the 1590 Ma Mammoth and the Western Channel Diabase WC-2 groups. The compositions of groups GR-3 and CUR-3, also have an age of ca. 1590 Ma (Stewart 1992; Fricke 2005; Figure 4.10) are only seen within the Gawler and Curnamona cratons. Higher $(\text{Gd/Yb})_{\text{PM}}$ in GR-3 and CUR-3 samples is consistent with deeper melting of the source rocks beneath the Gawler and Curnamona cratons (Figure 4.11) and more negative $\epsilon\text{Nd}_{(i)}$ values indicate more contamination (by metasomatized lithospheric mantle) than the 1590 Ma Mammoth and WC-2 groups (Figure 4.12).

On a Th/Nb vs. TiO_2/Yb diagram (Figure 4.13; Pearce et al. 2015) the evolution of magmas for the three geographical areas can be easily appreciated. On this diagram the Th/Nb axis represents a proxy for crustal input, and the TiO_2/Yb axis is a proxy for melting depth and garnet in the residue. According to the field on these diagrams, the source of these magmas is a mixture of subduction-modified lithosphere (SML), to the oceanic island basalt modified

lithosphere (OML). Specifically, the Gawler Range Volcanics plot close to middle crust-like values, whereas, WC-1 plots closer to the OML field. The 1550 Ma Ramshorn Creek group plots even closer to the oceanic island basalt modified lithosphere field.

ϵNd values for ca. 1595 Ma Hiltaba Suite Granites within the Gawler craton are more juvenile than their host rocks but these values are seen to vary with the host-rock system Nd-isotopic composition (e.g., Hand et al. 2007). For example, the Hiltaba Granites intruding the juvenile St. Peter Suite are also relatively juvenile ($\epsilon\text{Nd}_{1610\text{Ma}} = +0.1\text{--}1.2$), whereas the Hiltaba Granites intruding crust with a significant Achaean component are commonly more evolved ($\epsilon\text{Nd}_{1590\text{Ma}} = +5.8$ to -9.1 ; (Hand et al. 2007). This pattern of the Hiltaba suite varying in Nd-isotopic signature with the St. Peter Suite vs. the Archaean basement host rocks, suggests the Hiltaba Suite was derived from a mantle source mixed with crustal components and is consistent with the presence of regional differences in the lower crustal mafic component that partially melted to produce the granites; these mafic lower crustal rocks had compositions that would correlate with different underlying lithospheric compositions (that had experienced terrane-specific metasomatism and enrichment in crustal components). This variation in the compositions of the Hiltaba suite granites is evidence for heterogeneity in the metasomatism of the underlying Gawler craton lithosphere.

The South Australia TDM model ages for groups GR-1 through GR-3 and CUR-1 through CUR3 can be compared to the ca. 1590 Ma Mammoth, Western

Channel Diabase and 1550 Ma Ramshorn Creek groups. GR-2 and CUR-2 are similar to the 1590 Ma Mammoth group but were derived from an older Nd-isotopic source. The GR-3 and CUR-3 geochemical groups are more tightly clustered with TDM ages ranging from 2398-2021 Ma, indicating they were produced from a more homogenous source with respect to Nd (Figure 4.15c).

4.9.5 Models to Produce the ca. 1590 Ma Magmatism

A number of proposed reconstruction models for ca. 1600 Ma to 1550 Ma for the Gawler, Curnamona and western Laurentia cratons are currently under debate including but not limited to the SWEAT, AUSWUS, and other unnamed models (Bell and Jefferson 1987; Moores 1991; Sears and Price 2000; Karlstrom et al. 2001; Betts et al. 2007; Finn and Pisarevsky 2007; Betts et al. 2009; Hamilton and Buchan 2010; Zhang et al. 2012; Furlanetto et al. 2013; Medig et al. 2014; Betts et al. 2016; Furlanetto et al. 2016; Medig et al. 2016; Nordsvan et al. 2017; Volante et al. 2017). This section aims to discuss three more recent reconstruction models proposed by Betts et al. (2016), Medig et al. (2014) and Hamilton and Buchan (2010).

4.9.5.1 Hotspot Track

Betts et al. (2007); (2016) have proposed the age-progressive ca. 1600-1550 Ma belt of magmatism extending from South Australia to North Australia was produced by a hotspot track. In the Betts model, the plate with the South and

North Australia cratons would be moving southward relative to the stationary plume. Therefore, the magmatism on the southern Gawler craton would be younging towards the north (Figure 4.16).

In an attempt to account for published geological and paleomagnetic constraints Betts et al. (2016) suggested South Australia and Laurentia may not have remained together after amalgamation at ca. 1850 and 1740 Ma. Betts et al. (2016) suggests an ocean opened between South Australia and Laurentia between ca. 1740 and 1710 Ma with subduction along the Laurentia margin. Around ca. 1640 and 1555 Ma subduction switched from Laurentia to Australia with convergence of South Australia and Laurentia around 1595 Ma but still separated by a small ocean (Figure 4.16).

One issue with the Betts model is the presence of a short duration but widespread 1590 Ma mafic magmatic pulse (discussed above) in South Australia and western Laurentia (Tobacco Root Mountains and Western Channel Diabase). The presence of subduction zones along the eastern margin of South Australia and western margin of Laurentia would not permit the uniformity in chemistry, and would also be problematic for the common 1590 Ma age. The subduction zone magmatism along each margin would presumably yield different geochemical signatures depending on the overlying lithosphere, and the composition of subducting slab and overlying sediments. Additionally, ca. 1590 Ma felsic magmatism on South Australia may not be related to subduction but rather may be crustal melts caused by crustal underplating (Blissett et al. 1993;

Johnson and Cross 1995; Skirrow et al. 2002; Agangi et al. 2011) associated with a plume (See Section 4.9.4.2).

Any small ocean modelled to exist between western Laurentia and Australia should have closed by 1590 Ma or would have ceased contracting (Figure 4.16). A hypothesis that is supported by Thorkelson and Laughton (2016) who suggest that the ocean would have closed between 1.64 and 1.60 Ga with the obduction of the Bonnetia microcontinent (?) onto western Laurentia. Additionally, geological evidence supports South Australia and western Laurentia being joined until ca. 1460 Ma with rifting of the Belt-Purcell basin (Medig et al. 2014, 2016; Furlanetto et al, 2016; Thorkelson and Laughton 2016).

4.9.5.2 1590 Ma Plume Center-Dyke Swarm Model

Hamilton and Buchan (2010) place the Gawler and Curnamona cratons next to northwestern Laurentia ca. 1590 Ma based on paleomagnetic and geochronological data of the Gawler Range units in comparison with the Western Channel Diabase (Figure 4.17). This model does not include any subduction zone between Laurentia and Australia at this time (cf. Hamilton and Buchan, 2010, particularly their Figure 4.9). The absence of subduction zones would allow a single plume to emplace similar mafic dyke swarms and evolved magmas in all three cratons at ca. 1590 Ma.

Mapping of sedimentary basins suggest that by 1600 Ma the two cratons were connected (Figure 18; Medig et al. 2014,).

In both the Hamilton and Buchan (2010) and the Medig et al. (2014) reconstructions the plume emplacement model based on geochemistry is similar.

The plume head melts metasomatized lithospheric mantle that is locally enriched with three crustal-type components: 1) upper crust-type metasomatized lithosphere with ϵNd of -9 (ML-1), 2) upper crust-type metasomatized lithosphere with ϵNd of -4 (ML-2) and 3) middle crust-type metasomatized lithosphere with ϵNd of +1 (ML-3; Figure 4.14). The data in this ϵNd vs. Th/Y plot (Figure 4.19a and b) plot between the mixing curves of ML-1-EMORB and ML-2-EMORB, suggesting three-way mixing of ML-1, ML-2 and EMORB end-member sources rather than two distinct mixing trends of ML-1-EMORB and ML-2-EMORB. Also, both Hamilton and Buchan (2010) and Medig et al. (2014) models will emplace dykes into areas over 1000 km from the plume centre.

The Medig et al. (2014) model is similar, but places the South Australia Craton approximately 500-1000 km further south along the western Laurentia margin than the Hamilton and Buchan (2010) model. Additional geological constraints are required to favour one model over the other.

4.9.5.3 Homogeneity of Dykes Along Strike

Figure 4.19a and b shows dyke emplacement laterally in the crust for a distance of approximately 2000 km from local chambers, but we are inferring that the compositional characteristics do not vary during such long-distance lateral emplacement. Studies have shown in similar size LIP events (e.g., Great Abitibi Dyke, Marathon-Fort Frances LIP) that REE (and other incompatible element) geochemistry may not be modified along strike (Ernst and Bell 1992; Halls et al. 2008; Ernst, 2014). Contamination was typically limited to the first 50 cm of the

dyke-host rock contact (Ernst and Bell 1992) and rapid cooling of magma in contact with the cooler host rock may have insulated magmas in the central parts of the dyke from further contamination. Therefore, dykes in the Tobacco Root Mountains, and Western Channel Diabase may have also been emplaced long distances laterally through the crust without further contamination.

4.9.5.4 Olympic Dam and Wernecke Breccias, Underplate Association

Magmatic underplate at the base of the crust may be the catalyst for hydrothermal brecciation of the ca. 1590 Ma Olympic Dam breccias (Oreskes and Einaudi 1990; Blissett et al. 1993; Johnson and Cross 1995; Skirrow et al. 2002; Agangi et al. 2011) and 1599 Ma Wernecke breccias (Thorkelson et al. 2005; Furlanetto et al. 2013). The Hiltaba Suite granitoids, specifically the Roxby Downs granite, may have formed by crustal underplating or mantle diapirism (Figure 4.16; Giles 1988; Blissett et al. 1993; Johnson and Cross 1995).

Geophysical evidence supports this view, indicating the presence of large volumes of mafic material in the lower crust (Stewart and Foden 1990 as cited in Johnson and Cross 1995). Johnson and Mcculloch (1995) suggested crustal rocks cannot account for ϵNd -isotope signatures in the Olympic Dam deposit but at least 13% of the Nd was derived from mantle melts leading to approximately 50% of the Cu coming from mantle sources.

Both the Olympic Dam region and the Wernecke breccias are located between 200-300 km from our proposed plume centre, and could conceivably be

located along the edge of the underplate caused by this plume (Figure 4.16).

This is consistent with a recent model that suggests large intrusions may circumscribe a plume centre at a distance of between 150 and 500 km away and be associated with the margin of a magmatic underplate centered above an underlying mantle plume (Blanchard et al. 2017).

Similarly, this underplate model may also explain the compositional differences between the 1590 Ma mafic magmatism of South Australia, and NW to W Laurentia. Magma chambers maybe generated along the edge of the magmatic underplate (Baragar et al. 1996, Blanchard et al. 2017), for the different 1590 Ma units on different sides of the plume centre and potentially pond in overlying magma chambers before being erupted or injected laterally outward from the plume centre region via dykes (which has noted can remain uncontaminated over long distances of lateral transport). Each region of 1590 Ma magmatism could therefore have a different lithospheric contamination story. For instance, the Gawler and Curnamona craton magmas would be generated from a source region on the north side (present coordinates) of the 1590 Ma plume centre (i.e. under the edge of the Gawler craton), and thus have the greater depth of melting and contamination with ML-1 components (Figure 4.19). On the other hand, the Western Channel and Tobacco Root magmas of Laurentia would be generated from the eastern and southeastern sides (present coordinates) of the 1590 Ma plume centre at the edge of the hypothesized underplate. This Laurentian 1590 Ma magmatism is predicted to be generated from thinner lithosphere on the eastern side (present coordinates) of the plume centre and

with ML-2 type crustal component contamination, and then been laterally emplaced via dykes to the Western Channel and Tobacco Root regions.

4.9.6 Origin of 1550 Ma (post-1590 Ma) Magmatism

In contrast to the 1590 Ma magmatism, which represents a widespread plume head pulse encompassing W and NW Laurentia and the South Australian craton, the 1550 Ma Ramshorn Creek mafic magmatism is recognized (so far) only in the Tobacco Roots mountains. It is also notable the 1550 Ma Ramshorn Creek group has similar geochemistry to the 1590 Ma WC-1 group of the Western Channel Diabase, GR-1 and CUR-1 of the South Australia craton. Therefore, the Ramshorn Creek group was derived from the same mantle source and/or from similar processes, but this occurred approximately 40 Ma later. With a geochemical composition closer to the MORB-OIB array (Figure 4.10), it is conceivable the ca. 1550 Ma magmatism is associated with attempted rifting and decompression melting.

Consider the 1590 Ma dykes as part of a radiating swarm associated with domal uplift above a 1590 Ma plume. One arm of associated triple junction rifting (associated with that uplift) could be developed parallel to the western margin of Laurentia. In this case the rifting (40 Ma later) can be associated with a second pulse of dykes (the 1550 Ma Ramshorn Creek dykes) that are possibly emplaced vertically above decompression melting of the mantle source underlying the zone of rifting and yielding more EMORB like chemistry. In other words, the 1590 Ma widespread pulse is related to mantle plume arrival while the ca. 1550 Ma

Ramshorn Creek pulse (in the Tobacco Root Mountains) would be related to an onset of attempted breakup and decompression melting 40 Ma later along the Laurentian margin.

The time gap between the first LIP pulse (related to plume head arrival) and a second pulse (associated with onset of rifting and decompression melting) can be variable (Ernst, 2014, p. 494-495). It can be hypothesized that if regional plate boundary stress regimes are not favorable to breakup, then the second LIP pulse will not occur, or be delayed until the stress regime changes to being more favourable to breakup (or attempted breakup). An example of delayed rifting associated with a mantle plume is the ca. 2125-2100 Ma Marathon and 2075 Ma Fort Frances dykes of the Marathon-Fort Frances LIP of the southern Superior craton (Halls et al. 2008; Ernst and Bleeker 2010). The Marathon dykes are thought to represent deeper melts as a result of the plume impacting the lithosphere and the later Fort Francis dykes are melts of thinned lithosphere possibly as a result of the onset of rifting 25-50 Ma later.

An example of attempted but failed breakup is the following. The massive 250 Ma Siberian Trap LIP attempted to cause breakup between Asia and Europe in the West Siberian Basin; however, plate boundary stress were not favourable to new ocean formation and so although major rifting was developed in the West Siberian basin breakup did not occur (see discussion in Ernst, 2014).

A period of minimal subaerial deposition of sediments in northwest Laurentia represents a period of crustal stability between 1600 to 1380 Ma (Thorkelson et al. 2005), whereas at ca. 1470 Ma in western Laurentia (the Belt-

Purcell Basin) started to undergo extension (Ross et al. 1992; Thorkelson et al. 2005). An older deformation event predating the Moyie-Purcell LIP consists of Proterozoic faulting in a west-northwest trending rift at about 1.5 Ga. (Chandler, 2000). The 1550 Ma Ramshorn Creek group may represent that earlier attempted rifting (Figure 4.1A).

4.9.7 Model Summary

It is obvious from the preceding discussion that the relationship between South Australia and western Laurentia is quite complex and current models have yet to explain all the geological constraints. The true story of Australia and Laurentia is probably a combination of several models. Our plume model brings some support to the Betts 1590-1550 Ma plume and hotspot track model (Section 4.9.4.1) with several modifications. A plume head at ca. 1600 Ma centered between Australia and Laurentia can induce widespread melting of the lithosphere, which is observed in the ca. 1590 Ma mafic rocks in the Tobacco Root Mountains, Western Channel Diabase and South Australia. These melts in turn could rise to underplate the crust and provide heat to generate crustal melts of the Gawler Range granites that fed the felsic components of the Gawler Range and Benagerie Volcanic Suite. Additionally, both Olympic Dam and Wernecke Breccias are located a few hundred km away from this plume centre are hypothesized to be linked with mafic magmatism associated with the edges of a magmatic underplate. However, for the plume to provide heating that fueled

the hydrothermal circulation it would have arrived at the base of the lithosphere ca. 1600 Ma.

Arrival of the plume head and crustal underplating is probably the source of the mafic melts in the Tobacco Root Mountains, Western Channel Diabase and South Australia craton ca. 1590 Ma. The samples from the Gawler and Curnamona cratons were generated at a greater mantle depth than the samples belonging to the 1590 Ma Mammoth group or the 1590 Ma Western Channel Diabase (Figure 4.11). Also, the samples from the Gawler and Curnamona cratons have more crustal-like enrichment than the samples from western Laurentia. A scenario is proposed to generate the ca. 1590 Ma magmas:

- 1). It is possible that a thick lithosphere beneath the Gawler and Curnamona cratons thinned towards the Laurentian craton further supporting a heterogeneous mantle composition for the ca. 1590 Ma pulse (Figure 4.19). Magma from the underplate interacted with the different lithospheric terranes (with different metasomatic crustal-like components) on opposite sides of the plume head and yielded the different geochemical signatures. Magmas were then injected laterally through the crust away from the plume centre to their sampled locations in NW and W Laurentia and the Gawler and Curnamona cratons.

The 1590 Ma hot spot track for the Betts model is still valid as it accurately explains the younging of magmatism northward on the South Australia and North Australia cratons. However, the ca. 1550 Ma mafic magmatism in the Tobacco

Roots Mountains could be explained by the onset of a pulse of rifting and attempted breakup along the western Laurentia margin.

4.10 CONCLUSIONS

- 1) New U-Pb baddeleyite ages of $\text{Ma } 1590 \pm 5$ and 1550.6 ± 5.2 Ma ages for dykes in the Mammoth and Ramshorn Creek groups, respectively, confirm the presence of a previously unrecognized intraplate magmatic pulse in western Laurentia. Thus the 1590 Ma Mammoth and 1550 Ma Ramshorn Creek groups dykes are not related to the widespread ca. 1460 Ma Moyie-Purcell LIP, nor the 780 Ma Gunbarrel LIP;
- 2) The 1590 Ma Mammoth group matches geochronologically and geochemically with group WC-2 of ca. 1590 Ma Western Channel Diabase intrusions suggesting a previously unrecognized ca. 1590 Ma Mammoth-Western Channel LIP extending from the Wyoming craton to northwestern Laurentia 2000 km to the north, and plausibly in between under younger cover rocks;
- 3) Detrital zircon studies in east-central Idaho and the Belt Supergroup have noted a ca. 1590-1550 Ma age - within the 1610-1490 Ma North American Magmatic Gap - that had not previously been linked with any units in western Laurentia and were used to argue for an external source in a crustal block formerly to the west. Felsic magmatism inferred to be associated with the proposed ca. 1590 Ma Mammoth-

Western Channel LIP and 1550 Ma Ramshorn Creek magmatic pulse provide a plausible local provenance for this population of detrital ages;

- 4) Previous studies suggesting the South Australian craton was connected to NW Laurentia support a link between the ca. 1590 Ma Western Channel Diabase and ca. 1599 Ma Wernecke Breccias of NW Laurentia and the ca. 1590 Ma Gawler Range bimodal magmatism and associated Olympic Dam IOCG ore deposits of the Southern Australian craton. A continuation of ca. 1590 Ma magmatism into the Wyoming craton expands the size (~3000 linear km) and potential metallogenic significance of this reconstructed LIP, and suggests a single plume is responsible;
- 5) The plume centre can be located on the basis of 1590 Ma dyke orientations in the Tobacco Root Mountains and Western Channel Diabase, which may form part of a radiating dyke swarm whose trends can be extrapolated to locate the plume centre west of the western Laurentia craton. In the preferred Gawler craton vs Laurentia reconstruction, this plume centre would be located just south of the Gawler craton;
- 6) With reference to this plume centre, Olympic Dam and Wernecke Breccias are both located a few hundred km away from this interpreted plume centre and are possibly along the edge of a magmatic underplate, a region that can be associated with major mid-crustal

intrusions from which magma can be laterally injected as dykes to the different 1590 Ma units in the Tobacco Root Mountains.

- 7) The 1590 Ma magmas with their unique chemistries (of a common E-MORB composition, but variable enrichment from metasomatized lithosphere) can be understood in a model in which the magmas are generated from the edge of the underplate on different sides of the plume centre and therefore interacting with different lithospheric terranes and then being erupted as lavas on South Australia and laterally through the crust as dykes away from the plume centre region in the Tobacco Root Mountains.
- 8) A modified version of the Betts plume track model is a valid hypothesis for generation of mafic magmas on South Australia, and Laurentia cratons, without the presence of subduction activity along the margins of Laurentia and South Australia that would need to have ended prior to arrival of the plume head ca. 1590 Ma. The location of South Australia with respect to western Laurentia cannot be ascertained from this study but locations from Hamilton and Buchan (2010) or Medig et al. (2014) are both possible.
- 9) The ca. 1550 Ma Ramshorn Creek Group may represent a phase of rifting prior to the main rifting event at ca. 1470 Ma that generated the Belt-Purcell Basin. Similar geochemistry from ca. 1590 Ma samples from WC-1, GR-1 and CUR-1 may be generated from melting under thinner lithosphere during initial melting on arrival of the plume head.

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Figure 4.1a: Map of Proterozoic mafic magmatism in eastern Laurentia. Symbols represent samples from this study RCG=Ramshorn Creek Group, MG=Mammoth Group (modified from Rogers et al. 2016).

Figure 4.1b: Map of Proterozoic mafic magmatism in the Tobacco Root Mountains. Symbols represent samples from this study RCG-Ramshorn Creek Group, MG=Mammoth Group (modified from Rogers et al. 2016).

Figure 4.1c: Map of Western Channel Diabase outcrops and sample locations WC-1=Ramshorn Creek Group like samples, WC2-Mammoth Group like samples (modified from Irving et al. 1972).

Figure 4.2: Concordia plot of sample TR-05 which dates the Ramshorn Creek swarm.

Figure 4.3 Concordia plot of sample 14-CR-1-1, which dates the Mammoth swarm

Figure 4.4 TAS diagram of samples from the Tobacco Root Mountains, Western Channel Diabase and South Australia Craton. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3, 14-CR-1-1 (MG), TR-05 (RCG), and FA66-045 (WC-1) samples dated in this study.

Figure 4.5 7 Zr/Y vs. Ti/Y plot showing intraplate nature of samples in the Tobacco Root Mountains, Western Channel Diabase and South Australia Craton. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3, 14-CR-1-1 (MG), TR-05 (RCG), and FA66-045 (WC-1) samples dated in this study.

Figure 4.6 Rare earth element plot of samples in the Tobacco Root Mountains, Western Channel Diabase, (NWT) South Australia craton. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Cumamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3.

Figure 4.7 Extended rare earth element plot of samples in the Tobacco Root Mountains, Western Channel Diabase, (NWT) South Australia craton. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1=Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3=Gawler Range Volcanics group, CUR-1=Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3=Curnamona craton volcanic rocks group similar to GR-3.

Figure 4.8 Concordia plot of sample FA66-045-6 from the Western Channel Diabase.

Figure 4.9 Plot of detrital zircon from the Gunsight Fm in the Belt-Purcell Basin. After Link et al. 2000, with arrows added to located 1590 and 1550 Ma magmatic pulses of this study).

Figure 4.10 Plot of the MORB-OIB array showing samples of the Tobacco Root Mountains, Western Channel Diabase and South Australia Craton. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1=Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3=Gawler Range Volcanics group, CUR-1=Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3=Curnamona craton volcanic rocks group similar to GR-3, 14-CR-1-1 (MG), TR-05 (RCG), and FA66-045 (WC-1) samples dated in this study. (modified after Pearce, 2008).

Figure 4.11 Plot of $(Gd/Yb)_{PM}$ vs. $(La/Sm)_{PM}$ showing depth of melting relative to crustal contamination for the Tobacco Root Mountains, Western Channel Diabase and South Australia Craton. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1=Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3=Gawler Range Volcanics group, CUR-1=Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3=Curnamona craton volcanic rocks group similar to GR-3, 14-CR-1-1 (MG), TR-05 (RCG), and FA66-045 (WC-1) samples dated in this study.

Figure 4.12 Plot of $\epsilon_{Nd(i)}$ vs. $(La/Sm)_{PM}$ of the he Tobacco Root Mountains, Western Channel Diabase and South Australia Craton. Inset is plot of $\epsilon_{Nd(i)}$ vs. SiO_2 . MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3, 14-CR-1-1 (MG), TR-05 (RCG), and FA66-045 (WC-1) samples dated in this study.

Figure 4.13 Plot of Th/Nb vs. TiO_2/Nb showing mantle source and crustal contamination. DUL=Depleted Unmodified Lithosphere, AM=Asthenospheric Mantle, OML=Ocean Island Basalt Modified Lithosphere, SML=Subduction Modified Lithosphere. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3, 14-CR-1-1 (MG), TR-05 (RCG), and FA66-045 (WC-1) samples dated in this study (after Pearce et al. 2015).

Figure 4.14 Th/Y vs. $\epsilon\text{Nd}(i)$ mixing curves for the Ramshorn Creek group, Mammoth group and South Australia craton samples. MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3, 14-CR-1-1 (MG), TR-05 (RCG), and FA66-045 (WC-1) samples dated in this study.

Figure 4.15a Plot DePaolo Nd evolution curve for the Ramshorn Creek and geochemically similar samples. Red Star=RCG, Grey Stars=Mammoth Group, and GR-3/CUR-3, MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3.

Figure 4.15b Plot DePaolo Nd evolution curve for the Mammoth Group and geochemically similar samples. Red Star=Mammoth Group, Grey Stars= RCG, and GR-3/CUR-3, MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3.

Figure 4.15c Plot DePaolo Nd evolution curve for the GR-3 and CUR-3 geochemical groups. Red Star= GR-3/CUR-3, Grey Stars=RCG and Mammoth Group, MG=Mammoth Group, RCG=Ramshorn Creek Group, WC-1=Western Channel Diabase group similar to RCG, WC-2=Western Channel Diabase group similar to MG, GR-1= Gawler Range Volcanics group similar to RCG, GR-2=Gawler Range Volcanics group similar to MG, GR-3= Gawler Range Volcanics group, CUR-1= Curnamona craton volcanic rocks group similar to RCG, CUR-2=Curnamona craton volcanic rocks group similar to MG, CUR-3= Curnamona craton volcanic rocks group similar to GR-3.

Figure 4.16 Schematic map of the Betts plume track model showing the location of Western Channel Diabase, Tobacco Root Mountains and South Australia samples. (modified after Bettes et al. 2016)

Figure 4.17 Schematic map of the location of ca. 1590 Ma mafic magmatism on western Laurentia and South Australia cratons. GR=Gawler Range Volcanics 1592 Ma; GC=Gawler Craton (Outlined in solid black line); HS=Hiltaba Suite granites 1600-1580 Ma (Outlined in dashed line); CC=Curnamona Craton (Outlined in solid black line); PMWB=Wernecke Breccias 1599 Ma (Outlined in light blue); ODB=Olympic Dam Breccias 1593 Ma; BV=Benagerie volcanic rocks 1590-1550? Ma; WC=Western Channel Diabase 1590 Ma; DC=ca. 1600 Ma Diatrema clast in Mackenzie Mountains; PC=Plume centre located by large red star; MU=Magmatic underplate (Outlined by red circle); A-A' (blue dashed line) is cross-section between plume centre, Wernecke Breccias and Western Channel Diabase Figure 4.19; B-B' (blue dashed line) is cross-section between Gawler Range Volcanics, plume centre and Mammoth group, Figure 4.19b; red dashed line between GR and plume centre, inferred trend of feeder dykes; red dashed line between BV and plume centre, inferred trend of feeder dykes.

Figure 4.18 Cartoon of paleocontinental reconstruction of South Australia with respect to western Laurentia(after Medig et al., 2014). Star and red lines are superimposed. Star represents proposed plume center in this reconstruction and red lines represents trend of dykes in the Tobacco Root Mountains and associated with the Western Channel diabase.

Figure 4.19a Schematic of the cross-section of A-A' on Figure 4.16 showing a possible mantle configuration that produced the ca. 1590 Ma magmatism on western Laurentia

Figure 4.19b Schematic of the cross-section of B-B' on Figure 4.16 showing a possible mantle configuration that produced the ca. 1590 Ma magmatism on western Laurentia and South Australia

Table 4.1 Table of Sm-Nd

Sample	Location	Nd	Sm	AGE	Nd	Sm	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}_{(i)}$	eNd _(i)	TDM _(Ndi)
RCG											
MT-04	TRM	10.76	3.12	1550	9.88	2.88	0.512583	0.176193	0.510785	3.01	2138
14-CR-1-1	TRM	9.5	2.75	1550	10.96	3.14	0.512571	0.173231	0.510804	3.37	2028
TR-05	TRM	10.7	2.74	1550	10.19	2.91	0.512568	0.172692	0.510806	3.42	2013
TR-60	TRM	14.1	3.49	1550	13.31	3.65	0.512496	0.166014	0.510803	3.35	1959
HR-05	TRM	16.4	4.37	1550	16.27	4.32	0.512474	0.160643	0.510836	4	1825
FA66-045-06	WCD	14	3.6	1550	13.91	3.67	0.51241	0.159622	0.510783	2.93	1970
Mammoth Gp.											
TR-44	TRM	19.7	4.06	1590	19.52	4.39	0.512254	0.13587	0.510833	4.93	1676
10RB105	TRM	9.8	2.47	1590	9.94	2.49	0.512159	0.1515	0.510476	0.46	2320
FA66-042-07	WCD	9.3	2.2	1590	18.45	3.52	0.511888	0.115329	0.510682	1.97	1890

Table 4.2 U-Pb baddeleyite data for mafic dyke samples from the Wyoming craton (Tobacco Root Mountains) and Western Channel Diabase Northwest Territories.

Analysis No.	U ppm	Th/U	Pbc (pg)	Pb _T /Pbc	206Pb/208Pb measured	Ages (Ma)										Disc. (%)	
						27Pb/235U	206Pb/238U	2 σ	206Pb/238U	207Pb/206Pb	2 σ	206Pb/238U	± 2 σ	207Pb/238U	± 2 σ		207Pb/206Pb
TR-5 northwest-trending mafic dyke, Tobacco Root Mountains, Wyoming Craton																	
Bd-1	50	0.16	0.2	56.3	3688	3.539	0.019	0.0012	0.841	0.09618	0.00029	1525	6	1536	4	1551	1.9
Bd-2	38	0.14	0.6	4.2	294	3.508	0.102	0.0045	0.622	0.09572	0.00217	1520	23	1529	23	1542	1.6
Bd-3	24	0.15	0.2	10.1	683	3.449	0.070	0.0043	0.827	0.09571	0.00109	1497	22	1516	16	1542	3.3
14-CR-1-1 northwest-trending mafic dyke, Tobacco Root Mountains, Wyoming Craton																	
Bd-1 (2 grains)	na	na	na	7.2	435	2.976	0.036	0.0027	0.897	0.09742	0.00106	1290.2	13	1401.6	9	1575	18.1
Bd-2 (4 grains)	na	0.011	na	19.5	1300	3.449	0.024	0.0016	0.897	0.09811	0.00061	1464.1	8	1515.7	6	1588	7.8
Bd-3 (3 grains)	na	0.015	na	14.2	946	3.569	0.032	0.0023	0.914	0.09781	0.00072	1513.6	12	1542.7	7	1583	4.4
Bd-4 (6 grains)	na	0.013	na	46.3	3008	3.638	0.013	0.0007	0.748	0.09809	0.00047	1557.9	4	1535.6	3	1588	3.3
FA66045 Western Channel Diabase, eastern Great Bear Lake area, Northwest Territories																	
Bd-1	167	0.04	0.5	39.7	2688	3.716	0.016	0.0009	0.834	0.09794	0.00023	1567	5	1575	3	1585	1.3
Bd-2	194	0.06	0.4	46.4	3120	3.717	0.013	0.0007	0.823	0.09794	0.00020	1567	4	1575	3	1585	1.3
Bd-3	127	0.06	1.0	32.2	2171	3.741	0.014	0.0006	0.712	0.09804	0.00027	1575	3	1580	3	1587	0.9
Bd-4	132	0.07	0.5	75.6	5064	3.737	0.010	0.0006	0.863	0.09804	0.00014	1574	3	1579	2	1587	1.0

Notes:

na is not available
Th/U calculated from radiogenic 208Pb/206Pb ratio and 207Pb/206Pb age assuming concordance.
PbT/Pbc is total Pb (radiogenic+blank+initial)/total common Pb (blank+initial)
PbT is total amount of Pb excluding blank (U of T; Lund includes blank).
206Pb/204Pb corrected for fractionation and common Pb in the spike.
Pb/U ratios corrected for fractionation, common Pb in the spike, blank, and initial Pb using Stacey and Kramers (1975).
Error Corr is correlation coefficients of X-Y errors on the concordia plot.
Correction for 230Th disequilibrium in 206Pb/238U and 207Pb/206Pb assuming Th/U of 4.2 in the magma.
Disc is percent discordance for the given 207Pb/206Pb age

Chapter 5: Summary and Conclusions

5.1 SUMMARY

This dissertation has explored the geochemical, geochronological and tectonic characteristics of Mesoproterozoic mafic magmatism of the Michael-Shabogamo and Moyie-Purcell LIPs of eastern and western Laurentia, respectively. Both LIPs are approximately coeval at ca. 1460 Ma and were potentially considered to be two parts of a single magmatic event. However, through this study, distinct origins were determined for these widely separated ca. 1460 Ma LIPs and furthermore, additional magmatic suites were recognized in western Laurentia. The following sections assess the conclusions of Chapters 2, 3 and 4 followed by a statement on the comparison of the ca. 1460 Ma Moyie-Purcell and the Michael-Shabogamo LIPs.

5.2 REVIEW OF THE MOYIE-PURCELL LIP(S), WESTERN LAURENTIA

Chapter 2 identifies 17 geochemical signatures (GS) from NW-SE trending dykes and sills of the Belt-Purcell Basin and Wyoming craton (Table 5.1). Seven of them (GS 2, 3, 4, 5, 6, 11 and 12) can be correlated to the ca. 1460 Ma Moyie-Purcell LIP, and one group corresponds to the Gunbarrel LIP (GS 1). Geochemistry allows the 17 geochemical groups to be correlated over the region. Based on the geochemistry the Moyie-Purcell LIP should now be divided into two pulses: Pulse 1 at ca.1470 Ma (GS 2, 3, 5, 6, and 12) and a second younger Pulse 2 at 1455 Ma (GS 4 and GS 11) (Figure 5.1).

Two of the geochemical signatures (GS 7 and GS 8) are now recognized to represent a geochemically and geochronologically distinct event and I propose a new ca. 1550-1590 Ma Mammoth-Western Channel LIP (See Chapter 4 for details). Additional new groups, based on geochemistry and geochronology, include the 1418 Ma Highland Range Group (GS 9; Rogers unpublished data) and the 2480 Ma Elbow Creek Group (GS 10; Rogers unpublished data). In addition, the undated Nevada City Group (GS 13) and four other unnamed-undated groups cannot be correlated, based on geochemistry to either the Moyie-Purcell or Gunbarrel LIPs, nor the additional groups now dated at 2480, 1590, 1550, and 1418 Ma). It is now apparent that there are multiple Proterozoic intraplate events present in Western Laurentia besides the long-recognized ca. 1460 Ma Moyie-Purcell and 780 Ma Gunbarrel events (Figure 5.1).

5.3 REVIEW OF THE MICHAEL-SHABOGAMO LIP, EASTERN LAURENTIA

Originally considered as separate events, the Michael-Shabogamo Gabbro (MSG) are sub-alkaline, arc-like mafic intrusions that are part of a short multi-pulse event. New U-Pb baddeleyite ages of 1449 ± 3 Ma, 1437 ± 3 Ma, and 1435 ± 10 Ma presented in Chapter 3 augment older ages of 1426 ± 6 Ma, and $1452^{+15/-13}$ Ma. Detailed U-Pb geochronology and geochemical analysis of the MSG has shown that they were produced from melting of a metasomatized subcontinental lithospheric mantle (M-SCLM) that contained approximately 10% apatite and 15% mica. Heat, to stimulate melting, was from a slab window

opening beneath the M-SCLM allowing the influx of hot asthenosphere. Melting took place in two pulses and generated a distinct geochemical signature for each pulse. The P/Zr ratios, which inversely may correlate with time (e.g., older MSG units have the lowest P/Zr ratio and vice-versa) show that melting of apatite increased and the melting of phlogopite decreased over time as the M-SCLM dehydrated. The M-SCLM may have persisted for at least 325 Ma years after the MSG because younger mafic intrusions, as young as approximately 1100 Ma, are also enriched in P_2O_5 (Figure 5.1).

5.4 REVIEW OF THE MAMMOTH-WESTERN CHANNEL LIP

In Chapter 4 new U-Pb baddeleyite ages of 1550.6 ± 5.2 Ma and 1590 ± 3 Ma for some Tobacco Root Mountains dykes build on geochemical differences identified in Chapter 2. They demonstrate a previously unknown intraplate magmatic pulse in western Laurentia, the Mammoth-Western Channel LIP, which is 100-150 Ma older than the widespread two-pulsed 1470-1455 Ma Moyie-Purcell LIP (Chapter 2).

It is then shown that the 1550 Ma Ramshorn Creek and 1590 Ma Mammoth groups of the Tobacco Root Mountains are geochemically and geochronologically related to the 1590 Ma Western Channel Diabase of northwest Laurentia. Previous paleomagnetic data and other lines of evidence support a reconstruction in which the South Australian craton was connected to NW Laurentia at this time. This reconstruction results in a regional extensive

pulse of 1590 Ma magmatism comprising the Mammoth Group of western Laurentia, the Western Channel Diabase, and the Gawler Range bimodal LIP and associated Olympic Dam IOCG ore deposits of the Southern Australian craton. Overall, the geochemistry comparison of these ca. 1590 Ma mafic rock packages indicates that an EMORB mantle source that has been contaminated by different lithospheric sources, all associated with a single mantle plume.

Trends of the ca. 1590 Ma dykes in the Tobacco Root Mountains (Mammoth swarm) and Western Channel Diabase converge towards an interpreted plume centre located between the reconstructed South Australian (Gawler and Curnamona) and Laurentian cratons at ca. 1590 Ma. Previous studies have shown that a belt of felsic intrusions younging from 1590-1550 Ma from southern Australia to northern Australia are linked to the continuation of the 1590 Ma plume as a hotspot track (with Australia moving southward over the hotspot). However, the 1550 Ma Ramshorn Creek mafic pulse in the Tobacco Root Mountains was derived from metasomatized lithospheric mantle and EMORB-like mantle, possibly associated with a pulse of attempted rifting and decompression melting along western Laurentia.

5.5 ARE THE CA. 1460 MA MAGMATISM IN WESTERN AND EASTERN LAURENTIA RELATED?

Research into the geochemistry and geochronology of ca. 1460 Ma mafic magmatism has been successful in accomplishing the goals of this thesis. The

preceding chapters have: 1) characterized the geochemical variations within the ca. 1460 Ma magmatism of eastern and western Laurentia and 2) determined the source, tectonic setting and modeled the ca. 1460 Ma magmatism of eastern and western Laurentia in terms of source and subsequent differentiation processes. As well, additional unexpected suites in western Laurentia were discovered and modeled (e.g., at 1590-1550 Ma; Chapter 4).

The final goal of this thesis was to compare the petrogenesis of ca. 1460 Ma magmatism of eastern and western Laurentia and test if they are related by a single superplume, or unrelated and coincidentally formed at ca. 1460 Ma. Chapter 2 confirmed the Moyie-Purcell LIP was formed by intraplate magmatism and was plume related. However, Chapter 3 demonstrated the Michael-Shabogamo Gabbro was formed by intraplate magmatism and are melts of a metasomatized subcontinental lithospheric mantle. Thus ca. 1460 Ma Moyie-Purcell LIP is not related to the ca. 1460 Ma Michael-Shabogamo Gabbro. The formation of the ca. 1460 Ma magmatism on eastern and western Laurentia was therefore *not* related to a single underlying plume (Figure 5.1).

5.6 LESSONS MOVING FORWARD

Without taking a step back and looking at the larger regional framework, smaller isolated studies of geochemistry and geochronology alone may not tell the whole story. For example, localized geochemical and geochronological studies by Anderson and Davis (1995); Anderson and Goodfellow (2000);

Anderson and Parrish (2000) of the Moyie sills, combined with geochronological studies by Sears et al. (1998) and Chamberlain et al. (2000) led to the conclusion that most of the Proterozoic magmatism in western Laurentia was related to the ca. 1460 Ma Moyie-Purcell or ca. 780 Ma Gunbarrel LIPs. With the available data it was a good interpretation. However, with an intensive regional geochemical and geochronological sampling program this project was able to identify and date many more geochemical groups that range in age.

This is well illustrated for the intrusive (dyke and sill) units of western Laurentia, where a majority of the samples studied, about 69%, belonged to the the Gunbarrel and Moyie-Purcell LIPs. Smaller percentages of samples belonged to the new events discovered in Chapters 2 and 4: 18% for the 1590-1550 Ma Mammoth-Western Channel LIP, 4% for the 1420 Ma Highland Mountain group, 3.5% for the undated Nevada City group, 1.5% for the 2480 Ma Elbow Creek group, and the 3 remaining groups comprises 4% of the total samples collected. Consequently, it is easy to appreciate why the events with smaller number of units are only likely to be recognized in more comprehensive studies.

5.7 PUBLICATIONS FROM THIS THESIS.

To date multiple abstracts (9), publications (3) and internal reports (7) have been produced. Conference abstracts are listed in Appendix 5.1.

5.7.1 Peer Reviewed Publications

- a) **Rogers, C.**, Harlan, S., C., Kamo, S., Söderlund, U., Hamilton, M., Ernst, R.E., and Cousens, B., 2017, A Newly Discovered ca. 1550 - 1590 Ma Intraplate Mammoth-Western Channel LIP in the Wyoming Craton, and NW Laurentia, and Links With the South Australia craton, Australia, Submitted to Journal of Petrology Accepted with revisions August 25 2017
- b) **Rogers, C.**, Soderlund, U., Cousens, B., and Ernst, R.E., 2017, Phosphorous and Potassium Metasomatic Enrichment In the Mantle Source Of theca. 1450-1425 Ma Michael-Shabogamo Gabbros Of Eastern Laurentia. Submitted to Journal of Petrology June 9, 2017
- c) **Rogers, C.**, Mackinder, A., Ernst, R.E., and Cousens, B., 2016, Mafic magmatism in the Belt-Purcell Basin and Wyoming Province of western Laurentia, in MacLean, J.S., and Sears, J.W., eds., Belt Basin: Window to Mesoproterozoic Earth: Geological Society of America Special Paper 522,1–40

5.7.2 Conferences

- a) **Rogers, C.**, Ernst, R.E., Cousens, B., Soderlund, U., Hamilton, M., Harlan, S. 2016 Newly recognized 1550-1590 Ma Tobacco Root -Western Channel LIP, and further evidence for bringing South Australia back home to Western Laurentia. Abstracts with Program GAC-MAC Whitehorse, YT Canada, June 1-3

- b) **Rogers, C.**, Ernst, R.E., Cousens, B., Soderlund, U., Gower, C.2016
Phosphorous and Potassium enrichment in the Michael-Shabogamo
magmatic event of eastern Laurentia; can intense mantle metasomatism
be responsible? Abstracts with Program GAC-MAC Whitehorse, YT
Canada, June 1-3
- c) Rogers, C., Ernst, R.E., Cousens, B., Soderlund, U., and Gower, C.2016
Persistent Proterozoic Metasomatized Mantle Produces the Phosphorous-
Potassium Enriched Michael-Shabogamo Gabbros, Seal Lake Dykes and
Aillik Dykes of Eastern Laurentia Abstracts with Program AESRC Ottawa
Canada April 1-3
- d) **C. Rogers**, R.E. Ernst, B. Cousens, S. Harlan., Soderlund, U., 2015
Newly discovered 1550 Ma mafic magmatism in the Tobacco Root
Mountains, MT USA: An end to the North American Magmatic Gap?
Abstracts with Program AGU/GAC-MAC Joint Assembly Montreal Canada
May 3-7
- e) **Rogers, C.**, Mackinder, A., Ernst, R.E., and Cousens, B., 2014.
Geochemical and geochronological characterization of multiple
generations of mafic magmatism in the Belt-Purcell and Wyoming Basins,
focusing on the Moyie-Purcell ca. 1460 Ma intraplate magmatic event.
Abstracts with Programs - Geological Society of America Rocky
Mountain/Cordilleran Joint Sections, 19–21 May, Bozeman,
Montana,46,70

- f) **Rogers C.**, Ernst R. and Cousens B. 2014 Geochemistry and Geochronology of ca. 1460 Ma Mafic Magmatic Nodes Beneath the Laurentian Craton: Characterization of Plume and Lithosphere Activity Below Laurentia. Abstracts with Programs AESRC Ottawa, ON March 28-30
- g) **Rogers, C.**, Mackinder, A., Ernst, R.E., and Cousens, B., 2014. Sm-Nd isotopic, and geochemical characterization of mafic magmatism in the Belt-Purcell and Wyoming Basins, comparing the single pulse ca. 780 Ma Gunbarrel and the multiple pulses of the Moyie-Purcell ca. 1460 Ma intraplate magmatic events. Abstracts with Programs - Geological Society of America GSA Vancouver Canada October 19-22, 46,708
- h) **Rogers, C.**, Ernst, R., Cousens, B., and Gower, C., Harlan, S., 2013. Characterization of distinct nodes of ca. 1460 Ma intraplate magmatism in the Laurentian craton, using petrography, geochemistry, geochronology and paleomagnetism, and implications for the configuration of the supercontinent Columbia (Nuna) and associated metallogeny. Poster - Belt Symposium V, July 31-August 4, Salmon ID, USA.
- i) **Rogers, C.**, 2013. Characterization of ca. 1460 Ma magmatism in the Laurentian Craton, and implications for the Configuration of the supercontinent Columbia (Nuna) and associated metallogeny. Presentation PDAC Sponsors meeting - Reconstruction of Supercontinents Back to 2.7 Ga Using the Large Igneous Province (LIP)

Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution. Sponsors Workshop: Year 3 Results Moving Forward on Reconstructions, 2 March 2013, Toronto, Canada.

- j) **Rogers, C.**, Ernst, R., Cousens. B., and Gower, C., 2013).

Characterization of distinct nodes of ca. 1460 Ma intraplate magmatism in the Laurentian craton, using geochemistry, geochronology and paleomagnetism and implications for the configuration of the supercontinent Columbia (Nuna). Poster - Reconstruction of Supercontinents Back to 2.7 Ga Using the Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution. Sponsors Workshop: Year 3 Results Moving Forward on Reconstructions, 2 March 2013, Toronto, Canada.

- k) **Rogers, C.**, Ernst, R., Cousens. B., and Gower, C., 2013.

Characterization of distinct nodes of ca. 1460 Ma intraplate magmatism in the Laurentian craton, using geochemistry, geochronology and paleomagnetism and implications for the configuration of the supercontinent Columbia (Nuna). Poster - PDAC-SEG Canada Student Minerals Colloquium, 4 March 2013, Toronto, Canada.

5.7.3 Non Peer Reviewed Publications and Reports

- a) **Chris Rogers**, Richard Ernst, Brian Cousens, Ulf Söderlund, Steve Harlan and Alana Mackinder, 2016. Importance of geochemistry as a fingerprinting tool for LIPs: Example from Proterozoic mafic magmatism in the Belt-Purcell Basin and Wyoming province of western Laurentia LIPs Commission Website, LIP of the Month Series, July 2016
<http://largeigneousprovinces.org/16jul>
- b) **Chris Rogers**, Ulf Söderlund, Richard E. Ernst, and Charlie Gower 2015. The ca.1647-1623 Ma Ossok Mountain Intrusive Suite intraplate event of Labrador *Unpublished Report A209 of the Project: Reconstruction of Supercontinents Back to 2.7 Ga Using the Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution*(www.supercontinent.org).
- c) **C. Rogers**, U. Söderlund, R.E. Ernst, C. Gower, A. Kerr, & B. Cousens 2015 the ca.1440 Ma Michael-Shabogamo LIP of eastern Laurentia: new U-Pb geochronology and geochemical characterization *Unpublished Report A207-208 of the Project: Reconstruction of Supercontinents Back to 2.7 Ga Using the Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution* (www.supercontinent.org).

- d) **Chris Rogers**, Ulf Söderlund & Richard E. Ernst, 2015 Evidence supporting widespread ca.1420 Ma intraplate magmatism in western Laurentia, from the Belt Basin to the Wyoming Craton. *Unpublished Report A199 of the Project: Reconstruction of Supercontinents Back to 2.7 Ga Using the Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution (www.supercontinent.org).*
- e) **Chris Rogers**, Ulf Söderlund & Richard E. Ernst 2014. The 2480 Ma Elbow Creek- Blue Draw event of the Wyoming craton: link with the Matachewan LIP of the Superior craton. *Unpublished Report A191 of the Project: Reconstruction of Supercontinents Back to 2.7 Ga Using The Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution (www.supercontinent.org).*
- f) **C. Rogers**, R. Ernst, S. Harlan, & U. Söderlund 2013 Potentially widespread 1590 (-1550) Ma intraplate event in western and northwestern Laurentia and link with the Southern Australia craton *Unpublished Report A183 of the Project: Reconstruction of Supercontinents Back to 2.7 Ga Using The Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution (www.supercontinent.org).*

- g) S. Harlan, S. Kamo, U. Söderlund, **C. Rogers**, & R. Ernst 2013, New 1550 Ma intraplate event recognized in the Wyoming Craton *Unpublished Report A146 of the Project: Reconstruction of Supercontinents Back to 2.7 Ga Using The Large Igneous Province (LIP) Record: With Implications For Mineral Deposit Targeting, Hydrocarbon Resource Exploration, and Earth System Evolution* (www.supercontinent.org).

5.8 REFERENCES

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Figure 5.1 Summary sketch of the results of this thesis. MPL-P1=1st ca. 1470 Ma pulse of the Moyie-Purcell LIP, MPL-P2=2nd ca. 1470 Ma pulse of the Moyie-Purcell LIP, HR=ca. 1420 Ma Highland Range Group, Gunbarrell LIP= ca. 780 Ma Gunbarrell LIP, RCG=ca 1550 Ma Ramshorn Creek Group, pulse of the proposed ca. 1590 Mammoth-Western Channel LIP, MG=ca. 1590 Ma pulse of the Mammoth Group pulse of the proposed Mammoth-Western Channel LIP, EC=ca. 2840 Ma Elbow Creek Group, MSG-H. P/Zr=ca. 1425 Ma pulse of the Michael-Shabogamo Gabbro event, MSG-L. P/Zr= ca. 1435-1450 Ma pulse of the Michael-Shabogamo Gabbro event.

Table 5.1 List of geochemical signatures recognized in this thesis. Abbreviations Int.=Intermediate, EL= eastern Laurentia, WL=western Laurentia, MSG=Michael-Shabogamo, MP=Moyie-Purcell, RC=Ramshorn Creek, EC=Elbow Creek, HM=Highland Mountain, NC=Nevada City, MWC= Mammoth-Western Channel, PS1=Paradise Sill, PS2=Plains Sill, U=Unknown, WCD=Western Channel Diabase, OMIS =Ossokmanuan Mountain Intrusive Suite, ¹=geochronology obtained by this study, ²=corresponding geochemical study related to geochronology

Geochemical Event	Location	LIP Association	Geochronology	Reference
High P/Zr Group	EL	MSG	1426 ± 6 Ma	Schärer et al. (1986)
Int. P/Zr Group	EL	MSG	1435 ± 3 Ma ¹	
Low P/Zr Group	EL	MSG	1449 ± 3 Ma ¹ , 1437 ± 4 Ma ¹ , 1452 ⁺¹⁵ ₋₁₃ Ma	Connelly and Heaman (1993)
GS1-Gunbarrel	WL	Gunbarrel	780.3 ± 1.4 Ma	Harlan et al. (2003); Mackinder (2014)
GS2-TMA	WL	MP	1468 +3/-2	Anderson and Parrish (2000), Anderson and Goodfellow (2000) ²
GS3-MA	WL	MP	1468 +3/-2	Anderson and Parrish (2000), Anderson and Goodfellow (2000) ²
GS4-TLA	WL	MP	1468 ± 2 Ma	Anderson and Davis (1995), Anderson and Goodfellow (2000) ²
GS5-BLA	WL	MP	1468 +3/-2	Anderson and Parrish (2000), Anderson and Goodfellow (2000) ²
GS6-GF	WL	MP	1471 ± 3 Ma	Chamberlain et al. (2000)
GS7-Ramshorn Creek	WL	MWC	1550.6 ± 5.2 Ma ¹	
GS8-Mammoth	WL	MWC	1590 ± 3 Ma ¹	
GS9-Highland Mountain	WL	Unknown	1418.3 ± 6.3 Ma ¹	
GS10-Elbow Creek	WL	Unknown	2480 ± 4 Ma ¹	

Geochemical Event	Location	LIP Association	Geochronology	Reference
GS11-Paradise Sill	WL	MP	1457 ± 2 Ma	Sears et al. (1998)
GS12-Plains Sill	WL	MP	1469 ± 2.5 Ma	Sears et al. (1998)
GS13- Nevada City	WL	Unknown	Unknown	
GS14- Unnamed	WL	Unknown	Unknown	
GS15- Unnamed	WL	Unknown	Unknown	
GS16- Unnamed	WL	Unknown	Unknown	
GS17- Unnamed	WL	Unknown	Unknown	
Western Channel Diabase	WL	MWC	1592 ± 6 Ma ¹	

Appendix 2.1: Table of analytical results accuracy analyses

Table of analytical results accuracy analyses. IBS=Internal Blind Standard, 20 of 12 samples. BVHO-2 = Basalt Hawaiian Volcano Observatory, ALS = ALS Global analytical laboratory, USGS=United States Geological Survey, CV=Certified results.

Sample Laboratory	IBS ALS 20	BVHO-2 ALS Avg. of 2 analyses	BVHO-2 USGS CV
Al ₂ O ₃	0.22	13.18	13.5
CaO	7.34	11.23	11.4
FeO	0.13	12.28	11.07
K ₂ O	0.02	0.50	0.52
MgO	9.19	7.15	7.23
MnO	4.51	0.17	
Na ₂ O	0.11	2.20	2.22
P ₂ O ₅	24.75	0.27	0.27
SiO ₂	0.58	49.20	49.9
TiO ₂	0.03	2.67	2.73
LOI	0.19	-0.54	
Ba	15.68	125.75	130
Ce	1.91	36.60	38
Co	1.54	41.50	45
Cr	11.46	290.00	280
Cs	0.03	0.10	0.1
Cu	2.57	134.50	127
Dy	0.13	5.03	
Er	0.08	2.42	
Eu	0.06	2.00	
Ga	0.57	22.05	21.7
Gd	0.22	5.93	6.3
Hf	0.15	4.30	4.1
Ho	0.04	0.97	1.04
La	0.79	14.85	15
Lu	0.01	0.27	0.28
Nb	0.40	17.10	18
Nd	0.95	24.20	25
Ni	4.28	127.50	119
Pb	1.65	3.00	
Pr	0.25	5.17	
Rb	0.34	8.95	9.8
Sc	1.06	29.00	32
Sm	0.27	6.14	6.2
Sr	18.54	405.00	389
Ta	0.06	1.05	1.4
Tb	0.03	0.90	0.9
Th	0.10	1.24	1.2
Tm	0.02	0.33	
U	0.05	0.41	
V	8.66	331.00	317
Y	0.60	24.25	26
Yb	0.11	1.84	2
Zn	3.14	101.50	103
Zr	5.74	165.50	172

Appendix 2.2: Table of Samples.

Mackinder,(2014)

Sample	Group	Sample	Groups
AM-01	Group01	AM-12	Group01
AM-02	Group01	AM-13	Group01
AM-03	Group01	AM-14	Group01
AM-05B	Group01	AM-15	Group01
AM-11	Group01	AM-26B	Group01
LAAT2-A	Group01	MT-03	Group01
LAAT2-B	Group01	MT-09	Group01
LAAT2-C	Group01	MT-10	Group01
MT-01	Group01	T003-1A	Group01
MT-02	Group01	T1-2A	Group01

AndersonandGoodfellow,(2000)

Sample	Group	Sample	Groups
AZ-02b	Group05	AZ-6448-11A	Group03
AZ-03a	Group05	AZ-6448-14	Group03
AZ-03c	Group05	AZ-6464-02	Group02
AZ-06	Group05	AZ-6464-04	Group03
AZ-07	Group03	AZ-65	Group05
AZ-09A	Group02	AZ-6799-01	Group04
AZ-10	Group02	AZ-6799-04	Group04
AZ-100	Group03	AZ-6799-06	Group04
AZ-101	Group03	AZ-6799-08	Group04
AZ-102	Group03	AZ-6799-10	Group05
AZ-105B	Group03	AZ-6799-12	Group05
AZ-106B	Group03	AZ-6799-15	Group05
AZ-11	Group02	AZ-6799-16	Group05
AZ-16	Group05	AZ-6799-18	Group05
AZ-18B	Group05	AZ-6799-19	Group05
AZ-18C	Group05	AZ-68	Group05
AZ-19	Group05	AZ-70	Group05
AZ-27	Group04	AZ-72	Group05
AZ-28	Group04	AZ-74A	Group03
AZ-29A	Group03	AZ-75	Group04
AZ-35	Group05	AZ-78a	Group03
AZ-37	Group05	AZ-78B	Group03
AZ-38	Group05	AZ-79	Group03
AZ-40	Group05	AZ-80	Group03
AZ-41	Group05	AZ-81	Group03

Anderson and Goodfellow, (2000)

Sample	Group	Sample	Groups
AZ-44A	Group05	AZ-82	Group03
AZ-45A	Group05	AZ-83	Group03
AZ-46a	Group02	AZ-84	Group04
AZ-46b	Group02	AZ-85	Group03
AZ-49	Group05	AZ-C83-1-1	Group04
AZ-51C	Group02	AZ-C83-1-5	Group04
AZ-52	Group02	AZ-C83-1-6	Group04
AZ-54a	Group02	AZ-C83-1-7	Group05
AZ-54b	Group02	AZ-C83-1-8	Group04
AZ-56	Group05	AZ-C91-2-1	Group03
AZ-57	Group05	AZ-C91-3-1	Group03
AZ-58	Group05	AZ-C91-3-2	Group03
AZ-59	Group05	AZ-C91-3-3	Group03
AZ-63B	Group05	AZ-C91-3-4	Group03
AZ-64	Group05	AZ-C91-3-6	Group03
AZ-6448-01	Group02	AZ-MM91-1-1	Group03
AZ-6448-03	Group02	AZ-MM91-1-2	Group03
AZ-6448-04	Group02	AZ-MM91-1-3	Group03
AZ-6448-05	Group02	AZ-MM91-1-4	Group03
AZ-6448-06	Group02	AZ-MM91-1-5	Group03
AZ-6448-07	Group03	AZ-MM91-1-6	Group03
AZ-6448-08	Group03	AZ-MM91-1-8	Group03
AZ-6448-09	Group03	AZ-MM91-1-9	Group03
AZ-6448-10	Group03	AZ-N85-1-6	Group03

Sample Groups	14-CR-3-1 Group01	MM-01- AG Group01	13-CR-33- 02 Group03	PS-2d Group03	04RB347 Group04	13-CR-29- 09 Group04	13-CR-29- 10 Group04	13-CR-32- 05 Group05	13-CR-33- 03 Group05	13-CR-34- 01A Group05	13-CR-34- 01B Group05
Lat	47.282	-	49.079	47.358	48.335	48.915	48.913	48.78	49.084	49.616	49.616
Long	-112.476	-	-116.128	-114.564	-116.38	-116.26	-116.258	-116.281	-116.078	-116.179	-116.179
SiO ₂	51.9	49.94	48.1	52.4	76	64.2	58	51.7	52.1	54.6	51.6
Al ₂ O ₃	10.55	12.94	14.2	14.1	11.95	12.35	14.1	14.3	14.95	13.35	13
Fe ₂ O ₃	18.25	16.44	15.85	11.25	3.1	12.65	13.55	8.32	9.34	12	10.5
CaO	7.02	9.094	9.97	9.96	1.98	4.92	7.72	13.1	12.25	9.69	11.8
MgO	3.96	5.13	4.71	6.46	0.5	1.24	4.23	9.47	7.8	4.65	9.26
Na ₂ O	2.48	2.38	1.92	2.22	3.22	2.37	2.27	1.16	1.28	2.35	1.64
K ₂ O	1.54	0.91	0.36	0.32	2.2	1.37	1.02	0.15	0.5	0.28	0.19
TiO ₂	2.88	2.21	1.5	1.14	0.47	1.25	0.9	0.39	0.53	1.72	0.66
MnO	0.22	0.235	0.2	0.17	0.04	0.15	0.21	0.14	0.15	0.18	0.17
P ₂ O ₅	0.34	0.247	0.13	0.09	0.06	0.13	0.07	0.02	0.04	0.17	0.05
LOI	1.6	0.4	2.13	2.16	0.71	0.89	0.94	1.17	1.6	1.55	1.28
Total	100.81	99.93	99.11	100.3	100.3	101.58	>102.00	100	100.6	100.56	100.21

Sample Groups	13-CR-34- 02 Group05	14-CR-4-1 Group05	PS-4 Group05	13-CR-20- 08 Group06	14-CR-1-3 Group06	14-CR-6- 5a Group06	14-CR-6- 5b Group06	GF-1A Group06	HR-01 Group06	HR-03 Group06	HR-04 Group06
Lat	49.642	47.129	47.386	45.407	45.596	48.846	48.846	43.315	45.596	45.622	45.61
Long	-115.998	-113.141	-114.78	-112.069	-112.429	-116.222	-116.222	-109.672	-112.447	-112.46	-112.452
SiO ₂	54.3	49	59.8	48.5	48.8	52.4	48.3	48.16	50.04	48.97	49.09
Al ₂ O ₃	14.25	12.2	12.55	14.5	11.2	13.6	12.5	13.71	14.8	13.14	14.01
Fe ₂ O ₃	10.95	18.5	11.95	11	12.25	10.5	11.95	13.82	11.44	12.19	12.68
CaO	11.15	8.58	7.98	13.2	10.25	11.45	10.9	10.543	12.05	12.207	12.195
MgO	6.74	4.03	2.19	7.53	12.55	8	11.05	7.46	7.73	7.98	7.82
Na ₂ O	1.34	2.39	2.33	2.24	1.56	1.49	1.42	2.07	1.93	1.86	1.95
K ₂ O	0.52	0.89	0.63	0.37	0.31	0.46	0.62	0.63	0.39	0.26	0.19
TiO ₂	0.68	3.36	1.37	0.9	0.83	0.61	0.84	1.23	0.79	1.12	1.2
MnO	0.16	0.24	0.17	0.17	0.19	0.17	0.17	0.171	0.182	0.201	0.197
P ₂ O ₅	0.05	0.27	0.12	0.06	0.07	0.06	0.06	0.039	0.077	0.079	0.075
LOI	1.5	0.26	0.95	0.74	0.38	1.03	1.17	1.85	0.29	0.96	0.66
Total	101.68	99.8	100.06	99.28	98.56	99.84	99.12	99.68	99.72	98.97	100.07

Sample Groups	HR-16		MT-08		14-CR-1-2a		14-CR-1-2b		HR-05		HR-06		HR-07		HR-08		HR-09		HR-15		MRZ	
	Group06	Group06	Group06	Group06	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	
Lat	45.579	45.406	45.618	45.618	45.618	45.618	45.618	45.618	45.61	45.608	45.608	45.608	45.608	45.608	45.6	45.601	45.582	45.582	45.582	45.422	45.422	
Long	-112.487	-112.128	-112.335	-112.335	-112.335	-112.335	-112.335	-112.335	-112.44	-112.428	-112.428	-112.428	-112.436	-112.436	-112.432	-112.431	-112.474	-112.474	-112.474	-112.053	-112.053	
SiO ₂	50.3	48.92	49.7	49.7	49.1	49.1	49.1	49.1	49.04	49.18	49.18	49.18	48.92	48.92	47.63	48.62	49	49	49	42.4	42.4	
Al ₂ O ₃	14.86	15.02	14	14	14.55	14.55	14.55	14.55	13.16	13.18	13.18	13.18	12.96	12.96	14.7	13.35	13.24	13.24	13.24	14.45	14.45	
Fe ₂ O ₃	11.06	9.84	12.25	12.25	13.55	13.55	13.55	13.55	15.11	15.42	15.42	15.42	14.86	14.86	14.11	14.54	15.48	15.48	15.48	13.25	13.25	
CaO	12.124	13.142	11.1	11.1	10.5	10.5	10.5	10.5	10.34	10.361	10.361	10.361	10.478	10.478	10.228	10.393	10.232	10.232	10.232	7.25	7.25	
MgO	7.98	7.77	7.5	7.5	6.6	6.6	6.6	6.6	6.15	6.03	6.03	6.03	6.29	6.29	6.73	6.01	6.19	6.19	6.19	6.07	6.07	
Na ₂ O	1.83	2.4	2.27	2.27	2.16	2.16	2.16	2.16	2.29	2.31	2.31	2.31	2.16	2.16	2.07	2.14	2.25	2.25	2.25	2.14	2.14	
K ₂ O	0.47	0.47	0.45	0.45	1.01	1.01	1.01	1.01	0.3	0.33	0.33	0.33	0.34	0.34	0.75	0.48	0.55	0.55	0.55	1.96	1.96	
TiO ₂	0.75	0.81	1.15	1.15	1.3	1.3	1.3	1.3	1.84	1.99	1.99	1.99	1.9	1.86	1.86	2.09	2.13	2.13	2.13	2.06	2.06	
MnO	0.18	0.157	0.22	0.22	0.21	0.21	0.21	0.21	0.221	0.232	0.232	0.232	0.22	0.211	0.211	0.252	0.233	0.233	0.233	0.18	0.18	
P ₂ O ₅	0.07	0.059	0.09	0.09	0.13	0.13	0.13	0.13	0.167	0.174	0.174	0.174	0.167	0.204	0.204	0.191	0.198	0.198	0.198	0.35	0.35	
LOI	0.58	0.56	1.7	1.7	1.2	1.2	1.2	1.2	0.73	0.54	0.54	0.54	0.7	1.43	1.43	1.39	0.53	0.53	0.53	8.78	8.78	
Total	100.2	99.15	100.5	100.5	100.36	100.36	100.36	100.36	99.35	99.75	99.75	99.75	99	99.92	99.92	99.46	100.03	100.03	100.03	98.99	98.99	

Sample Groups	MT-04		RR-05		TR-05		TR-12-AG		TR-18		TR-46		TR-49		TR-51		TR-54		TR-60		TR-73	
	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	Group07	
Lat	45.42	45.058	45.419	45.419	45.422	45.422	45.422	45.422	45.389	45.68	45.68	45.415	45.415	45.42	45.387	45.387	45.387	45.387	45.395	45.424	45.424	
Long	-112.153	-112.409	-112.151	-112.151	-112.114	-112.114	-112.114	-112.114	-112.055	-112.039	-112.039	-112.122	-112.122	-112.155	-112.052	-112.052	-112.052	-112.052	-112.059	-112.122	-112.122	
SiO ₂	44.66	47.2	48.89	48.89	49.4	49.4	49.4	49.4	49.2	46.23	46.23	49.32	49.32	49.47	48.7	48.7	48.7	48.7	49.63	50	50	
Al ₂ O ₃	14.11	13.5	13.56	13.56	13.17	13.17	13.17	13.17	13.79	15.83	15.83	13.29	13.29	13.87	13.76	13.76	13.76	13.76	13.36	13.55	13.55	
Fe ₂ O ₃	10.8	15.25	13.71	13.71	14.51	14.51	14.51	14.51	13	13.9	13.9	14.72	14.72	13.42	12.12	12.12	12.12	14.05	14.75	14.75	14.75	
CaO	19.316	8.81	11.676	11.676	11.072	11.072	11.072	11.072	11.842	9.217	9.217	10.602	10.602	11.84	10.756	10.756	11.1	10.95	10.95	10.95	10.95	
MgO	5.37	5.23	7.46	7.46	6.76	6.76	6.76	6.76	7.44	6.75	6.75	6.47	6.47	7.61	7.64	7.64	6.85	6.65	6.65	6.65	6.65	
Na ₂ O	0.79	2.46	2.06	2.06	2.2	2.2	2.2	2.2	2.05	2.25	2.25	2.24	2.24	2.1	2.05	2.05	2.15	2.38	2.15	2.38	2.38	
K ₂ O	0.04	1.24	0.19	0.19	0.27	0.27	0.27	0.27	0.3	0.89	0.89	0.54	0.54	0.34	1.73	1.73	0.25	0.48	0.25	0.48	0.48	
TiO ₂	0.94	2.37	1.21	1.21	1.48	1.48	1.48	1.48	1.2	2.04	2.04	1.51	1.51	1.18	1.06	1.06	1.41	1.52	1.41	1.52	1.52	
MnO	0.178	0.22	0.209	0.209	0.221	0.221	0.221	0.221	0.2	0.212	0.212	0.225	0.225	0.208	0.196	0.196	0.214	0.22	0.214	0.22	0.22	
P ₂ O ₅	0.077	0.36	0.096	0.096	0.133	0.133	0.133	0.133	0.095	0.369	0.369	0.142	0.142	0.095	0.086	0.086	0.127	0.13	0.127	0.13	0.13	
LOI	2.94	2.2	0.35	0.35	0.48	0.48	0.48	0.48	0.79	2.02	2.02	0.51	0.51	0.46	1.29	1.29	0.46	1.07	0.46	1.07	1.07	
Total	99.22	98.93	99.41	99.41	99.7	99.7	99.7	99.7	99.91	99.71	99.71	99.57	99.57	100.59	99.39	99.39	99.6	101.74	99.6	101.74	101.74	

Sample Groups	10RB105 Group08	11MDM037 Group08	11RB173 Group08	13-CR-20-06 Group08	13-CR-20-07 Group08	13-CR-20-6 Group08	13-CR-21-01 Group08	13-CR-28-07 Group08	13-CR-28-09 Group08	13-CR-28-10 Group08	14-CR-1-1 Group08
Lat	48.99	48.804	48.923	45.428	45.405	-	45.679	48.664	48.602	48.605	45.71
Long	-116.208	-116.119	-116.058	-112.083	-112.075	-	-112.037	-116.182	-116.1	-116.253	-112.07
SiO ₂ %	53.1	52.8	51.6	53	48.6	53.2	56.8	50.6	54.1	52.8	57.4
Al ₂ O ₃ %	14.3	13.9	14.25	14.4	14.35	13.9	12.6	14.75	14.05	13.3	12.75
Fe ₂ O ₃ %	10.55	11.05	10.6	12	12.6	11.6	11.85	10.5	12.35	12.25	13.7
CaO %	9.62	9.2	11.65	8.86	12.65	8.48	5.63	11.55	9.83	10.95	7.23
MgO %	6.53	6.85	7.39	5.99	7.22	5.9	3.14	7.69	5.53	6.98	3.38
Na ₂ O %	1.54	0.6	1.39	2.38	2.17	2.13	2.72	1.44	2.31	1.75	2.61
K ₂ O %	1.39	1.72	0.57	1.24	0.33	1.47	2.14	0.52	0.69	0.62	1.56
TiO ₂ %	0.69	0.69	0.57	0.98	1.15	0.98	1.73	0.77	1.02	1.01	1.82
MnO %	0.17	0.22	0.17	0.18	0.18	0.17	0.28	0.18	0.19	0.2	0.17
P ₂ O ₅ %	0.06	0.06	0.05	0.11	0.09	0.11	0.21	0.06	0.08	0.1	0.22
LOI %	2.09	2.48	1.03	1.85	0.53	1.23	1.16	0.97	0.96	0.68	0.19
Total %	100.1	99.63	99.32	101.06	99.95	99.25	98.34	99.09	101.14	100.68	101.11

Sample Groups	14-CR-2-1 Group08	14-CR-2-2 Group08	14-CR-2-5b Group08	14-CR-6-2 Group08	14-CR-6-6 Group08	14-CR-7-1 Group08	14-CR-7-2 Group08	AM-06 Group08	RR-06 Group08	RR-07 Group08	TR-17 Group08
Lat	45.597	45.598	45.613	48.169	48.748	48.591	48.597	45.005	45.054	45.032	45.368
Long	-112.402	-112.405	-112.365	-116.888	-116.22	-116.21	-116.192	-109.409	-112.405	-112.365	-111.927
SiO ₂ %	52	50.4	47.7	54.7	60.6	52	52.3	51.66	52.7	51.8	49.78
Al ₂ O ₃ %	15.35	14.3	11.9	14.3	11.8	13.6	13.85	14.13	11.9	12.35	12.18
Fe ₂ O ₃ %	8.29	13.45	11.75	12.25	13.45	10.55	10.65	12.39	12.65	11.05	17.1
CaO %	7.4	10.2	11.3	8.16	5.42	11.25	11.8	9.352	9.63	8.32	8.048
MgO %	3.92	5.68	12	4.13	1.3	7.46	7.52	5.96	7.15	8.55	4.53
Na ₂ O %	1.15	2.08	1.39	2.05	2.02	1.78	1.78	2.61	1.55	2.31	2.51
K ₂ O %	2.86	0.7	0.43	1.24	1.95	0.56	0.42	1.52	0.63	0.83	1.07
TiO ₂ %	0.75	1.2	0.83	1.42	1.18	0.74	0.76	1.14	1.16	1.02	2.47
MnO %	0.13	0.2	0.18	0.16	0.2	0.17	0.18	0.191	0.16	0.2	0.223
P ₂ O ₅ %	0.19	0.13	0.06	0.12	0.23	0.07	0.06	0.11	0.13	0.1	0.223
LOI %	9.23	0.67	1.18	1	0.59	1.06	0.83	1.36	2.72	2.99	1.2
Total %	101.43	99.06	98.87	99.56	98.79	99.28	100.19	100.43	100.52	99.64	99.33

Sample Groups	TR-30-AG		TR-32		TR-36		TR-44		TR-45		TR-55		TR-56		TR-61		TR-62		13-CR-19-03		13-CR-27-01	
	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09	Group08	Group09
Lat	45.416	45.434	45.434	45.362	45.362	45.36	45.36	45.396	45.681	45.567	45.681	45.567	45.369	45.423	45.369	45.423	45.595	45.595	45.595	45.595	48.765	48.765
Long	-112.119	-112.118	-112.118	-111.802	-111.802	-111.935	-111.935	-111.878	-112.041	-111.698	-112.041	-111.698	-111.927	-112.106	-111.927	-112.106	-112.476	-112.476	-112.476	-112.476	-114.37	-114.37
SiO ₂	51.21	50.15	50.15	51.76	51.76	52.79	52.79	49.81	55.65	57.58	55.65	57.58	52.12	53.53	52.12	53.53	47.1	47.1	47.1	47.1	48.8	48.8
Al ₂ O ₃	13.31	14.03	14.03	14.81	14.81	14.65	14.65	12.45	12.87	12.99	12.87	12.99	14.46	14.52	14.46	14.52	18.2	18.2	18.2	18.2	13.2	13.2
Fe ₂ O ₃	16.1	12.31	12.31	10.93	10.93	11.69	11.69	17.38	13.97	11.93	13.97	11.93	11.39	13.86	11.39	13.86	13.7	13.7	13.7	13.7	16.95	16.95
CaO	8.129	10.913	10.913	8.409	8.409	7.421	7.421	7.707	5.424	5.757	5.424	5.757	8.219	7.097	8.219	7.097	9.85	9.85	9.85	9.85	1.49	1.49
MgO	4.85	7.49	7.49	6.62	6.62	6.21	6.21	4.2	3.56	3.21	3.56	3.21	5.82	2.64	5.82	2.64	5.41	5.41	5.41	5.41	6.88	6.88
Na ₂ O	2	2.11	2.11	2.32	2.32	2.13	2.13	2.58	2.91	3.14	2.91	3.14	2.26	3.06	2.26	3.06	3.1	3.1	3.1	3.1	2.09	2.09
K ₂ O	1.05	0.72	0.72	1.86	1.86	2.7	2.7	1.21	2.05	1.9	2.05	1.9	2.22	1.69	2.22	1.69	0.2	0.2	0.2	0.2	2.39	2.39
TiO ₂	2.06	1.04	1.04	0.86	0.86	0.97	0.97	2.65	1.81	1.8	1.81	1.8	0.98	1.92	0.98	1.92	1.23	1.23	1.23	1.23	3.98	3.98
MnO	0.199	0.191	0.191	0.17	0.17	0.181	0.181	0.23	0.319	0.266	0.319	0.266	0.172	0.176	0.172	0.176	0.21	0.21	0.21	0.21	0.2	0.2
P ₂ O ₅	0.167	0.093	0.093	0.096	0.096	0.113	0.113	0.232	0.229	0.216	0.229	0.216	0.114	0.318	0.114	0.318	0.42	0.42	0.42	0.42	0.76	0.76
LOI	0.76	0.84	0.84	1.67	1.67	1.37	1.37	1.15	0.8	0.87	0.8	0.87	1.57	0.77	1.57	0.77	0.26	0.26	0.26	0.26	4.38	4.38
Total	99.84	99.89	99.89	99.51	99.51	100.23	100.23	99.6	99.59	99.66	99.59	99.66	99.33	99.58	99.33	99.58	99.84	99.84	99.84	99.84	101.2	101.2

Sample Groups	13-CR-27-03A		13-CR-27-03B		13-CR-29-02		13-CR-32-01		13-CR-33-06		14-CR-5-2		14-CR-6-7		HR-10		HR-12		AM-07		AM-08	
	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group09	Group10	Group10	Group10	Group10
Lat	48.413	48.413	48.413	48.86	48.86	48.995	48.995	49.018	48.831	48.831	48.831	48.685	45.591	45.588	45.591	45.588	45.588	45.588	45.394	45.394	48.335	48.335
Long	-115.505	-115.505	-115.505	-116.166	-116.166	-115.01	-115.01	-115.745	-114.88	-114.88	-114.88	-116.055	-112.465	-112.475	-112.465	-112.475	-112.475	-112.475	-109.883	-109.883	-117.827	-117.827
SiO ₂	41.2	43.3	43.3	45.9	45.9	44.9	44.9	47.1	58.4	58.4	58.4	47.7	45.71	46.87	45.71	46.87	46.87	46.87	51.56	51.56	51.4	51.4
Al ₂ O ₃	15.7	16.15	16.15	15.7	15.7	18.15	18.15	15.95	14.95	14.95	14.95	15.4	15.11	14.59	15.11	14.59	14.59	14.59	9.49	9.49	9.13	9.13
Fe ₂ O ₃	17.95	15.2	15.2	13.75	13.75	12.4	12.4	14.4	12.55	12.55	12.55	14.9	16.89	15.71	16.89	15.71	15.71	15.71	11.04	11.04	10.8	10.8
CaO	1.84	2.39	2.39	7.86	7.86	0.89	0.89	8.04	0.64	0.64	0.64	6.52	7.561	8.339	7.561	8.339	8.339	8.339	8.089	8.089	7.79	7.79
MgO	6.86	6.62	6.62	6.36	6.36	9.26	9.26	6.58	0.28	0.28	0.28	4.71	5.18	4.88	5.18	4.88	4.88	4.88	16.09	16.09	16.15	16.15
Na ₂ O	2.19	2.83	2.83	2.5	2.5	1.59	1.59	2.53	4.21	4.21	4.21	2.59	2.45	3.24	2.45	3.24	3.24	3.24	1.63	1.63	1.52	1.52
K ₂ O	3.59	3.23	3.23	1.26	1.26	4.2	4.2	1.31	5.49	5.49	5.49	2.66	1.45	0.74	1.45	0.74	0.74	0.74	0.52	0.52	0.63	0.63
TiO ₂	3.93	3.89	3.89	1.6	1.6	2.04	2.04	1.63	1.42	1.42	1.42	2.48	3.05	3.63	3.05	3.63	3.63	3.63	0.52	0.52	0.52	0.52
MnO	0.3	0.18	0.18	0.17	0.17	0.04	0.04	0.18	0.23	0.23	0.23	0.18	0.202	0.281	0.202	0.281	0.281	0.281	0.186	0.186	0.18	0.18
P ₂ O ₅	0.73	0.72	0.72	0.31	0.31	0.4	0.4	0.33	0.41	0.41	0.41	0.45	0.578	0.634	0.578	0.634	0.634	0.634	0.075	0.075	0.08	0.08
LOI	4.23	4.31	4.31	3.37	3.37	6.02	6.02	3.76	1.43	1.43	1.43	2.75	1.38	0.51	1.38	0.51	0.51	0.51	1.26	1.26	2.37	2.37
Total	98.75	98.97	98.97	98.91	98.91	100	100	101.94	100.38	100.38	100.38	100.51	99.56	99.42	99.56	99.42	99.42	99.42	100.46	100.46	100.92	100.92

Sample Groups	AM-09		AM-10		13-CR-18-04		13-CR-22-01		13-CR-25-04		13-CR-26-06		13-CR-28-02		13-CR-28-11		13-CR-29-04		13-CR-29-05		13-CR-29-07	
	Group10	Group11	Group10	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	
Lat	48.871	48.875	46.991	46.275	47.305	47.387	48.517	48.609	48.819	48.835	48.929											
Long	-117.146	-117.146	-112.357	-111.318	-114.607	-114.787	-116.332	-116.258	-116.22	-116.249	-116.314											
SiO ₂	52.5	50.46	59.6	59.4	52.2	57.6	51.3	55.2	65.8	51.6	53.7											
Al ₂ O ₃	9.56	8.76	11.45	12.4	15.15	13.15	14.5	13.05	11.7	15.1	14.15											
Fe ₂ O ₃	11	10.71	14.6	10.45	10.6	13.05	11.1	14.45	11.6	9.5	10.75											
CaO	7.82	7.04	4.78	4.72	10.6	6.55	11.6	8.56	4.66	11.4	9.56											
MgO	15.65	17.75	0.62	1.4	6.81	2.15	7.3	3.48	1	7.95	6.76											
Na ₂ O	1.7	1.22	2.74	2.55	1.36	2.26	1.51	2.79	2.73	1.44	2.7											
K ₂ O	0.67	0.44	2.55	3.27	0.78	1.62	0.47	0.75	1.6	0.39	0.69											
TiO ₂	0.53	0.5	1.16	1.6	0.56	1.44	0.58	1.5	1.29	0.55	0.8											
MnO	0.18	0.171	0.2	0.16	0.16	0.17	0.21	0.19	0.18	0.17	0.15											
P ₂ O ₅	0.07	0.066	0.38	0.45	0.05	0.1	0.04	0.07	0.27	0.04	0.07											
LOI	1.23	3.12	0.69	2.49	2.04	0.76	0.73	0.66	0.42	1.12	2.17											
Total	101.24	100.24	98.85	98.98	100.35	98.91	99.36	100.72	101.3	99.3	101.55											
Sample Groups	13-CR-29-08		13-CR-31-01		13-CR-32-04		13-CR-35-01		86BT06		03RL099		08RB029		13-CR-18-03		13-CR-19-01		13-CR-20-03		13-CR-20-09	
	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group11	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	
Lat	48.92	48.445	48.781	49.47	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
Long	-116.258	-116.061	-116.265	-115.803	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	
SiO ₂	51.8	58	56.2	51.4	50.7	51.5	48.2	48.687	47.044	45.604	45.416	45.387	48.6	49.9	49.4	48.6	48.6	48.6	48.6	48.6	48.6	
Al ₂ O ₃	14.65	10.8	13.55	12.25	11.15	13.35	12.15	12.15	12.35	13.15	13.65	13.4	13.05	13.15	13.65	13.4	13.05	13.05	13.05	13.05	13.05	
Fe ₂ O ₃	9.44	16.55	12.6	17.1	19.6	12.6	17.9	16.6	16.6	16.15	12.8	13.05	16.15	16.15	12.8	13.05	13.05	13.05	13.05	13.05	13.05	
CaO	11.8	6.53	9.48	7.12	8.29	10.2	8.97	9.13	8.83	8.83	12.15	11.75	8.83	8.83	12.15	11.75	11.75	11.75	11.75	11.75	11.75	
MgO	7.85	1.22	5.02	4.43	3.26	6.01	4.61	5.53	5.02	5.02	7.77	7.57	5.02	5.02	7.77	7.57	7.57	7.57	7.57	7.57	7.57	
Na ₂ O	1.37	2.44	2.13	2.83	2.03	1.52	2.25	2.35	2.55	2.55	2.1	2.09	2.35	2.55	2.1	2.09	2.09	2.09	2.09	2.09	2.09	
K ₂ O	0.48	0.53	0.76	0.38	0.68	0.51	0.86	0.78	0.48	0.48	0.2	0.3	0.78	0.48	0.2	0.3	0.3	0.3	0.3	0.3	0.3	
TiO ₂	0.5	1.61	0.76	1.82	2.39	0.79	2.76	2.38	1.33	1.33	1.06	1.07	2.38	1.33	1.06	1.07	1.07	1.07	1.07	1.07	1.07	
MnO	0.14	0.24	0.2	0.22	0.27	0.19	0.22	0.22	0.23	0.23	0.19	0.19	0.23	0.23	0.19	0.19	0.19	0.19	0.19	0.19	0.19	
P ₂ O ₅	0.03	0.89	0.07	0.13	0.17	0.05	0.26	0.19	0.08	0.08	0.2	0.08	0.26	0.26	0.08	0.26	0.26	0.26	0.26	0.26	0.26	
LOI	1.81	0.71	1.09	1.7	0.39	1.14	0.99	1.3	0.9	0.9	0.77	1.13	1.3	0.9	0.77	1.13	1.13	1.13	1.13	1.13	1.13	
Total	99.92	99.55	101.9	99.41	98.96	97.88	99.21	98.89	98.67	100.23	99.29	99.29	98.89	98.67	100.23	99.29	99.29	99.29	99.29	99.29	99.29	

Sample Groups	13-CR-20-10	13-CR-22-03	13-CR-22-04	13-CR-23-02	13-CR-23-04	13-CR-23-05	13-CR-24-02A	13-CR-24-04	13-CR-25-01	13-CR-25-03	13-CR-25-06
	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12
Lat	45.392	46.273	46.228	46.908	46.898	47.033	46.716	-	47.325	47.313	47.279
Long	-112.043	-111.011	-111.092	-112.348	-112.413	-112.579	-113.581	-	-114.565	-114.589	-114.667
SiO ₂	48.8	48.4	49.3	48.9	51.6	50.8	50.1	47.8	51.9	51.4	51.9
Al ₂ O ₃	13	12.45	12.7	11.15	12.8	12	13.2	11.7	12.9	15.6	14.15
Fe ₂ O ₃	14.6	15.25	15.3	16.75	16.1	16.75	16.05	15.45	13.75	12.25	11.65
CaO	10.45	9.92	9.61	9.68	9.95	9.64	8.44	7.56	9.32	9.8	10.55
MgO	6.63	6.16	6.12	6.33	5.85	5.82	5.75	5.12	5.69	5.4	7.86
Na ₂ O	2.28	2.22	2.27	1.98	2.43	2.28	2.64	4.27	2.86	2.47	1.76
K ₂ O	0.95	0.39	0.87	0.78	0.65	0.66	0.61	0.93	0.27	0.52	0.25
TiO ₂	1.38	2.04	2.07	2.42	2.04	2.03	1.95	2.28	1.24	0.76	0.91
MnO	0.21	0.21	0.21	0.24	0.22	0.23	0.22	0.25	0.18	0.18	0.17
P ₂ O ₅	0.12	0.14	0.17	0.17	0.16	0.2	0.17	0.2	0.11	0.07	0.07
LOI	1.44	0.82	0.64	0.66	-0.24	0.53	0.39	2.95	1.1	0.98	1.69
Total	99.91	98.05	99.32	99.11	101.61	100.99	99.55	98.55	99.35	99.46	101.03

Sample Groups	13-CR-26-01	13-CR-26-02	13-CR-26-03	13-CR-26-04	13-CR-26-05	13-CR-26-09	13-CR-26-10	13-CR-26-11	13-CR-28-05	13-CR-28-06	13-CR-28-08
	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12
Lat	47.361	47.441	47.443	47.55	47.488	47.411	47.392	47.381	48.692	48.668	48.618
Long	-114.564	-114.541	-114.562	-114.651	-114.841	-114.9	-114.904	-114.9	-116.185	-116.172	-116.071
SiO ₂	53	49	50.6	51.2	50.9	51.8	50.2	51.5	47.5	53	50
Al ₂ O ₃	13.75	14.9	14.85	13.5	14.6	14	13.6	11.9	12.5	14.6	11.7
Fe ₂ O ₃	12.55	14.4	11	12.95	15.55	12.4	15.25	19.9	16.4	10.9	19.7
CaO	9.99	7.68	10.3	9.74	9.96	10.2	7.83	5.56	10.85	10.8	8.16
MgO	5.99	4.8	7.46	5.87	5.42	6.46	4.9	2.83	6.41	5.79	3.37
Na ₂ O	2.79	3.66	1.88	2.4	2.51	1.75	3.81	3.58	2.01	2.07	2.48
K ₂ O	0.36	0.6	0.19	0.25	0.26	0.54	0.51	0.72	0.28	0.39	0.87
TiO ₂	1.11	1.38	0.83	1.06	1.47	1	1.82	2.55	1.37	0.74	2.54
MnO	0.17	0.19	0.15	0.19	0.18	0.21	0.18	0.21	0.19	0.19	0.25
P ₂ O ₅	0.1	0.12	0.07	0.09	0.12	0.09	0.14	0.18	0.06	0.05	0.17
LOI	0.93	2.61	1.53	1.15	0.94	1.69	1.34	0.97	0.96	0.5	0.35
Total	100.78	99.4	98.94	98.42	101.93	100.19	99.62	99.93	98.55	99.04	99.63

Sample Groups	13-CR-29-11	13-CR-30-02	13-CR-33-01	13-CR-35-02	13-CR-36-01	13-CR-36-02	14-CR-6-1	14-CR-6-3	86BT02	86BT05	RR-04
	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12	Group12
Lat	48.904	48.943	48.99	49.446	45.064	45.063	48.148	48.155	48.602	48.699	45.076
Long	-116.244	-117.082	-116.492	-115.834	-112.334	-112.339	-116.834	-116.812	-116.068	-116.164	-112.359
SiO ₂	51.3	51.1	50.8	49.5	49.9	52.6	53.9	52.7	50	51.9	48.6
Al ₂ O ₃	12	15.65	14.3	15.05	14.35	14.15	13.55	14.4	13.9	13.35	15.5
Fe ₂ O ₃	17.85	12.7	12.4	10.75	15.7	10.55	9.1	10.4	13.55	13.25	11.6
CaO	8.28	10.1	9.73	11.6	7.92	11.35	11.3	10.2	10.05	9.71	11.8
MgO	3.86	5.19	8.7	7.19	5.17	8.31	7.38	6.73	5.75	6.09	6.82
Na ₂ O	2.22	2.4	1.92	1.88	3.24	1.6	1.18	2.2	2.13	2.18	2.02
K ₂ O	0.52	0.37	0.6	1.13	0.34	0.36	0.67	0.94	0.44	0.74	1.06
TiO ₂	1.62	1.01	0.89	0.77	1.45	0.67	1.12	0.88	1.04	1.05	0.95
MnO	0.23	0.18	0.18	0.16	0.21	0.16	0.15	0.17	0.19	0.19	0.18
P ₂ O ₅	0.19	0.08	0.07	0.06	0.12	0.05	0.1	0.08	0.07	0.09	0.08
LOI	0.67	0.76	1.93	1.92	1.52	1.94	1.2	1.19	1.13	1.42	1.71
Total	98.76	99.57	101.58	100.14	99.96	101.82	99.71	99.93	98.27	100.03	100.39

Sample Groups	RR-08	RR-10	RR-11	RR-12	13-CR-22-02	13-CR-28-04	13-CR-29-01	13-CR-31-04	14-CR-3-2	MT-06	MT-11
	Group12	Group12	Group12	Group12	Group13	Group13	Group13	Group13	Group13	Group13	Group13
Lat	45.032	45.18	45.177	45.177	46.279	48.694	48.781	47.029	47.477	45.42	45.387
Long	-112.365	-112.439	-112.428	-112.428	-111.308	-116.257	-116.187	-112.723	-112.87	-112.153	-112.052
SiO ₂	50.5	50.7	48.2	47.9	48.5	48.6	44	49.7	48.7	49.25	49.23
Al ₂ O ₃	13.7	13.85	14.55	13.8	12.1	12.9	10.85	12.25	11.45	13.81	13.81
Fe ₂ O ₃	12.95	12.65	12.3	15.3	16.05	16.65	18.85	14.8	17.45	13.2	12.35
CaO	9.79	9.51	11.1	10.3	9.44	8.93	11.2	10.65	9.29	11.697	11.938
MgO	6.39	6.62	5.69	6.08	5.98	4.19	5.02	6.84	5.52	7.44	7.69
Na ₂ O	2.19	2.27	3.1	2.25	2.25	2.47	2.26	2.08	2.14	2.09	1.98
K ₂ O	0.55	1.07	0.33	0.62	0.75	0.91	0.33	0.46	0.85	0.21	0.27
TiO ₂	1.5	1.42	1.05	1.54	2.06	2.8	5.08	1.84	2.65	1.18	1.08
MnO	0.19	0.19	0.18	0.21	0.22	0.22	0.42	0.22	0.24	0.208	0.195
P ₂ O ₅	0.16	0.16	0.08	0.11	0.19	0.27	0.18	0.15	0.22	0.097	0.085
LOI	1.21	1.75	2.22	1.29	0.85	0.78	0.93	-0.05	0.38	0.36	0.69
Total	99.25	100.27	98.86	99.44	98.44	98.76	99.17	98.99	98.94	99.54	99.32

Sample Groups	MT-12		MT-14		MT-15		14-CR-1-4		14-CR-2-4		13-CR-28-03		13-CR-29-03		14-CR-2-6a		14-CR-2-6b		RR-03		13-CR-16-06	
	Group13	Group13	Group13	Group13	Group13	Group13	Group14	Group14	Group14	Group14	Group15	Group15	Group15	Group15	Group16	Group16	Group16	Group16	Group16	Group16	Group17	Group17
Lat	45.387	45.385	45.385	45.385	45.385	45.385	45.6	45.608	48.688	48.811	48.688	48.811	48.688	48.811	45.438	45.438	45.438	45.438	45.064	45.064	44.946	44.946
Long	-112.052	-112	-112	-112	-112	-112	-112.443	-112.362	-116.279	-116.211	-116.279	-116.211	-116.279	-116.211	-112.104	-112.104	-112.104	-112.104	-112.339	-112.339	-109.495	-109.495
SiO ₂	49.15	49.17	49.17	49.17	46.87	46.87	48.2	48	49.7	47.3	49.7	47.3	49.7	47.3	35.2	35.2	35.6	35.6	37.2	37.2	55	55
Al ₂ O ₃	13.85	13.36	13.36	13.36	13.16	13.16	12.85	12.9	16.9	16.15	16.9	16.15	16.9	16.15	1.52	1.52	1.57	1.57	1.85	1.85	15.45	15.45
Fe ₂ O ₃	12.71	12.96	12.96	12.96	16.81	16.81	15.6	14.45	7.78	9.14	7.78	9.14	7.78	9.14	14	14	13.4	13.4	11.25	11.25	9.27	9.27
CaO	11.739	9.829	9.829	9.829	6.887	6.887	11.05	11.55	12.4	11.15	12.4	11.15	12.4	11.15	0.02	0.02	0.02	0.02	0.09	0.09	7.37	7.37
MgO	7.26	6.42	6.42	6.42	6.85	6.85	6.42	6.83	9.1	11	9.1	11	9.1	11	36.5	36.5	36.8	36.8	36.3	36.3	5.23	5.23
Na ₂ O	2.08	2.43	2.43	2.43	3.13	3.13	2.51	2.25	1.27	1.14	1.27	1.14	1.27	1.14	0.01	0.01	0.02	0.02	0.03	0.03	3.6	3.6
K ₂ O	0.3	1.46	1.46	1.46	0.43	0.43	0.23	0.15	0.36	0.41	0.36	0.41	0.36	0.41	0.17	0.17	0.16	0.16	BD	BD	2.25	2.25
TiO ₂	1.2	1.52	1.52	1.52	1.53	1.53	1.36	1.12	0.42	0.37	0.42	0.37	0.42	0.37	0.08	0.08	0.08	0.08	0.09	0.09	0.89	0.89
MnO	0.197	0.229	0.229	0.229	0.193	0.193	0.25	0.24	0.15	0.15	0.15	0.15	0.15	0.15	0.03	0.03	0.08	0.08	0.1	0.1	0.12	0.12
P ₂ O ₅	0.097	0.137	0.137	0.137	0.137	0.137	0.1	0.07	0.03	0.02	0.03	0.02	0.03	0.02	0.03	0.03	0.02	0.02	0.01	0.01	0.42	0.42
LOI	0.85	1.69	1.69	1.69	3.02	3.02	1.01	0.49	1.47	1.68	1.47	1.68	1.47	1.68	12.25	12.25	12.45	12.45	12.7	12.7	1.21	1.21
Total	99.43	99.21	99.21	99.21	99.02	99.02	99.61	98.08	99.75	98.56	99.75	98.56	99.75	98.56	101.24	101.24	101.51	101.51	100.68	100.68	101.01	101.01

Sample Groups	13-CR-16-07		13-CR-24-02B	
	Group17	Group17	Group17	Group17
Lat	44.928	46.716	46.716	46.716
Long	-109.64	-113.581	-113.581	-113.581
SiO ₂	58	71.7	71.7	71.7
Al ₂ O ₃	14.7	13.75	13.75	13.75
Fe ₂ O ₃	8.68	2.07	2.07	2.07
CaO	5.92	1.64	1.64	1.64
MgO	3.35	0.7	0.7	0.7
Na ₂ O	3.31	3.16	3.16	3.16
K ₂ O	1.98	4.39	4.39	4.39
TiO ₂	1	0.25	0.25	0.25
MnO	0.12	0.02	0.02	0.02
P ₂ O ₅	0.36	0.09	0.09	0.09
LOI	1.02	1.78	1.78	1.78
Total	98.6	99.73	99.73	99.73

Sample	14-CR-3-1	MM-01-AG	13-CR-33-02	PS-2d	04RB347	13-CR-29-09	13-CR-29-10	13-CR-32-05	13-CR-33-03	13-CR-34-01A	13-CR-34-01B
Ba	352	141.5	52.4	65.4	486	321	184	21.5	75.3	41.2	38.2
Ce	64.5	34.5	21.7	17.7	56.6	59.8	33.4	8.5	15.2	31.1	9.7
Co	50	47	46	39	4	19	36	35	36	32	39
Cr	40	70	50	110	10	BD	10	560	280	10	360
Cs	1.07	1.69	0.32	2.1	6.36	2.59	2.7	0.2	2.05	0.87	0.3
Cu	225	269	121	187	3	7	6	56	80	79	61
Dy	9.78	6.97	5.16	3.83	5.7	6.95	4.27	1.85	2.55	6.97	2.39
Er	5.3	4.13	3.29	2.42	4.14	4.52	2.84	1.26	1.66	4.03	1.56
Eu	2.69	1.74	1.3	1	1.03	1.43	0.83	0.44	0.53	2.2	0.58
Ga	25.7	20.8	23.1	17.3	16	19.8	19.7	12.7	15.1	21.7	15.1
Gd	10.05	6.81	4.73	3.44	5.52	6.55	3.91	1.45	2.1	5.86	2.14
Hf	7.6	4.3	3.2	2.4	8.5	5.7	3.1	0.9	1.6	3.8	1.3
Ho	2.03	1.5	1.13	0.85	1.32	1.39	0.94	0.42	0.54	1.37	0.5
La	27.8	14.6	9.4	7.8	26.3	28.3	16.1	4	6.8	12.9	4.2
Lu	0.73	0.5	0.45	0.35	0.69	0.57	0.42	0.16	0.22	0.57	0.2
Nb	18.9	13.8	6.5	5.4	12.6	10.5	5.7	1.5	3.2	9.5	2.5
Nd	38.6	21.3	14.1	11.3	24.8	27.8	16.2	4.9	7.7	18.8	6.3
Ni	44	56	55	67	2	BD	5	100	40	49	121
Pb	32	3	3	BD	19	17	5	BD	7	6	BD
Pr	8.76	4.68	2.83	2.45	6.37	6.98	4.01	1.1	1.9	4.18	1.33
Rb	52.4	40.3	9	11.5	103	49.3	42	3.8	23.4	7.2	2.9
Sc	34	38	40	43	10	30	40	41	31	44	41
Sm	9.86	5.69	3.61	3.1	5.44	6.17	3.36	1.29	1.9	4.96	1.91
Sr	207	150	163.5	123	177	127	124.5	79.4	82.8	161.5	91.2
Ta	1.2	0.8	0.4	0.3	0.9	0.7	0.4	0.1	0.2	0.6	0.2
Tb	1.63	1.04	0.81	0.6	0.88	1.02	0.68	0.28	0.33	0.99	0.35
Th	6.4	2.78	1.71	1.85	14.65	7.91	4.22	0.98	1.78	2.51	0.85
Tm	0.83	0.59	0.43	0.34	0.63	0.64	0.37	0.16	0.19	0.56	0.21
U	1.65	0.72	0.51	0.43	2.81	2.15	1.22	0.24	0.44	0.67	0.24
V	546	410	457	339	26	90	329	218	249	491	254
Y	51.4	35.4	27.9	22.4	36.8	38.8	24.3	10.8	14.1	37.1	13.8
Yb	4.85	3.47	3.08	2.25	4.42	4.2	2.6	1.2	1.51	3.83	1.35
Zn	84	137	116	106	25	103	129	59	59	74	74
Zr	268	152	99	88	297	181	98	28	48	126	42

Sample	13-CR-34-02	14-CR-4-1	PS-4	13-CR-20-08	14-CR-1-3	14-CR-6-5a	14-CR-6-5b	GF-1A	HR-01	HR-03	HR-04
Ba	60	440	79.2	155	133.5	76.5	119	92.8	128	56.1	43.6
Ce	18	41.8	43.8	13.4	15.4	16.8	13.6	13	14.7	12.9	11.4
Co	32	43	27	46	68	41	72	51	47	46	49
Cr	150	20	10	200	1160	360	890	180	230	300	290
Cs	0.75	1.92	0.38	0.16	0.49	1.9	1.33	0.59	0.48	0.45	0.13
Cu	63	351	3	161	106	103	110	280	107	186	246
Dy	3	8.76	5.14	2.79	2.82	2.85	2.5	2.76	2.98	3.6	3.17
Er	2.1	5.13	3.15	1.55	1.51	1.71	1.41	1.55	1.82	2.09	2
Eu	0.67	2.34	1.34	0.91	0.86	0.67	0.8	0.61	0.69	0.91	0.74
Ga	15.9	24.7	19	17.3	15.9	14.6	16	15	15.6	16.2	16.4
Gd	2.53	8.49	4.88	2.58	2.82	2.46	2.48	2.43	2.56	3.02	3.02
Hf	2	6	3.7	1.6	1.7	1.6	1.5	1.1	1.7	2	1.5
Ho	0.64	1.86	1.11	0.55	0.6	0.61	0.51	0.52	0.62	0.75	0.66
La	8.5	17.4	21.1	5.9	7.5	8.1	6.2	5.9	6.9	5.4	4.6
Lu	0.24	0.69	0.51	0.18	0.2	0.25	0.18	0.19	0.25	0.29	0.25
Nb	3.6	13.7	7.6	4.6	2.7	3.2	2.9	3	5.1	4.7	4.5
Nd	9.8	27.6	21.1	9	8.9	8.9	8.9	7.5	8.3	8.5	8
Ni	42	35	2	111	326	70	318	93	114	98	120
Pb	BD	11	10	BD	3	BD	6	3	3	BD	BD
Pr	2.24	5.99	5.27	1.98	1.95	2.12	1.86	1.72	1.78	1.76	1.71
Rb	23.1	31.6	10.9	10.8	10.1	19.1	29.5	34	12.8	7.3	3.9
Sc	36	37	37	38	26	42	29	38	36	46	44
Sm	2.2	7.7	4.6	2.08	2.42	2.39	2.18	1.99	2.32	2.36	2.44
Sr	92.2	168.5	145.5	203	138	97.1	135.5	194.5	117.5	125.5	125.5
Ta	0.2	0.8	0.5	0.3	0.2	0.2	0.2	0.1	0.3	0.2	0.3
Tb	0.46	1.38	0.83	0.48	0.45	0.43	0.38	0.4	0.44	0.53	0.5
Th	2.2	3.48	6.44	0.77	1.74	2.15	1.46	1.57	1.51	0.72	0.61
Tm	0.26	0.74	0.49	0.24	0.22	0.26	0.2	0.23	0.25	0.28	0.27
U	0.65	0.92	1.6	0.22	0.33	0.51	0.29	0.27	0.52	0.2	0.21
V	280	535	356	278	255	279	268	437	232	323	362
Y	17.3	47.8	30	13.9	14.7	16.2	13	14	16.5	18.6	17.2
Yb	1.7	4.88	3.23	1.24	1.36	1.8	1.25	1.35	1.6	1.92	1.74
Zn	73	156	92	69	80	70	86	47	82	77	85
Zr	64	216	123	52	60	57	53	32	54	55	51

Sample	HR-16	MT-08	14-CR-12a	14-CR-12b	HR-05	HR-06	HR-07	HR-08	HR-09	HR-15	MRZ
Ba	115.5	102.9	197	131	106.5	87.4	98.9	211	106	179	435
Ce	14.7	11.6	14.4	17.1	24.7	25.9	25.1	27	29.6	29.8	35.3
Co	46	48.3	46	50	47	50	52	48	44	49	50
Cr	300	220	190	130	110	110	120	120	110	120	120
Cs	0.41	0.18	0.27	0.74	0.29	0.31	0.41	0.68	0.4	0.6	1.82
Cu	100	125	165	165	119	161	221	48	167	178	32
Dy	3.04	2.52	3.75	4.33	5.18	5.29	4.85	4.54	5.54	5.62	4.22
Er	1.93	1.38	2.26	2.44	3.01	3.1	2.83	2.8	3.35	3.25	2.48
Eu	0.72	0.83	1.03	1.17	1.35	1.35	1.34	1.59	1.51	1.56	1.57
Ga	16.3	16.09	17.8	19.2	19.8	20.2	19.3	20.5	19.3	20	20.4
Gd	2.59	2.44	3.41	3.8	4.88	5.02	4.76	4.56	5.36	5.27	4.92
Hf	1.6	0.75	1.9	2.3	3.4	3.5	3.2	3	3.6	3.4	3.1
Ho	0.6	0.48	0.79	0.88	0.99	0.98	1.03	0.88	1.1	1.12	0.84
La	6.9	5.17	6	7.4	10	10.7	10.3	11.5	12.3	12.3	15.4
Lu	0.26	0.17	0.32	0.37	0.41	0.43	0.39	0.38	0.45	0.44	0.3
Nb	4.9	3.54	5.3	6.1	11.9	12.6	11.3	9.7	13.9	13.8	8.2
Nd	8.7	7.84	9.5	11	16.4	17.3	17.1	17.4	19	19.6	21.7
Ni	120	127	88	74	65	55	62	58	61	69	62
Pb	BD	1.1	5	3	BD	5	3	BD	BD	4	5
Pr	1.83	1.7	2.04	2.34	3.41	3.65	3.53	3.65	4.12	4.01	4.69
Rb	16.2	16.33	16.5	44.1	7.9	8	11.7	23.9	14.8	21.4	84.5
Sc	37	42	36	40	44	44	45	39	42	44	28
Sm	2.46	2.12	2.75	3.19	4.37	4.84	4.32	4.35	4.6	5.31	4.96
Sr	125	214	202	209	162.5	163	162	296	209	176.5	226
Ta	0.3	0.2	0.3	0.3	0.8	0.8	0.7	0.5	0.8	0.8	0.4
Tb	0.46	0.399	0.57	0.66	0.79	0.78	0.77	0.78	0.81	0.93	0.68
Th	1.41	0.64	0.85	1.02	1.42	1.37	1.39	0.92	1.55	1.53	0.87
Tm	0.28	0.182	0.33	0.37	0.4	0.43	0.39	0.38	0.45	0.41	0.35
U	0.45	0.14	0.26	0.31	0.41	0.35	0.46	0.21	0.38	0.45	0.16
V	242	287.08	355	387	407	407	410	329	410	416	264
Y	16.6	13.05	20.9	23.2	26.3	26.6	26	24.7	28.7	28.5	21.3
Yb	1.69	1.138	2.29	2.58	2.56	2.65	2.51	2.28	2.93	2.8	2.07
Zn	82	53.58	174	98	115	124	115	106	104	121	119
Zr	54	18	66	80	112	116	107	106	126	128	113

Sample	MT-04	RR-05	TR-05	TR-12-AG	TR-18	TR-46	TR-49	TR-51	TR-54	TR-60	TR-73
Ba	22.2	411	53.2	60	233	327	109	59.9	227	404	83
Ce	15.26	54.2	14.8	20.9	14.6	36.8	21.6	14.2	20.4	20.4	20.5
Co	30.8	48	49	49	50	46	49	48	46	50	52
Cr	245	90	340	100	230	150	120	270	310	140	90
Cs	0.04	0.24	0.24	0.23	0.43	0.82	0.18	0.32	0.32	0.12	0.23
Cu	288	40	180	219	184	44	217	183	182	219	206
Dy	4.17	7.4	3.98	5.04	3.71	4.44	4.94	3.7	3.73	4.39	4.69
Er	2.31	4.48	2.23	2.91	2.41	2.42	3.05	2.24	2.23	2.84	2.98
Eu	2.09	2.12	0.96	1.15	0.98	1.83	1.31	1.07	1.02	1.24	1.11
Ga	24.39	22.1	17.7	17.7	16.9	22	18	17.3	18	19	18.5
Gd	3.93	7.72	3.39	4.44	3.35	4.69	4.65	3.64	3.27	4.3	4.37
Hf	1.64	6.1	2.1	2.9	2	3.4	3.1	1.9	2	2.9	2.9
Ho	0.84	1.52	0.82	1.01	0.86	0.9	1.04	0.78	0.78	0.99	0.95
La	6.85	23.8	6.1	8.6	6.1	15.9	9	5.7	5.6	8.4	8.2
Lu	0.28	0.6	0.32	0.38	0.31	0.31	0.43	0.34	0.31	0.43	0.42
Nb	4.35	18.7	5.7	8	5.5	8.6	8.5	5.5	5.5	7.8	7.9
Nd	10.76	32	10.7	13.7	9.7	24.3	15.2	9.7	10.3	14.1	13.2
Ni	56	41	86	71	94	74	66	90	96	76	68
Pb	4.9	BD	2	BD	BD	5	3	BD	BD	3	BD
Pr	2.27	6.92	2.21	2.97	2.06	5.14	3.13	1.97	2.05	2.91	2.79
Rb	0.42	40.1	4.3	8.3	13	15.5	16.6	12.3	80.8	5.7	14.1
Sc	39.1	36	44	44	44	29	42	43	45	42	43
Sm	3.12	7.36	2.74	3.96	2.76	5.17	3.76	3	2.88	3.49	3.47
Sr	443	228	128.5	131	143	323	143	126.5	196.5	145	132.5
Ta	0.3	1	0.4	0.5	0.3	0.5	0.5	0.3	0.3	0.5	0.5
Tb	0.64	1.19	0.57	0.71	0.52	0.78	0.81	0.61	0.61	0.71	0.71
Th	0.71	2.17	0.88	1.21	0.78	1	1.42	0.89	0.77	1.25	1.21
Tm	0.317	0.64	0.33	0.4	0.34	0.34	0.46	0.33	0.34	0.39	0.43
U	0.25	0.49	0.25	0.31	0.23	0.2	0.4	0.23	0.24	0.33	0.38
V	287.46	340	311	356	323	289	353	306	324	350	333
Y	22.71	39	21	25.9	20.5	23.1	28.4	20.5	20.8	26.4	25.7
Yb	1.95	3.97	2.14	2.47	2.22	2.03	2.87	2.12	2.05	2.68	2.76
Zn	326.53	123	93	102	94	138	107	87	87	97	100
Zr	56	227	67	93	66	134	102	62	68	98	90

Sample	10RB105	11MDM037	11RB173	13-CR-20-06	13-CR-20-07	13-CR-20-6	13-CR-21-01	13-CR-28-07	13-CR-28-09	13-CR-28-10	14-CR-1-1
Ba	281	138.5	80.9	285	248	337	564	69.6	109	103.5	404
Ce	17.8	17	13.7	59	45	43	61.6	13.6	23.8	22.8	60.5
Co	32	39	38	43	51	40	33	43	37	41	38
Cr	110	160	250	130	190	120	20	270	10	110	20
Cs	1.67	11.25	2.51	1.46	0.23	2.03	0.46	2.1	1.86	2.37	1.37
Cu	74	9	61	13	172	15	114	119	59	71	181
Dy	2.96	2.92	2.37	4.99	3.21	4.43	5.63	2.59	4.2	3.9	5.33
Er	1.92	1.99	1.51	2.81	1.97	3.05	3.15	1.77	2.57	2.5	2.85
Eu	0.69	0.72	0.54	1.15	1.1	1.27	1.58	0.63	0.91	0.82	1.72
Ga	15.8	15.3	14.7	19.6	18.9	19	21	15.3	18.2	17.2	20.3
Gd	2.93	2.86	2.33	4.45	3.14	4.38	6.26	2.47	3.64	3.48	6.05
Hf	2.1	2	1.8	3.7	2.3	3.7	5.4	1.8	3.4	2.7	5.1
Ho	0.65	0.62	0.55	0.95	0.61	1.02	1.03	0.55	0.85	0.78	1.08
La	8.4	8.6	6.3	19.8	8.2	20.7	28.3	6.2	11	10.3	28.4
Lu	0.29	0.29	0.23	0.42	0.2	0.45	0.4	0.22	0.33	0.34	0.4
Nb	3.5	3.5	2.6	13.9	6.3	13.4	14.6	3.1	5.6	5.2	13.3
Nd	9.8	9.7	7.5	20.3	12.3	19.4	32.9	7.9	13.6	12.4	30
Ni	51	58	71	45	110	39	33	87	36	62	34
Pb	6	58	7	2	3	2	6	BD	2	2	14
Pr	2.26	2.19	1.75	5.02	2.67	5.04	8.05	1.7	3.04	2.88	7.41
Rb	75.4	127	34.2	56.8	10.1	58	71.7	21.8	20.5	27.4	55
Sc	35	39	34	33	38	31	29	34	38	41	28
Sm	2.47	2.11	1.79	4.52	2.61	4.48	6.69	2.15	3.31	3.16	6.37
Sr	153.5	127.5	90.1	181	206	178	253	103	121	99.7	274
Ta	0.3	0.6	0.2	0.9	0.4	0.9	1	0.2	0.3	0.4	0.9
Tb	0.45	0.45	0.36	0.72	0.52	0.82	0.95	0.42	0.61	0.62	0.88
Th	2.31	2.16	1.67	5.32	1.26	5.44	7.02	1.34	2.81	2.37	6.84
Tm	0.28	0.27	0.23	0.42	0.25	0.45	0.48	0.25	0.35	0.34	0.41
U	0.6	0.52	0.44	1.28	0.28	1.31	1.68	0.38	0.84	0.67	1.68
V	283	283	252	285	293	283	358	247	315	329	390
Y	17.8	18.3	15	27.1	16.4	26.6	29.5	14.6	22.3	21.9	28
Yb	1.8	1.86	1.64	2.63	1.49	2.81	2.84	1.59	2.36	2.21	2.82
Zn	91	487	89	86	88	100	65	94	97	100	111
Zr	71	70	62	136	77	134	199	49	105	85	192

Sample	14-CR-2-1	14-CR-2-2	14-CR-2-5b	14-CR-6-2	14-CR-6-6	14-CR-7-1	14-CR-7-2	AM-06	RR-06	RR-07	TR-17
Ba	1065	211	57.5	210	307	92.3	61.5	262.2	170.5	149.5	199
Ce	35.9	30.1	11.6	50.9	59.8	19.2	17.6	29.93	32.7	26.9	40.8
Co	25	50	68	31	23	43	42	46	54	46	46
Cr	40	150	960	20	BD	180	170	113	510	610	60
Cs	1.66	0.88	0.77	3.12	11.35	2.58	0.64	0.74	0.08	0.57	0.95
Cu	41	169	132	7	8	73	71	73	86	101	227
Dy	2.99	5	2.15	5.31	6.98	3.32	3.21	4.35	3.92	3.14	6.84
Er	1.9	3.13	1.25	3.08	4.04	2.05	1.91	2.61	2.33	1.9	3.84
Eu	1.27	1.3	0.71	1.59	1.65	0.82	0.8	1.21	1.28	0.64	1.74
Ga	17.6	18.5	14.2	23.4	18.5	16.6	15.9	17.55	18.3	14.8	23.1
Gd	3.58	4.4	2.34	5.65	6.7	2.92	2.84	4.16	3.71	3.22	7.07
Hf	2.6	3.4	1.3	4.6	5.2	2	1.8	2.82	3.2	2.5	5.2
Ho	0.7	1.1	0.47	1.13	1.57	0.7	0.67	0.88	0.82	0.6	1.35
La	19.3	14.9	5.1	24.2	29.2	9.1	8.1	14.44	15.6	12.6	16.8
Lu	0.28	0.44	0.18	0.44	0.62	0.31	0.31	0.35	0.32	0.27	0.45
Nb	5.6	7.7	2.5	9.9	9.7	3.9	3.6	6.28	7.5	6.5	11.2
Nd	17.5	15.6	7.2	26	29.2	10.6	9.5	15.9	16.8	14.3	25.4
Ni	16	83	336	3	BD	74	74	46	89	110	47
Pb	5	7	5	4	11	9	9	6.1	BD	3	9
Pr	4.3	3.76	1.58	6.35	7.25	2.43	2.26	3.83	3.97	3.38	5.5
Rb	91.2	26.3	15.9	58.1	109.5	21.9	7.6	55.75	12.7	30.9	41.8
Sc	18	38	30	31	33	37	32	39.4	34	34	35
Sm	3.68	4.12	2.02	5.9	6.41	2.75	2.56	3.82	3.51	3.33	6.27
Sr	315	133	120.5	172.5	147.5	123	124.5	170	432	180.5	165
Ta	0.2	0.5	0.2	0.6	0.7	0.2	0.2	0.4	1.4	0.4	0.8
Tb	0.51	0.76	0.36	0.89	1.09	0.54	0.51	0.676	0.61	0.51	1.07
Th	2.28	3	1.22	6.84	8.02	2.25	1.94	3.61	3.75	3.18	3.99
Tm	0.29	0.45	0.19	0.44	0.66	0.28	0.28	0.371	0.36	0.26	0.56
U	0.72	0.78	0.28	1.77	1.96	0.59	0.57	0.94	1.12	0.81	1.09
V	183	292	252	482	83	274	268	278.4	260	253	519
Y	17.1	27.9	11.7	29.3	40.5	19	17.9	24.28	21.1	16.8	35.4
Yb	1.77	3.04	1.12	3	4.22	2.01	1.96	2.379	2.3	1.73	3.35
Zn	80	107	77	88	123	95	88	91.91	52	57	135
Zr	96	121	44	164	174	74	65	107	98	78	176

Sample	13-CR-19-										13-CR-27-	
	TR-30-AG	TR-32	TR-36	TR-44	TR-45	TR-55	TR-56	TR-61	TR-62	03	01	01
Ba	210	148	316	281	199	410	443	398	269	470	654	
Ce	30.7	18.5	31.5	37.7	41.3	57.7	58.4	39.2	57.8	54.9	74.9	
Co	52	49	41	45	51	37	31	41	34	36	26	
Cr	30	240	160	150	70	60	20	170	40	10	10	
Cs	1.5	0.46	0.91	2.24	1.29	0.84	0.75	0.73	2.7	0.2	0.7	
Cu	137	205	26	25	259	120	182	17	171	2	31	
Dy	5.4	3.63	3.72	4.62	6.98	5.27	5.36	4.57	8.38	4.4	8.71	
Er	2.94	2.34	2.55	2.75	3.69	2.75	2.83	2.87	4.46	2.52	4.69	
Eu	1.42	0.87	0.85	1.08	1.95	1.25	1.34	1.13	2.41	1.81	2.73	
Ga	21.4	16.5	17.3	17.8	24	20	19.6	19	26	23.3	23.9	
Gd	5.04	3.41	3.49	4.02	6.96	5.57	5.65	4.26	8.4	4.64	9.56	
Hf	3.1	2.2	2.9	3.4	5.3	5.3	5.6	3.6	6.7	1.1	7.8	
Ho	1.01	0.78	0.81	0.91	1.37	0.98	1.03	0.93	1.58	0.84	1.69	
La	13.4	8.1	15.5	18.4	17.4	26.3	27.4	19.2	24.7	28.6	34	
Lu	0.37	0.31	0.33	0.39	0.48	0.37	0.4	0.43	0.58	0.32	0.6	
Nb	7.2	6.7	10.3	12.7	12.7	13.7	13.5	13.5	15.2	3.8	37.8	
Nd	18.2	10.9	15.3	19.7	26.2	29.6	31.7	20.9	35.5	30.7	42.4	
Ni	67	89	55	49	43	36	34	42	22	10	15	
Pb	7	3	3	8	8	4	9	3	9	BD	15	
Pr	3.92	2.44	3.85	4.77	5.74	7.29	7.49	4.78	8.05	6.91	9.79	
Rb	38.4	23.5	63	83.4	50.4	56.4	57.4	109	70.9	1.5	41.6	
Sc	33	43	34	34	34	28	28	31	24	24	24	
Sm	4.47	2.53	3.39	4.06	6.42	6.24	6.06	4.42	8.01	5.63	9.77	
Sr	150	144.5	171	222	180.5	225	244	166	206	905	59.8	
Ta	0.4	0.4	0.7	0.8	0.8	1	1	0.9	1.1	0.2	2.1	
Tb	0.82	0.54	0.58	0.72	1.17	0.84	0.91	0.74	1.41	0.71	1.46	
Th	2.3	1.72	3.63	5.12	4.35	6.89	6.75	5.24	6.84	0.37	2.89	
Tm	0.42	0.3	0.36	0.4	0.55	0.37	0.46	0.43	0.67	0.35	0.63	
U	0.57	0.42	0.91	1.3	1.13	1.67	1.53	1.3	1.88	0.09	0.58	
V	510	286	249	273	514	364	348	278	273	308	151	
Y	26.6	20.5	20.8	25.4	36.7	25.9	28.5	26.2	43	23	45.3	
Yb	2.26	1.99	2.25	2.72	3.26	2.72	2.38	2.77	4.01	2.02	4.08	
Zn	111	91	92	98	131	64	66	89	150	128	301	
Zr	100	73	94	126	186	189	194	124	253	32	299	

Sample	13-CR-27-03A	13-CR-27-03B	13-CR-29-02	13-CR-32-01	13-CR-33-06	14-CR-5-2	14-CR-6-7	HR-10	HR-12	AM-07	AM-08
Ba	1800	1080	606	949	573	3210	969	714	634	225.6	247
Ce	86.9	88.3	54.1	68.3	51.1	174.5	78	65	70.9	23.16	23.4
Co	65	58	51	44	49	6	53	51	47	71.1	68
Cr	60	90	20	10	20	BD	20	90	70	600	2420
Cs	2.78	1.89	0.45	4.1	0.37	7.24	9.29	1.25	0.79	0.7	0.89
Cu	23	2	14	BD	15	12	34	83	105	72	67
Dy	7.87	7.96	4.96	4.57	4.38	13.9	6.67	6.12	7.17	2.35	2.33
Er	4.4	4.48	2.83	2.53	2.73	7.72	3.69	3.28	3.78	1.38	1.26
Eu	2.67	3.07	1.88	1.96	1.84	5.37	2.73	2.31	2.61	0.68	0.64
Ga	29.4	27.5	23.2	23.6	21.6	35.7	25.7	26.3	25.6	11.4	10.7
Gd	9.19	9.6	5.88	5.34	5.5	15.25	7.55	7.2	8.56	2.41	2.29
Hf	7.3	7.1	4.3	4.1	4.2	14.3	6.6	5.3	6	1.69	1.9
Ho	1.55	1.59	0.94	0.88	0.87	2.86	1.37	1.24	1.38	0.48	0.47
La	38.7	39	25.9	28	24.5	79.4	37.4	28.6	30.6	11.74	11.8
Lu	0.54	0.51	0.31	0.29	0.3	1.1	0.52	0.39	0.45	0.19	0.19
Nb	34.8	32.8	16.4	16.7	15.3	66.8	23.5	18.4	20.5	3.2	3.1
Nd	49.2	48	29.3	30.7	27.7	86.7	40.4	38.7	43.3	11.5	10.9
Ni	34	34	77	33	73	1	31	82	72	406	413
Pb	BD	BD	2	2	5	6	4	8	3	4.8	6
Pr	11.1	11	6.95	7.19	6.57	21.3	9.89	8.6	9.59	2.85	2.8
Rb	58.9	54.3	30.8	83.3	30.2	106	71.3	35.8	19.6	21.16	23.9
Sc	24	23	17	12	17	25	25	26	35	24.9	23
Sm	9.86	10.15	6.18	5.78	5.83	17.6	8.5	8.19	9.14	2.37	2.39
Sr	77.8	68.5	510	31.3	473	146	506	370	359	129	131.5
Ta	1.9	1.8	0.9	1	0.8	3.3	1.2	1	1.1	0.2	0.2
Tb	1.29	1.33	0.83	0.77	0.79	2.34	1.15	1.02	1.21	0.373	0.39
Th	2.59	2.49	2.13	1.22	2.07	9.34	3.75	2.41	2.52	3.21	3.18
Tm	0.6	0.56	0.39	0.32	0.35	1.07	0.5	0.43	0.51	0.196	0.2
U	0.53	0.63	0.36	0.26	0.33	2.13	0.59	0.59	0.65	0.89	0.89
V	176	165	132	101	122	BD	185	243	273	171.34	132
Y	40.4	41.4	25.4	22.6	23.2	71.7	35.3	30.6	33.7	13.14	12.6
Yb	3.82	3.86	2.29	1.92	2.28	6.96	3.29	2.73	2.78	1.272	1.28
Zn	223	200	185	60	189	179	129	170	154	70.99	84
Zr	269	255	158	140	154	628	267	205	224	66	61

Sample	AM-09	AM-10	13-CR-18-04	13-CR-22-01	13-CR-25-04	13-CR-26-06	13-CR-28-02	13-CR-28-11	13-CR-29-04	13-CR-29-05	13-CR-29-07
Ba	238	164.9	546	596	138	303	107.5	94.7	276	65.9	120.5
Ce	24.4	20.96	115	103.5	18.1	43.4	14.1	33.1	63.1	14.3	20.7
Co	68	76.4	15	11	36	30	40	40	17	39	35
Cr	2310	600	BD	BD	40	10	20	10	BD	130	140
Cs	0.68	0.61	5.97	2.15	2.15	5.76	1.47	1.45	4.93	2.12	0.63
Cu	78	68	91	22	59	11	61	17	9	87	54
Dy	2.33	2.08	19.3	13.8	2.84	5.42	2.51	5.12	9.25	2.63	3.61
Er	1.38	1.26	11.6	8.01	1.86	3.56	1.62	3.03	5.7	1.57	2.19
Eu	0.66	0.6	4.34	3.3	0.68	1.23	0.62	1.76	1.89	0.51	0.79
Ga	11.2	10.39	30.7	25.1	16.9	20.2	15.4	17.2	20.6	15.2	17
Gd	2.4	2.14	18.85	14.15	2.51	4.75	2.31	4.72	8.82	2.23	3.17
Hf	1.9	1.61	17.2	11.2	1.6	4.6	1.5	2.9	7.2	1.5	2.4
Ho	0.49	0.42	3.85	2.8	0.56	1.18	0.51	1.08	1.92	0.53	0.69
La	12.2	10.4	48.8	45.8	9	20.3	6.6	16.6	29.1	6.3	9.9
Lu	0.2	0.17	1.55	1.09	0.25	0.54	0.26	0.48	0.73	0.23	0.29
Nb	3.3	2.85	31.4	25	3.4	8.6	2.7	5.5	14.5	2.8	4.5
Nd	11.6	10.19	73.4	61.9	9.8	20.5	7.4	16	32.8	7.8	11.4
Ni	401	474	BD	BD	21	2	32	7	1	40	62
Pb	3	4.2	26	43	BD	5	10	BD	4	5	3
Pr	2.93	2.55	16.2	13.9	2.33	5.05	1.7	4.17	7.69	1.82	2.72
Rb	22.9	16.42	115	102	31.8	68.1	17.5	22.7	64.8	21.2	21.4
Sc	23	23.5	19	18	34	37	37	48	24	31	33
Sm	2.49	2.18	18.4	13.55	2.27	4.96	1.62	4.1	7.49	1.76	2.82
Sr	140	105	147.5	127	88.2	115	98.1	131	131	110	170.5
Ta	0.2	0.2	2	1.7	0.2	0.6	0.2	0.4	0.9	0.1	0.3
Tb	0.39	0.331	3.21	2.32	0.4	0.85	0.36	0.81	1.44	0.35	0.5
Th	3.34	2.81	11.5	11.6	2.39	5.96	1.65	3.71	7.32	1.77	2.24
Tm	0.2	0.177	1.7	1.23	0.25	0.51	0.27	0.48	0.78	0.23	0.31
U	0.97	0.78	3.02	3.56	0.66	1.65	0.42	1.02	1.9	0.55	0.56
V	143	164.21	5	22	246	283	248	701	29	247	274
Y	13.1	11.95	107	77.6	15.8	30.7	13.7	28.8	50.9	14.1	19.4
Yb	1.44	1.165	10.45	7.28	1.78	3.51	1.62	3.13	5.24	1.51	2
Zn	85	62.51	210	171	75	107	112	113	136	105	68
Zr	62	62	634	415	50	148	44	108	239	47	73

Sample	13-CR-29-08	13-CR-31-01	13-CR-32-04	13-CR-35-01	86BT06	03RL099	08RB029	13-CR-18-03	13-CR-19-01	13-CR-20-03	13-CR-20-09
Ba	51.8	125	135	73.4	169.5	73.3	148	137	99.9	88.3	82.8
Ce	14.7	85.6	22.7	25.2	34.6	17.5	31.3	27.9	18.3	12.8	13.5
Co	34	22	40	53	48	45	46	46	45	45	48
Cr	220	BD	10	BD	BD	10	BD	60	40	260	260
Cs	0.59	5.68	1.41	0.43	5.4	1.71	2.99	1.01	0.29	0.21	0.38
Cu	60	24	52	86	155	72	27	380	89	199	196
Dy	2.51	17.05	3.93	5.34	7.42	2.99	5.7	6.95	4.97	3.62	3.65
Er	1.59	9.68	2.56	3.42	4.48	1.9	3.26	4.04	2.98	2.35	2.25
Eu	0.48	3.35	0.74	1.1	1.9	0.67	1.7	1.79	1.16	0.95	0.9
Ga	14.4	24.6	18.1	18.4	21.6	16.7	23.9	23.7	21.5	17	17.2
Gd	2.17	16.55	3.48	5.14	7.05	2.76	6.02	6.24	4.23	3.07	3.19
Hf	1.3	7.6	2.5	3.3	5.6	1.8	4	3.9	2.6	1.9	1.9
Ho	0.51	3.37	0.81	1.09	1.58	0.66	1.14	1.43	1.01	0.75	0.74
La	6.7	38.1	10.6	10.6	14.4	8.1	13.2	11	8.2	5.4	5.5
Lu	0.21	1.13	0.33	0.46	0.63	0.29	0.41	0.56	0.4	0.29	0.3
Nb	2.8	13.2	4.2	6.9	10.2	4.4	8.1	10.1	3.5	5.1	5.3
Nd	7.5	54.5	11.7	15.8	21	9.4	19.7	20.2	13	9.8	9.9
Ni	38	BD	18	19	20	29	15	67	34	99	96
Pb	7	13	9	10	10	7	6	14	3	4	BD
Pr	1.9	11.9	2.73	3.36	4.63	2.15	4.29	4.32	2.62	2.08	1.91
Rb	21.4	11.9	22.6	5.1	35.1	19.4	34	34.7	13.8	5.3	15
Sc	34	30	42	46	46	44	35	41	42	45	44
Sm	1.73	14.1	2.81	4.13	5.81	2.18	5.65	5.51	3.33	2.79	2.45
Sr	80	176.5	125.5	159	117	103	171	178	95.6	135	135.5
Ta	0.2	0.8	0.3	0.4	0.6	0.2	0.6	0.6	0.2	0.3	0.3
Tb	0.37	2.66	0.52	0.83	1.23	0.47	0.98	1.13	0.78	0.52	0.51
Th	1.8	5.63	2.85	2.41	3.07	2.27	2.96	1.71	1.99	0.82	0.79
Tm	0.18	1.36	0.35	0.45	0.66	0.31	0.42	0.57	0.48	0.31	0.31
U	0.5	1.55	0.75	0.55	0.83	0.59	0.91	0.47	0.5	0.24	0.23
V	243	15	310	567	456	356	651	470	373	312	310
Y	13.4	90.9	21	30.4	39.8	17.9	30.4	38.1	28.2	19.5	19.9
Yb	1.42	8.41	2.2	3.25	4.54	1.95	2.78	3.92	2.73	2	1.93
Zn	53	180	141	127	166	92	156	150	131	84	82
Zr	42	222	84	119	205	64	133	128	84	61	63

Sample	13-CR-20-10	13-CR-22-03	13-CR-22-04	13-CR-23-02	13-CR-23-04	13-CR-23-05	13-CR-24-02A	13-CR-24-04	13-CR-25-01	13-CR-25-03	13-CR-25-06
Ba	151.5	108.5	130.5	149	146	151.5	123.5	96.2	33.4	68.8	47.3
Ce	21.2	23.9	26.1	27.6	27.4	30.9	25.8	32.6	20.2	17	13.4
Co	48	47	46	50	47	47	48	37	43	43	38
Cr	100	120	130	100	50	60	40	110	80	20	370
Cs	0.45	0.95	0.73	1.41	1.28	10.2	3.08	8.12	1.54	1.29	0.65
Cu	225	299	271	309	267	295	275	269	144	217	81
Dy	4.77	5.58	6.42	6.42	6.05	7.18	5.64	7.17	4.28	3.02	3.21
Er	2.93	3.04	3.51	3.98	3.63	4.3	3.42	4.27	2.9	2.05	2.07
Eu	1.14	1.49	1.6	1.52	1.59	1.66	1.42	1.87	0.98	0.94	0.79
Ga	18.4	21.6	22.2	21.4	21	22.4	22.9	22	18.8	19.6	15.9
Gd	4.38	5.11	5.97	6.15	5.52	6.87	5.43	6.85	4.09	2.74	2.77
Hf	2.8	3.6	4.1	4.1	4.2	4.7	4	4.9	3.3	2.4	2
Ho	1	1.15	1.26	1.25	1.27	1.36	1.22	1.39	0.94	0.67	0.67
La	8.8	9.8	10.7	11.1	11.7	12.8	10.7	13.4	8.6	7.6	5.7
Lu	0.4	0.46	0.51	0.47	0.49	0.56	0.42	0.54	0.39	0.28	0.27
Nb	8	8.3	8.8	9.5	8.7	9.1	8.5	10.3	6.2	3.5	4.3
Nd	15	16.8	18.9	19.6	18	21.1	16.3	21.1	12.4	9.8	8.2
Ni	69	80	72	76	66	64	64	58	69	42	97
Pb	BD	6	3	BD	BD	3	BD	BD	2	BD	BD
Pr	3.08	3.53	3.83	4	3.81	4.26	3.59	4.44	2.8	2.18	1.75
Rb	46.6	14.6	24.4	27.6	21.9	24.4	23.8	50.5	4.9	19.8	7
Sc	43	41	40	45	43	43	34	38	42	32	37
Sm	4.1	4.24	4.95	5.1	4.97	5.83	4.97	6.02	3.37	2.18	2.19
Sr	165	148.5	205	118.5	144	141.5	150	149	177	135.5	91.9
Ta	0.5	0.5	0.6	0.6	0.5	0.6	0.5	0.7	0.4	0.2	0.3
Tb	0.74	0.89	1.06	1.07	0.97	1.13	0.87	1.12	0.64	0.48	0.5
Th	1.28	1.99	2.11	2.41	2.25	2.47	2.04	2.47	2.14	1.9	1.34
Tm	0.45	0.48	0.52	0.56	0.48	0.56	0.46	0.6	0.41	0.28	0.28
U	0.4	0.5	0.58	0.56	0.57	0.65	0.58	0.78	0.53	0.5	0.29
V	357	441	430	463	423	442	378	444	348	273	260
Y	27.3	30.7	33.3	34.6	32.3	36.7	29.1	37.9	23.7	17.5	17.3
Yb	2.81	2.82	3.23	3.44	3.1	3.71	3.03	3.88	2.72	1.98	1.85
Zn	98	125	122	133	127	138	141	108	99	73	72
Zr	100	126	134	142	131	143	125	151	93	73	62

Sample	13-CR-26-01	13-CR-26-02	13-CR-26-03	13-CR-26-04	13-CR-26-05	13-CR-26-09	13-CR-26-10	13-CR-26-11	13-CR-28-05	13-CR-28-06	13-CR-28-08
Ba	62.3	101.5	140	45	16.3	199	130.5	131	59.9	35.7	134.5
Ce	18.4	18.5	13	16	19.1	18.9	22.8	26	49.7	18.5	26.9
Co	41	38	38	46	47	40	41	41	65	35	54
Cr	50	30	350	20	30	100	30	20	20	20	BD
Cs	3.51	8.59	0.09	0.12	0.14	1.19	2.64	7.86	0.59	0.96	8.34
Cu	198	27	91	87	91	137	20	BD	428	8	38
Dy	3.86	4.34	2.84	3.47	4.64	3.81	5.34	7.88	3.12	3.29	6.68
Er	2.55	2.78	1.99	2.21	2.91	2.27	3.43	5.17	2.08	2.2	3.94
Eu	1.01	1.05	0.69	0.99	1.21	0.94	1.13	1.69	0.71	0.73	1.66
Ga	17.4	20.9	16.4	18.6	19.7	17.7	20.1	24.1	20.1	18	23.3
Gd	3.43	4.03	2.83	3.75	4.4	3.3	4.91	7.4	2.74	2.99	6
Hf	2.6	2.5	2	2.3	2.7	2.2	3.3	4.7	2.3	2.3	3.9
Ho	0.86	0.91	0.63	0.8	0.91	0.74	1.11	1.74	0.62	0.67	1.39
La	7.7	7.9	5.6	7	8.6	8.5	9.8	10.8	4.9	8	11.8
Lu	0.34	0.42	0.28	0.32	0.41	0.32	0.45	0.67	0.24	0.3	0.52
Nb	5.6	5.6	4.3	4.2	5.4	4.3	7.3	9.7	3	4.1	8.4
Nd	11.4	11.9	8	10.1	12.3	11.2	14.2	19.6	7.4	10.3	17.6
Ni	67	47	98	68	56	57	52	BD	124	29	1
Pb	BD	11	BD	BD	3	7	BD	BD	BD	BD	6
Pr	2.44	2.48	1.74	2.18	2.61	2.42	2.94	3.87	1.56	2.38	3.73
Rb	13.3	23.8	4.9	3.6	1.5	18.7	17.5	20.7	6.8	6.1	46.6
Sc	41	36	26	41	39	39	42	44	52	35	45
Sm	3.05	3.16	2.29	2.86	3.26	2.79	4.07	5.79	2.15	2.49	5.05
Sr	154	209	108	97.8	163	123	129	60.2	107.5	114.5	141
Ta	0.3	0.3	0.2	0.3	0.4	0.3	0.4	0.6	0.2	0.2	0.5
Tb	0.61	0.65	0.42	0.6	0.7	0.55	0.76	1.2	0.47	0.51	0.97
Th	1.85	1.49	1.39	1.35	1.67	1.86	2.05	3.02	0.86	2.54	2.13
Tm	0.35	0.39	0.28	0.36	0.44	0.32	0.48	0.77	0.25	0.29	0.53
U	0.48	0.43	0.35	0.38	0.42	0.62	0.54	0.69	0.27	0.66	0.56
V	320	402	239	323	398	303	441	92	898	308	387
Y	21.7	23.6	16.3	20.4	24.7	20	28.4	43.6	16.6	19	34.9
Yb	2.26	2.56	1.76	2.18	2.65	2.01	2.94	4.49	1.81	2.13	3.38
Zn	81	116	76	94	114	179	58	37	90	80	169
Zr											

Sample	13-CR-29-11	13-CR-30-02	13-CR-33-01	13-CR-35-02	13-CR-36-01	13-CR-36-02	14-CR-6-1	14-CR-6-3	86BT02	86BT05	RR-04
Ba	44.1	61.2	99.1	805	103	91.7	52.1	104	56.5	144.5	227
Ce	29.8	14.1	13.4	10.2	20.3	13.5	28.8	28.7	14.3	18.5	11.6
Co	42	39	44	43	48	44	32	40	49	45	48
Cr	40	30	220	150	20	370	330	150	30	40	140
Cs	1.87	1.68	3.21	0.36	2.01	1.2	0.49	0.84	5.33	4.92	0.48
Cu	136	211	80	147	86	103	7	7	261	169	144
Dy	6.77	3.52	2.78	2.46	4.44	2.8	4.18	3.87	3.45	3.76	2.86
Er	4.14	2.19	1.88	1.66	2.82	1.61	2.28	2.23	2.07	2.26	1.75
Eu	1.56	0.77	0.74	0.75	1.11	0.63	1.25	1.12	0.77	0.96	0.74
Ga	21.5	20.1	16.2	14.4	20.4	13.9	18.2	18.7	18.6	17.4	17.2
Gd	6.19	2.73	2.68	2.54	4.23	2.46	3.92	3.84	3.07	3.48	2.54
Hf	4.3	2.2	1.8	1.6	2.7	1.7	2.8	2.7	2.1	2.4	1.8
Ho	1.34	0.68	0.57	0.51	0.96	0.54	0.82	0.77	0.75	0.78	0.6
La	12.6	6.2	6.1	4.1	8.7	5.6	12.6	13.4	5.9	8.6	4.6
Lu	0.54	0.32	0.25	0.19	0.37	0.2	0.31	0.3	0.27	0.34	0.22
Nb	8.5	3.9	3.4	3.1	5.8	2.7	6.6	6.2	3.6	4.5	3.9
Nd	19	9.4	8.2	7	12.4	7.8	16.2	15.6	9.1	11.6	7.9
Ni	29	58	131	90	51	126	33	24	83	64	84
Pb	3	3	6	BD	9	BD	11	7	12	12	BD
Pr	4.15	2	1.71	1.4	2.79	1.7	3.82	3.72	1.99	2.52	1.64
Rb	16.8	12.8	25.6	35.9	8.3	10.5	15.7	35.7	25.6	29.4	31.7
Sc	42	34	22	32	39	33	29	32	41	42	33
Sm	5.43	2.59	2.04	1.93	3.48	2.08	3.72	3.78	2.59	3.17	2.16
Sr	116.5	133.5	125.5	173	265	115	181.5	165	115	202	166
Ta	0.5	0.3	0.2	0.2	0.4	0.2	0.4	0.4	0.2	0.3	0.3
Tb	1	0.53	0.43	0.38	0.7	0.4	0.62	0.57	0.53	0.62	0.44
Th	2.48	1.07	1.19	0.57	1.78	1.5	3.47	3.43	1.23	2.04	0.7
Tm	0.52	0.33	0.23	0.22	0.38	0.23	0.35	0.33	0.29	0.34	0.22
U	0.67	0.3	0.38	0.12	0.44	0.37	0.96	1.02	0.26	0.47	0.15
V	451	316	296	243	432	250	302	269	391	347	260
Y	35.7	18.9	15.5	13.9	25.6	15.1	22.2	20.9	19	21.2	15.1
Yb	3.74	1.96	1.53	1.41	2.54	1.66	2.16	2.03	1.96	2.19	1.64
Zn	129	102	87	68	120	72	87	100	115	102	76
Zr	140	69	49	50	98	59	101	95	71	80	54

Sample	RR-08	RR-10	RR-11	RR-12	13-CR-22-02	13-CR-28-04	13-CR-29-01	13-CR-31-04	14-CR-3-2	MT-06	MT-11
Ba	595	261	72	100	124	159.5	25.9	110.5	154	50.4	152
Ce	26.6	24.6	15	18.5	28.4	33.1	41.2	22.2	36.3	14.78	13.61
Co	50	48	38	56	46	43	66	47	51	52.4	48.2
Cr	130	150	120	90	120	BD	BD	150	90	235	267
Cs	0.3	0.91	0.11	0.63	1.03	1.92	0.16	0.62	1.71	0.24	0.5
Cu	50	52	124	156	300	9	633	230	365	173	159
Dy	4.66	4.33	3.31	4.33	6.07	5.73	9.07	5.57	7.76	4.06	3.63
Er	2.79	2.34	2.05	2.51	3.6	3.31	6.23	3.23	4.48	2.45	2.22
Eu	1.38	1.23	1.12	0.99	1.62	1.73	2.54	1.4	2.03	1.03	0.96
Ga	19.6	20	19.3	19.9	22.2	23.3	27.6	20.3	22.5	16.84	15.52
Gd	4.65	4.16	3.35	3.58	6.33	5.78	8.53	5.62	7.67	3.59	3.26
Hf	3.1	2.9	2.1	2.6	3.9	3.9	5.3	3.5	5.4	1.97	1.7
Ho	0.88	0.81	0.69	0.82	1.28	1.09	1.84	1.07	1.7	0.83	0.76
La	11.4	10.6	6.6	7.8	11.6	14.3	18.5	8.9	15.4	6.21	5.65
Lu	0.34	0.35	0.26	0.32	0.47	0.35	0.72	0.36	0.62	0.34	0.31
Nb	9	8.4	4.9	6.2	9.2	8.5	12.4	7.1	11.1	5.39	4.67
Nd	16.3	15.8	9.6	11.4	20.3	19.7	25.7	15.6	24.6	10.38	9.66
Ni	51	55	67	71	70	9	47	81	60	86	93
Pb	BD	BD	BD	BD	9	6	10	4	10	1.3	1
Pr	3.51	3.39	2	2.53	4.15	4.35	5.43	3.06	5.17	2.22	2.01
Rb	14.3	43.4	10.7	19	25.7	36.1	7.4	15.6	32.3	4.27	10.79
Sc	38	36	37	37	40	34	44	42	42	45.9	44
Sm	3.91	4.02	2.85	3.23	5.54	5.3	7.17	4.26	6.84	2.97	2.67
Sr	243	240	252	130	167.5	172	374	134	186	138	142
Ta	0.5	0.5	0.3	0.4	0.6	0.5	0.7	0.4	0.7	0.3	0.3
Tb	0.73	0.65	0.51	0.6	1.02	0.9	1.43	0.87	1.23	0.598	0.55
Th	1.15	1.11	0.91	1.25	2.23	3.39	2.73	1.58	3.04	0.86	0.81
Tm	0.37	0.32	0.27	0.32	0.55	0.41	0.8	0.38	0.67	0.348	0.315
U	0.29	0.27	0.21	0.32	0.65	0.9	1.42	0.46	0.81	0.24	0.21
V	309	301	228	366	429	513	904	475	532	329.16	298.1
Y	23.4	21.9	17.9	21.6	34.7	29.4	51.2	28.6	43.3	22.88	20.38
Yb	2.42	1.98	1.75	2.2	3.52	2.79	5.11	2.76	4.13	2.25	2.026
Zn	100	97	78	97	141	154	78	113	153	84.49	67.57
Zr	103	92	64	83	142	127	158	103	190	72	61

Sample	MT-12	MT-14	MT-15	14-CR-1-4	14-CR-2-4	13-CR-28-03	13-CR-29-03	14-CR-2-6a	14-CR-2-6b	RR-03	13-CR-16-06
Ba	115.3	1852.4	206.4	117	50.9	180.5	71.1	2.3	1.4	19.2	902
Ce	15.32	22.22	19.92	11.1	8.3	7.6	7.9	1.1	1	1.8	113
Co	51.6	46.9	43.7	58	57	35	54	114	115	129	27
Cr	271	100	96	80	110	940	260	>10000	9790	7710	170
Cs	0.44	0.17	0.06	0.07	0.24	2.21	3.48	0.03	0.02	0.04	0.89
Cu	185	189	90	162	171	59	77	2	2	10	46
Dy	4.11	5.45	4.98	4.94	4.29	1.69	1.44	0.32	0.3	0.39	4.37
Er	2.45	3.33	2.77	2.99	2.61	1.13	1.07	0.25	0.19	0.19	2.15
Eu	1.04	1.26	0.94	1.17	1.02	0.33	0.41	0.05	0.09	0.08	2.13
Ga	16.76	17.73	15.9	19	17.9	13.4	13.5	3.6	3.6	2.9	22
Gd	3.76	5.08	4.59	4.2	3.58	1.28	1.36	0.26	0.26	0.25	5.62
Hf	2.02	2.75	2.15	2.3	1.9	1	0.8	0.2	0.2	0.2	6
Ho	0.86	1.13	0.99	1.07	0.96	0.28	0.32	0.06	0.07	0.07	0.8
La	6.39	10.16	8.74	4.1	2.9	3.5	3.7	0.5	0.5	0.9	56.5
Lu	0.34	0.45	0.31	0.43	0.39	0.16	0.13	0.04	0.04	0.04	0.31
Nb	5.48	8.11	8.2	2.5	2	1.7	1.7	0.3	0.3	0.3	8.5
Nd	10.6	15.76	14.24	9.4	7.5	3.8	4.4	0.5	0.5	0.9	55.3
Ni	93	66	75	68	79	103	232	2260	2250	1785	81
Pb	1.7	3.4	3	7	BD	39	BD	3	2	BD	13
Pr	2.25	3.37	3.03	1.71	1.38	0.94	1.03	0.1	0.1	0.23	14.05
Rb	10.87	72.36	12.92	4.3	3.4	13.3	20.1	0.3	0.2	0.2	84.2
Sc	45.2	44.9	45.1	46	49	27	19	7	7	8	17
Sm	3.02	4.19	3.88	3.36	2.63	1	1.21	0.25	0.28	0.21	8.86
Sr	142	262	139	97.6	104.5	85.6	84.1	BD	1.1	4.1	615
Ta	0.4	0.5	0.5	0.2	0.1	0.1	0.1	BD	BD	BD	0.4
Tb	0.625	0.832	0.766	0.75	0.64	0.24	0.22	0.05	0.05	0.04	0.76
Th	0.91	1.35	1.32	0.68	0.45	0.98	0.79	0.12	0.11	0.19	11.05
Tm	0.354	0.463	0.367	0.46	0.4	0.15	0.14	0.04	0.04	0.04	0.3
U	0.24	0.37	0.32	0.19	0.12	0.26	0.22	0.44	0.92	0.14	1.45
V	329.22	363.24	361.2	419	371	154	171	90	78	21	166
Y	22.69	31.94	27.4	27.6	24	8.8	8.9	1.8	1.8	1.8	22.3
Yb	2.281	2.954	2.181	2.89	2.48	1.12	0.96	0.22	0.28	0.21	2.01
Zn	75.97	90.85	105.25	99	103	106	68	84	83	68	85
Zr	73	101	70	76	60	24	22	10	8	BD	233

Sample	13-CR-16-		13-CR-24-	
	07	02B		
Ba	932	1260	ppm	
Ce	113	89.9	ppm	
Co	20	3	ppm	
Cr	100	10	ppm	
Cs	0.63	1.53	ppm	
Cu	35	4	ppm	
Dy	4.58	1.78	ppm	
Er	2.47	0.95	ppm	
Eu	1.65	0.82	ppm	
Ga	21.2	19.8	ppm	
Gd	6.19	2.76	ppm	
Hf	6.8	4.8	ppm	
Ho	0.88	0.33	ppm	
La	56.1	49.9	ppm	
Lu	0.3	0.12	ppm	
Nb	9.9	11.2	ppm	
Nd	53.1	31	ppm	
Ni	44	2	ppm	
Pb	6	25	ppm	
Pr	13.55	9	ppm	
Rb	66.2	138	ppm	
Sc	17	3	ppm	
Sm	7.8	4.37	ppm	
Sr	436	347	ppm	
Ta	0.5	0.9	ppm	
Tb	0.83	0.34	ppm	
Th	7.83	20.7	ppm	
Tm	0.33	0.13	ppm	
U	0.92	5.71	ppm	
V	159	18	ppm	
Y	24.9	8.4	ppm	
Yb	1.98	0.78	ppm	
Zn	94	41	ppm	
Zr	272	172	ppm	

Appendix 2.4: Fenner diagrams for 17 geochemical groups in Western Laurentia.

Figure A2.1-1: Fenner plots of GS 1

Figure A2.1-2: Fenner plots of GS 2, GS 3, GS 4, and GS 5.

Figure A2.1-3: Fenner plots of GS 7 and GS 8.

Figure A2.1-4: Fenner plots of GS 6, GS 11, and GS 12.

Figure A2.1-5: Fenner plots of GS 13

Figure A2.1-6: Fenner plots of GS 9, GS 10, GS14, GS 15, GS 16, and GS 17

Table of Geochemical analyses for eastern Laurentia. Unit=units analyses reported in, Group=geochemical group association, low P-Zr group, Intermediate-Amphibolite group (Int.-Amp. group), high P-Zr group, magma=most parental magma or evolved magma. Standards and 20 listed in Appendix 2.1.

Sample Group	Unit	Limit	13-CR-01-01a Low P-Zr Evolved -65.5019 53.5019	13-CR-01-01b Low P-Zr Evolved -65.4679 53.5019	13-CR-01-02 Low P-Zr Parental -65.5546 53.5385	13-CR-01-04 Low P-Zr Evolved -65.6143 53.5669	13-CR-01-05 Low P-Zr Parental -65.5405 53.5404	13-CR-01-07a Low P-Zr Evolved -65.4196 53.5246	13-CR-01-07d Low P-Zr Evolved -65.4196 53.5246	13-CR-02-02 Low P-Zr Evolved -65.4192 53.4508	13-CR-02-04 Low P-Zr Evolved -65.2329 53.4522	13-CR-02-05 Low P-Zr Evolved -65.0949 53.4696
Longitude	Wt%	0.01	20.85	20.85	16.98	14.05	17.23	14.45	14.67	15.40	15.19	15.90
Al2O3	Wt%	0.01	9.41	9.41	8.51	7.51	10.32	7.22	7.24	9.88	8.70	8.70
CaO	Wt%	0.01	10.08	10.08	12.70	15.13	10.03	13.99	13.97	11.65	12.80	12.89
FeO	Wt%	0.01	9.19	7.49	0.89	1.04	0.79	0.74	0.72	1.11	1.44	0.60
K2O	Wt%	0.01	0.48	0.89	0.91	1.04	6.26	12.68	12.82	7.02	5.57	12.05
MgO	Wt%	0.01	6.26	3.65	6.88	10.27	0.15	0.20	0.19	0.18	0.20	0.20
MnO	Wt%	0.01	0.13	0.11	0.19	0.20	3.09	2.47	2.40	2.45	3.05	1.56
Na2O	Wt%	0.01	2.97	3.97	3.14	2.71	0.18	0.21	0.21	0.16	0.31	0.15
P2O5	Wt%	0.01	0.20	0.33	0.27	0.33	50.88	46.74	46.51	50.87	51.05	47.18
SiO2	Wt%	0.01	48.45	51.82	48.56	46.81	1.06	1.31	1.27	1.28	1.57	0.78
TiO2	Wt%	0.01	1.29	1.47	1.87	1.94	0.53	3.00	2.94	0.24	-0.06	0.30
LOI	Wt%	0.01	0.56	0.56	0.94	0.91	0.53	3.00	2.94	0.24	-0.06	0.30
Ba	ppm	0.5	225.0	466.0	426.0	390.0	364.0	269.0	296.0	381.0	546.0	291.0
Ce	ppm	0.5	22.8	41.1	40.8	40.4	27.4	25.9	27.2	37.7	63.4	21.2
Co	ppm	1	45	26	49	76	42	83	86	41	48	80
Cr	ppm	10	50	20	150	70	290	160	200	220	50	90
Cs	ppm	0.01	0.24	1.00	0.26	0.27	0.43	1.16	1.16	1.19	0.24	0.56
Cu	ppm	1	44	30	44	36	54	34	33	108	58	61
Dy	ppm	0.05	2.98	5.02	4.79	5.47	4.00	3.24	3.72	4.87	7.38	3.35
Er	ppm	0.03	1.69	3.01	2.95	2.96	2.25	2.11	2.20	2.86	4.30	1.97
Eu	ppm	0.03	1.18	2.20	1.69	1.85	1.44	1.25	1.25	1.28	1.94	1.14
Ga	ppm	0.1	17.1	23.2	20.3	17.8	19.3	16.1	18.1	19.6	21.6	17.0
Gd	ppm	0.05	3.24	5.50	5.38	5.60	4.06	3.76	3.87	5.01	7.55	3.51
Hf	ppm	0.2	2.4	3.7	5.4	4.2	2.8	2.3	2.6	3.6	4.5	2.2
Ho	ppm	0.01	0.64	1.00	1.02	1.15	0.78	0.77	0.80	0.99	1.51	0.71
La	ppm	0.5	10.2	17.9	17.8	17.6	12.2	11.4	12.6	17.4	29.6	9.8
Lu	ppm	0.01	0.22	0.39	0.40	0.44	0.28	0.29	0.33	0.43	0.69	0.28
Nb	ppm	0.2	3.6	5.4	6.2	5.8	3.4	3.7	4.2	5.6	9.6	2.9
Nd	ppm	0.1	13.1	23.4	22.8	23.7	16.4	15.1	15.9	20.5	33.4	13.1
Ni	ppm	1	98	44	89	254	49	320	323	73	62	326
Pb	ppm	2	<2	5	4	5	<2	<2	3	5	9	2
Pr	ppm	0.02	3.14	5.41	5.47	5.40	3.81	3.53	3.62	4.88	7.91	2.86
Rb	ppm	0.3	8.2	18.9	17.6	17.0	15.8	16.1	17.8	28.8	28.8	12.2
Sc	ppm	1.00	10.00	14.00	18.00	25.00	29.00	15.00	14.00	36.00	33.00	16.00
Sm	ppm	0.03	3.19	5.38	5.28	5.23	4.05	3.59	4.07	4.90	7.54	3.41
Sr	ppm	0.1	355.0	392.0	304.0	215.0	315.0	283.0	307.0	242.0	253.0	269.0
Ta	ppm	0.1	0.2	0.3	0.3	0.3	0.2	0.2	0.3	0.4	0.6	0.2
Tb	ppm	0.01	0.50	0.84	0.85	0.94	0.65	0.57	0.60	0.76	1.18	0.54
Th	ppm	0.05	0.86	1.71	2.04	1.82	1.24	1.19	1.37	1.84	0.93	0.79
Tm	ppm	0.01	0.24	0.41	0.39	0.46	0.35	0.29	0.29	0.41	0.68	0.29
U	ppm	0.05	0.15	0.35	0.38	0.35	0.25	0.22	0.29	0.55	0.38	0.18
V	ppm	5	120	160	171	181	155	145	168	25.7	39.1	17.3
Y	ppm	0.5	14.9	25.9	25.6	27.9	20.5	17.8	19.7	25.7	39.1	17.3
Yb	ppm	0.03	1.68	2.85	2.71	2.84	2.18	1.85	1.89	2.80	4.23	1.86
Zn	ppm	2	81	81	129	148	89	129	129	91	124	112
Zr	ppm	2	93	142	219	169	111	91	113	145	186	85

Sample Group	Unit	Limit	13-CR-02-06 Low P-Zr Evolved -65.2395 53.4801	13-CR-03-01a Low P-Zr Evolved -65.2776 53.5540	13-CR-03-01b Low P-Zr Evolved -65.2776 53.5540	13-CR-03-01d Low P-Zr Evolved -65.2776 53.5540	13-CR-03-02 Low P-Zr Evolved -65.2087 53.5429	13-CR-03-05b Low P-Zr Evolved -65.2094 53.5954	13-CR-03-06a Low P-Zr Evolved -65.1217 53.4970	13-CR-03-06b Low P-Zr Evolved -65.1217 53.4970	13-CR-03-07 Low P-Zr Parental -65.1636 53.5816	13-CR-03-08 Low P-Zr Parental -65.2405 53.6011
Longitude	Wt.%	0.01	15.74	14.97	8.84	8.77	19.16	21.03	13.68	15.61	18.37	18.41
Latitude	Wt.%	0.01	9.45	7.23	3.43	3.43	8.99	10.00	7.15	9.10	9.11	8.80
Al2O3	Wt.%	0.01	12.59	13.37	18.14	18.08	10.37	8.25	11.89	11.96	11.43	11.74
CaO	Wt.%	0.01	0.73	0.37	0.06	0.06	0.62	0.50	2.50	1.02	0.53	0.65
FeO	Wt.%	0.01	6.21	14.71	23.44	23.45	7.20	6.29	4.50	6.43	8.22	7.76
K2O	Wt.%	0.01	0.19	0.17	0.23	0.23	0.14	0.18	0.14	0.19	0.15	0.15
MgO	Wt.%	0.01	2.88	2.23	0.46	0.44	3.16	3.22	3.04	3.05	2.89	2.94
MnO	Wt.%	0.01	0.30	0.12	0.11	0.11	0.20	0.14	0.35	0.32	0.18	0.20
Na2O	Wt.%	0.01	49.63	46.07	44.61	44.73	48.71	49.45	54.51	50.50	47.75	47.97
P2O5	Wt.%	0.01	2.27	0.76	0.68	0.69	1.44	1.00	2.22	1.81	1.36	1.38
SiO2	Wt.%	0.01	0.18	0.05	4.74	4.81	1.15	0.24	0.83	0.42	0.02	-0.04
TiO2	Wt.%	0.01	313.0	192.5	26.3	26.1	303.0	258.0	548.0	375.0	273.0	311.0
LOI	Wt.%	0.01	34.4	15.7	8.6	8.6	24.7	19.4	90.5	47.1	24.2	29.2
Ba	ppm	0.5	44	94	123	119	62	42	41	44	61	60
Ce	ppm	1	150	100	140	140	260	110	70	200	80	100
Co	ppm	10	0.37	0.41	0.19	0.22	0.80	0.15	1.75	0.75	0.23	0.18
Cr	ppm	0.01	42	37	56	54	78	27	44	45	35	40
Cs	ppm	1	5.31	2.14	1.51	1.47	3.14	2.67	7.76	5.54	3.39	3.59
Cu	ppm	0.05	3.04	1.22	0.85	0.90	1.81	1.55	4.42	3.00	1.92	2.19
Dy	ppm	0.03	1.62	0.85	0.33	0.30	1.20	1.02	1.86	1.64	1.27	1.31
Er	ppm	0.03	21.2	14.3	9.4	9.1	19.8	20.0	20.9	19.6	19.4	19.7
Eu	ppm	0.1	5.49	2.31	1.57	1.41	3.33	2.76	8.66	5.82	3.49	4.07
Ga	ppm	0.05	3.5	1.5	1.0	1.2	2.4	1.8	4.3	3.9	2.6	2.9
Gd	ppm	0.2	1.10	0.45	0.29	0.32	0.62	0.53	1.61	1.14	0.70	0.72
Hf	ppm	0.01	15.4	7.2	3.9	3.9	11.3	8.9	21.3	21.3	10.9	13.7
Ho	ppm	0.5	0.43	0.18	0.14	0.13	0.25	0.20	0.63	0.43	0.31	0.29
La	ppm	0.01	5.8	2.2	1.7	1.8	4.2	2.8	10.1	5.9	3.7	4.7
Nb	ppm	0.2	21.2	9.1	5.4	5.3	14.0	11.6	46.8	26.5	14.2	16.7
Nd	ppm	0.1	39	431	694	689	137	127	32	68	175	156
Ni	ppm	1	4	<2	4	5	10	4	11	3	<2	3
Pb	ppm	2	4.58	2.11	1.20	1.16	3.17	2.61	11.45	6.11	3.26	3.91
Pr	ppm	0.02	12.4	5.0	1.0	1.0	11.4	6.5	49.7	17.1	7.6	11.9
Rb	ppm	0.3	35.00	12.00	16.00	16.00	15.00	13.00	37.00	32.00	18.00	17.00
Sc	ppm	1.00	5.40	2.22	1.30	1.36	3.28	2.89	9.67	6.15	3.65	4.15
Sm	ppm	0.03	261.0	268.0	64.2	63.4	343.0	391.0	213.0	243.0	353.0	335.0
Sr	ppm	0.1	0.4	0.2	0.2	0.2	0.3	0.2	0.6	0.5	0.3	0.3
Ta	ppm	0.1	0.80	0.33	0.23	0.23	0.50	0.41	1.35	0.89	0.52	0.58
Tb	ppm	0.01	1.44	0.73	0.54	0.58	1.02	0.83	4.99	2.19	0.99	1.70
Th	ppm	0.05	0.45	0.19	0.16	0.15	0.29	0.22	0.64	0.48	0.29	0.31
Tm	ppm	0.01	0.22	0.13	0.10	0.11	0.18	0.15	0.77	0.36	0.18	0.21
U	ppm	0.05	255	91	85	84	118	118	360	244	158	152
V	ppm	5	27.8	11.0	8.0	8.0	16.3	13.6	40.3	28.8	17.6	19.1
Y	ppm	0.5	2.93	1.22	0.92	0.97	1.69	1.43	4.05	2.94	1.82	1.98
Yb	ppm	0.03	125	114	157	153	111	78	142	103	107	112
Zn	ppm	2	151	61	48	52	102	76	168	166	114	115
Zr	ppm	2										

Sample Group	Unit	Limit	13-CR-04-01a Low P-Zr Parental	13-CR-04-01b Low P-Zr Parental	13-CR-05-01c Low P-Zr Evolved	13-CR-05-04 Low P-Zr Evolved	13-CR-05-05 Low P-Zr Evolved	13-CR-05-09 Low P-Zr Parental	13-CR-05-12a Low P-Zr Evolved	13-CR-05-12b Low P-Zr Evolved	13-CR-05-13 Low P-Zr Evolved	13-CR-05-15a Low P-Zr Evolved
Longitude			-65.3843	-65.2897	-65.3843	-65.2897	-65.2859	-65.4426	-65.3808	-65.3808	-65.3177	-65.2137
Latitude			53.6962	53.6384	53.6962	53.6384	53.6100	53.5843	53.5396	53.5396	53.5474	53.6206
Al2O3	Wt%	0.01	17.06	17.36	14.46	17.94	15.13	17.34	18.87	18.89	12.83	14.67
CaO	Wt%	0.01	8.47	8.44	8.89	9.28	7.75	8.62	9.83	9.34	9.08	7.44
FeO	Wt%	0.01	12.86	12.31	14.98	11.24	14.03	12.99	9.67	9.62	18.55	14.81
K2O	Wt%	0.01	0.72	0.76	1.28	0.51	1.25	0.64	0.78	0.53	1.01	0.62
MgO	Wt%	0.01	8.22	8.10	4.83	9.27	3.86	0.78	8.44	9.13	5.31	11.36
MnO	Wt%	0.01	0.16	0.16	0.24	0.15	0.22	0.17	0.14	0.13	0.24	0.19
Na2O	Wt%	0.01	2.86	2.92	3.57	2.69	4.32	3.08	2.79	2.70	2.80	2.63
P2O5	Wt%	0.01	0.22	0.19	0.31	0.14	0.47	0.26	0.10	0.13	0.30	0.26
SiO2	Wt%	0.01	47.94	48.35	48.43	47.79	50.14	47.76	48.17	48.47	45.98	46.47
TiO2	Wt%	0.01	1.50	1.39	3.00	0.98	2.83	1.38	1.21	1.06	3.90	1.54
LOI	Wt%	0.01	0.03	0.03	0.55	0.05	0.57	1.58	1.33	0.66	0.31	
Ba	ppm	0.5	336.0	352.0	604.0	243.0	607.0	356.0	522.0	252.0	445.0	322.0
Ce	ppm	0.5	31.5	32.0	47.2	20.6	58.6	32.4	17.3	18.5	42.7	33.3
Co	ppm	1	63	62	43	65	38	59	52	55	57	82
Cr	ppm	10	280	170	140	210	20	100	390	250	20	50
Cs	ppm	0.01	0.18	0.20	1.15	0.06	1.02	0.32	0.42	0.34	1.06	0.48
Cu	ppm	1	51	48	72	53	45	39	37	33	47	42
Dy	ppm	0.05	3.81	4.32	7.02	2.94	7.92	4.41	2.60	2.56	6.16	4.44
Er	ppm	0.03	2.29	2.53	3.91	1.76	4.74	2.49	1.52	1.40	3.82	2.64
Eu	ppm	0.03	1.36	1.42	2.36	1.04	2.68	1.47	0.96	0.93	1.94	1.52
Ga	ppm	0.1	20.1	19.9	25.1	18.1	26.6	20.9	17.1	17.0	24.8	19.4
Gd	ppm	0.05	4.26	4.35	7.51	2.84	8.26	4.60	2.59	2.48	6.66	4.67
Hf	ppm	0.2	3.1	3.3	4.7	2.0	5.7	2.9	1.7	1.8	4.8	3.1
Ho	ppm	0.01	0.83	0.85	1.47	0.58	1.71	0.89	0.51	0.48	1.34	0.88
La	ppm	0.5	14.4	14.9	20.8	9.4	26.2	14.4	7.7	8.5	18.8	14.9
Lu	ppm	0.01	0.34	0.35	0.56	0.24	0.68	0.39	0.21	0.22	0.55	0.35
Nb	ppm	0.2	4.7	5.1	7.8	2.9	9.0	4.3	2.9	2.7	6.7	4.6
Nd	ppm	0.1	17.7	18.0	28.7	12.4	34.7	19.1	10.5	11.1	26.5	20.2
Ni	ppm	1	161	153	37	236	23	134	225	249	43	283
Pb	ppm	2	24	9	8	3	8	3	20	<2	6	<2
Pr	ppm	0.02	4.13	4.24	6.36	2.69	7.87	4.28	2.35	2.46	5.72	4.49
Rb	ppm	0.3	12.5	13.7	24.2	7.7	23.7	10.2	2.35	8.0	18.4	11.6
Sc	ppm	1.00	19.00	19.00	44.00	20.00	36.00	19.00	19.00	16.00	47.00	21.00
Sm	ppm	0.03	4.34	4.49	7.12	2.96	8.29	4.56	2.69	2.48	6.21	4.83
Sr	ppm	0.1	311.0	331.0	288.0	313.0	305.0	298.0	377.0	339.0	268.0	273.0
Ta	ppm	0.1	0.3	0.3	0.5	0.2	0.6	0.3	0.2	0.2	0.5	0.3
Tb	ppm	0.01	0.62	0.70	1.13	0.47	1.31	0.74	0.38	0.40	1.02	0.74
Th	ppm	0.05	1.56	1.74	2.11	0.95	2.47	1.58	0.80	0.88	1.78	1.41
Tm	ppm	0.01	0.34	0.38	0.62	0.25	0.70	0.37	0.22	0.21	0.58	0.39
U	ppm	0.05	0.27	0.30	0.35	0.16	0.48	0.25	0.12	0.14	0.38	0.28
V	ppm	5	194	157	437	126	337	175	118	126	658	179
Y	ppm	0.5	20.7	21.7	37.3	15.2	42.7	23.2	13.1	12.9	33.7	23.5
Yb	ppm	0.03	2.19	2.22	4.09	1.51	4.31	2.36	1.38	1.34	3.58	2.43
Zn	ppm	2	120	120	153	103	111	136	145	87	226	143
Zr	ppm	2	128	141	189	84	232	123	75	79	193	130

Sample Group	Unit	Limit	13-CR-05-15b Low P-Zr Evolved -65.2137 53.6206	13-CR-05-16a Low P-Zr Evolved -65.1953 53.6236	13-CR-05-16d Low P-Zr Parental -65.1953 53.6236	13-CR-05-17a Low P-Zr Evolved -65.2105 53.6424	13-CR-05-17d Low P-Zr Evolved -65.2105 53.6424	13-CR-06-03a Low P-Zr Evolved -65.3420 53.6848	13-CR-06-03b Low P-Zr Evolved -65.3420 53.6848	13-CR-06-04 Low P-Zr Evolved -65.2464 53.6502	13-CR-06-05 Low P-Zr Evolved -65.2935 53.7202	13-CR-06-06 Low P-Zr Parental -65.2071 53.7167
Latitude	Wt.%	0.01	14.57	19.22	15.28	20.91	18.89	18.37	20.74	18.35	18.52	16.48
Al2O3	Wt.%	0.01	7.54	9.56	8.79	8.23	8.15	8.87	8.23	9.36	9.12	8.27
CaO	Wt.%	0.01	14.61	9.38	14.96	9.12	10.58	12.07	8.17	10.22	10.54	14.32
FeO	Wt.%	0.01	0.75	0.58	0.93	1.14	0.95	0.59	1.29	0.48	0.53	0.92
K2O	Wt.%	0.01	11.66	9.13	6.76	4.61	6.46	7.00	4.07	8.73	8.52	6.26
MgO	Wt.%	0.01	0.19	0.13	0.20	0.15	0.16	0.14	0.14	0.14	0.14	0.20
MnO	Wt.%	0.01	2.55	2.72	2.81	4.16	3.80	3.13	4.23	2.89	2.99	2.97
Na2O	Wt.%	0.01	0.26	0.17	0.24	0.23	0.22	0.23	0.26	0.12	0.14	0.35
P2O5	Wt.%	0.01	46.22	48.26	48.02	50.04	49.59	48.09	51.59	48.72	48.51	48.01
SiO2	Wt.%	0.01	1.66	0.86	2.01	1.41	1.20	1.50	1.28	0.98	0.97	2.22
TiO2	Wt.%	0.01	1.69	0.28	0.89	2.13	3.67	0.14	1.95	0.23	0.14	0.90
LOI	Wt.%	0.01	318.0	275.0	388.0	429.0	512.0	314.0	468.0	278.0	268.0	417.0
Ba	ppm	0.5	33.5	26.3	34.2	34.3	28.4	53.3	20.7	21.7	21.7	46.4
Ce	ppm	0.5	81	58	59	33	45	58	28	57	59	56
Co	ppm	1	90	140	170	200	100	90	160	160	120	70
Cr	ppm	0.01	0.99	0.30	0.92	1.73	1.43	0.19	1.41	0.55	0.15	1.49
Cs	ppm	0.01	41	33	88	13	48	46	15	46	44	64
Cu	ppm	1	4.34	3.38	4.53	4.17	3.46	3.78	4.18	2.55	2.88	6.08
Dy	ppm	0.05	2.47	2.06	2.71	2.28	2.05	2.25	2.22	1.58	1.58	3.36
Er	ppm	0.03	1.37	1.20	1.55	1.52	1.27	1.66	1.87	1.22	1.24	2.14
Eu	ppm	0.03	18.4	17.9	20.7	20.7	20.3	20.4	23.0	18.2	18.2	23.0
Ga	ppm	0.1	4.54	3.64	4.71	4.43	3.79	4.04	4.31	2.87	2.93	6.55
Gd	ppm	0.05	3.2	2.7	3.2	3.4	2.7	2.8	4.0	2.2	2.5	4.9
Hf	ppm	0.2	0.90	0.67	1.01	0.80	0.71	0.87	0.89	0.63	0.62	1.35
Ho	ppm	0.01	15.0	12.0	15.6	15.7	12.9	13.1	17.0	9.5	9.8	20.9
La	ppm	0.5	0.37	0.26	0.38	0.30	0.26	0.32	0.32	0.23	0.23	0.47
Lu	ppm	0.01	5.1	4.0	4.9	4.3	4.1	4.6	4.4	3.0	3.4	6.7
Nb	ppm	0.2	20.1	15.3	20.9	19.6	16.1	16.7	20.0	12.1	12.1	26.9
Nd	ppm	0.1	284	258	70	58	90	114	53	177	176	84
Ni	ppm	1	7	5	5	69	29	<2	117	3	2	3
Pb	ppm	2	4.49	3.52	4.59	4.51	3.73	3.92	4.66	2.70	2.82	6.20
Pr	ppm	0.02	14.9	10.6	16.9	27.4	19.7	9.8	31.8	8.3	8.8	20.3
Rb	ppm	0.3	18.00	13.00	33.00	12.00	13.00	18.00	12.00	15.00	15.00	28.00
Sc	ppm	1.00	4.74	3.51	5.01	4.66	3.93	3.73	4.67	2.60	2.97	6.76
Sm	ppm	0.03	228.0	358.0	243.0	615.0	422.0	345.0	637.0	396.0	357.0	300.0
Sr	ppm	0.1	0.4	0.3	0.3	0.4	0.3	0.3	0.3	0.2	0.2	0.4
Ta	ppm	0.1	0.66	0.53	0.76	0.69	0.55	0.67	0.75	0.45	0.46	1.09
Tb	ppm	0.01	1.55	1.34	1.42	1.71	1.39	1.19	1.83	0.90	0.87	2.11
Th	ppm	0.05	0.35	0.27	0.41	0.34	0.29	0.32	0.34	0.23	0.25	0.51
Tm	ppm	0.01	0.27	0.22	0.26	0.40	0.27	0.21	0.32	0.17	0.22	0.70
U	ppm	0.05	173	65	319	159	130	159	144	127	107	244
Y	ppm	5	23.0	17.5	25.1	21.0	17.7	20.4	22.0	15.0	15.1	33.0
Yb	ppm	0.5	2.39	1.74	2.61	1.95	1.87	2.19	1.99	1.51	1.52	3.36
Zn	ppm	0.03	113	89	140	113	135	117	117	92	142	197
Zr	ppm	2	142	112	127	147	111	118	167	86	101	197

Sample Group	Unit	Limit	13-CR-06-07 High P-Zr Evolved -65.1873 53.7164	13-CR-06-09 Low P-Zr Evolved -65.3431 53.7298	13-CR-07-03 Low P-Zr Evolved -65.4754 53.7922	13-CR-07-06A Low P-Zr Evolved -65.3750 53.7296	13-CR-08-02b Low P-Zr Evolved -64.0819 53.5543	13-CR-08-03a High P-Zr Evolved -64.0359 53.5398	13-CR-08-03b Int.-Amp.b Parental -64.0359 53.5398	13-CR-08-04 High P-Zr Evolved -63.7692 53.5063	13-CR-09-01a Low P-Zr Evolved -63.9881 53.5350	13-CR-09-01b Low P-Zr Evolved -63.9877 53.5349
Al2O3	Wt.%	0.01	13.70	18.16	16.99	19.32	5.74	5.81	16.03	17.19	19.18	24.63
CaO	Wt.%	0.01	9.07	9.09	8.01	9.21	11.61	11.00	8.58	10.59	8.98	10.94
FeO	Wt.%	0.01	9.16	10.63	12.62	9.88	10.07	10.18	8.33	8.33	9.75	5.68
K2O	Wt.%	0.01	1.33	0.47	0.55	0.45	0.29	0.32	1.23	0.50	0.42	0.70
MgO	Wt.%	0.01	11.07	9.90	10.25	9.57	23.22	24.11	6.43	10.84	9.53	1.91
MnO	Wt.%	0.01	0.15	0.14	0.16	0.12	0.19	0.18	0.17	0.17	0.14	0.09
Na2O	Wt.%	0.01	2.83	2.63	2.73	2.79	0.79	0.85	3.22	1.34	2.72	3.71
P2O5	Wt.%	0.01	0.19	0.15	0.22	0.13	0.05	0.05	0.77	1.10	0.10	0.16
SiO2	Wt.%	0.01	52.00	47.79	47.24	47.72	47.70	47.17	47.64	50.60	48.54	51.08
TiO2	Wt.%	0.01	0.49	1.03	1.21	0.79	0.32	0.32	2.93	0.38	0.64	1.10
LOI	Wt.%	0.01	0.27	0.02	-0.26	0.05	2.67	2.98	-0.04	0.70	0.47	0.64
Ba	ppm	0.5	467.0	250.0	278.0	231.0	161.5	120.5	626.0	233.0	224.0	381.0
Ce	ppm	0.5	30.4	21.9	26.8	9.3	9.3	9.1	77.6	15.8	16.8	25.8
Co	ppm	1	49	61	76	66	84	88	48	48	66	18
Cr	ppm	10	730	180	80	80	2080	1980	150	170	140	30
Cs	ppm	0.01	1.92	0.11	0.10	0.11	0.43	0.52	0.28	0.84	0.39	0.93
Cu	ppm	1	52	35	36	25	27	21	34	51	34	34
Dy	ppm	0.05	2.14	2.98	3.32	2.22	1.34	1.33	6.91	1.55	1.93	2.94
Er	ppm	0.03	1.19	1.72	1.88	1.23	0.83	0.77	3.79	0.87	1.06	1.89
Eu	ppm	0.03	1.12	1.18	1.39	1.01	0.55	0.50	2.60	0.73	0.99	1.35
Ga	ppm	0.1	14.1	17.9	18.9	17.8	6.7	6.6	21.3	16.2	16.6	21.8
Gd	ppm	0.05	2.81	2.89	3.42	2.35	1.51	1.43	8.37	1.86	1.90	3.19
Hf	ppm	0.2	1.7	2.4	2.7	1.5	0.7	0.6	6.7	1.0	1.5	2.1
Ho	ppm	0.01	0.40	0.65	0.68	0.48	0.27	0.26	1.54	0.32	0.41	0.67
La	ppm	0.5	13.5	10.1	12.3	8.4	3.9	3.8	35.5	7.4	7.4	11.6
Lu	ppm	0.01	0.15	0.25	0.25	0.18	0.10	0.09	0.54	0.11	0.14	0.23
Nb	ppm	0.2	2.7	3.3	4.0	2.5	0.7	0.7	12.4	1.4	2.4	3.1
Nd	ppm	0.1	16.9	12.7	15.5	9.7	6.2	5.9	42.1	8.7	8.9	14.3
Ni	ppm	1	186	285	251	242	475	500	99	113	251	24
Pb	ppm	2	<2	2	4	<2	2	<2	7	7	<2	4
Pr	ppm	0.02	4.13	2.90	3.53	2.29	1.29	1.29	10.15	2.09	2.01	3.43
Rb	ppm	0.3	41.8	7.8	9.4	6.4	6.1	7.2	25.7	14.5	6.9	13.2
Sc	ppm	1.00	24.00	15.00	13.00	11.00	48.00	46.00	25.00	32.00	11.00	10.00
Sm	ppm	0.03	3.46	2.91	3.49	2.15	1.56	1.56	8.63	2.12	2.07	3.25
Sr	ppm	0.1	763.0	345.0	348.0	392.0	175.0	150.5	329.0	722.0	362.0	479.0
Ta	ppm	0.1	0.2	0.2	0.2	<0.1	0.1	0.1	0.7	0.1	0.1	0.2
Tb	ppm	0.01	0.42	0.51	0.60	0.39	0.24	0.21	1.23	0.28	0.32	0.55
Th	ppm	0.05	1.96	0.89	1.12	0.72	0.37	0.39	3.47	1.02	0.80	1.13
Tm	ppm	0.01	0.18	0.25	0.31	0.18	0.10	0.11	0.54	0.14	0.16	0.24
U	ppm	0.05	0.50	0.16	0.20	0.11	0.10	0.09	0.56	0.26	0.09	0.18
V	ppm	5	136	126	131	92	145	126	190	145	80	164
Y	ppm	0.5	11.1	15.4	18.3	11.7	7.1	6.9	37.0	8.0	10.2	16.5
Yb	ppm	0.03	1.11	1.67	1.90	1.23	0.69	0.66	3.31	0.84	1.04	1.69
Zn	ppm	2	85	93	114	83	64	70	145	73	85	57
Zr	ppm	2	57	93	107	60	22	19	299	31	61	88

Sample Group	Unit	Limit	13-CR-09-02 Low P-Zr Evolved -63.9186 53.5360	13-CR-09-05 Int.-Amp.b Evolved -63.9826 53.5594	13-CR-09-06 Low P-Zr Evolved -64.7131 53.4819	13-CR-10-03 Low P-Zr Evolved -64.3337 53.5964	13-CR-10-04 Low P-Zr Parental -64.8357 53.4874	13-CR-10-05 Low P-Zr Evolved -64.8693 53.4820	13-CR-10-06 Low P-Zr Parental -64.9116 53.4692	13-CR-10-09a Low P-Zr Evolved -65.1464 53.4280	13-CR-10-09b Low P-Zr Evolved -65.1789 53.4320	13-CR-10-10 Low P-Zr Evolved -65.1922 53.4322
Longitude	Wt.%	0.01	14.77	15.33	20.08	9.42	16.94	19.40	16.79	15.29	15.79	15.98
Al2O3	Wt.%	0.01	7.72	7.99	10.43	11.63	7.90	9.46	8.99	9.79	9.19	9.19
CaO	Wt.%	0.01	8.29	15.19	6.64	9.58	13.21	10.64	12.31	10.86	10.47	11.21
FeO	Wt.%	0.01	2.14	1.35	0.22	0.90	0.86	0.64	0.79	0.54	0.60	0.97
K2O	Wt.%	0.01	8.07	5.93	11.04	14.87	6.04	6.23	6.63	7.17	7.91	7.12
MgO	Wt.%	0.01	0.15	0.20	0.09	0.20	0.17	0.18	0.20	0.18	0.18	0.19
MnO	Wt.%	0.01	3.18	3.32	2.25	1.37	3.20	3.14	3.09	2.66	2.51	2.76
Na2O	Wt.%	0.01	0.29	0.89	0.06	0.10	0.30	0.20	0.38	0.16	0.13	0.22
P2O5	Wt.%	0.01	54.65	46.20	48.80	51.54	49.29	48.63	48.82	52.14	51.57	51.19
SiO2	Wt.%	0.01	0.75	3.60	0.39	0.40	2.10	1.50	2.01	1.19	1.06	1.17
TiO2	Wt.%	0.01	0.50	-0.07	0.19	1.31	-0.03	-0.07	0.18	0.11	-0.03	0.06
LOI	Wt.%	0.01	884.0	674.0	114.0	213.0	399.0	302.0	358.0	296.0	290.0	504.0
Ba	ppm	0.5	61.1	88.9	8.4	22.7	39.2	28.5	42.1	36.8	31.9	50.4
Ce	ppm	0.5	36	50	53	60	56	48	49	50	51	51
Co	ppm	1	500	100	320	1150	100	90	80	140	180	150
Cr	ppm	0.01	2.00	0.33	<0.01	1.97	0.45	0.17	0.32	0.15	0.29	0.68
Cs	ppm	0.01	46	37	21	18	41	43	44	131	102	144
Cu	ppm	1	3.82	8.20	1.17	2.17	4.42	3.69	5.00	4.68	4.29	4.69
Dy	ppm	0.05	2.21	4.55	0.64	1.11	2.52	2.02	2.92	2.82	2.74	2.90
Er	ppm	0.03	1.68	2.92	0.58	0.89	1.75	1.57	1.80	1.45	1.32	1.70
Eu	ppm	0.03	18.1	23.3	14.1	11.0	20.9	20.2	19.4	19.2	19.2	20.7
Ga	ppm	0.1	5.28	9.25	1.04	2.45	4.82	3.90	5.45	4.83	4.49	5.40
Gd	ppm	0.05	3.5	7.9	0.7	1.1	4.1	3.3	4.2	2.9	2.9	3.8
Hf	ppm	0.2	0.77	1.70	0.24	0.43	1.00	0.85	1.10	1.15	0.97	1.04
Ho	ppm	0.01	28.4	40.1	4.0	9.7	17.9	13.1	18.8	16.6	14.5	23.5
La	ppm	0.5	0.27	0.62	0.11	0.17	0.38	0.29	0.40	0.40	0.41	0.42
Lu	ppm	0.01	7.1	15.0	1.1	1.8	6.7	4.7	6.3	5.0	4.3	7.0
Nb	ppm	0.2	32.3	48.9	4.9	13.5	21.8	16.9	24.2	20.9	18.1	27.0
Nd	ppm	0.1	139	68	349	200	90	102	70	107	122	159
Ni	ppm	1	11	6	2	5	7	<2	<2	6	6	12
Pb	ppm	2	7.91	11.55	1.13	3.00	5.08	3.74	5.65	4.92	4.21	6.45
Pr	ppm	0.02	50.9	29.0	2.6	36.0	15.2	10.4	13.3	3.9	8.2	18.3
Rb	ppm	0.3	23.00	27.00	9.00	43.00	17.00	19.00	26.00	38.00	38.00	33.00
Sc	ppm	1.00	6.20	10.30	1.26	3.01	4.95	3.72	5.44	4.92	4.22	5.86
Sm	ppm	0.03	819.0	309.0	331.0	323.0	309.0	350.0	304.0	285.0	270.0	414.0
Sr	ppm	0.1	0.2	0.8	0.1	0.1	0.3	0.2	0.3	0.2	0.3	0.3
Ta	ppm	0.1	0.73	1.40	0.19	0.35	0.79	0.62	0.92	0.87	0.73	0.87
Tb	ppm	0.01	1.14	3.80	0.31	1.31	1.96	1.29	1.78	1.02	1.28	1.34
Th	ppm	0.05	0.27	0.66	0.10	0.19	0.38	0.33	0.41	0.39	0.37	0.43
Tm	ppm	0.01	0.27	0.59	0.06	0.36	0.35	0.23	0.26	0.25	0.29	0.26
U	ppm	0.05	173	214	62	142	196	157	201	286	260	267
V	ppm	5	19.7	42.8	6.3	11.3	25.1	20.1	26.7	26.8	24.5	27.1
Y	ppm	0.5	1.92	4.07	0.70	1.14	2.48	2.09	2.47	2.80	2.66	2.81
Yb	ppm	0.03	111	171	56	78	129	103	125	103	91	111
Zn	ppm	2	145	348	28	40	168	131	168	98	100	150
Zr	ppm	2										

Sample Group	Unit	Limit	13-CR-11-01a Int.-Amp.b Parental -67.0342 52.9199	13-CR-11-01b Int.-Amp.b Parental -67.0342 52.9199	13-CR-11-02a Int.-Amp.b Evolved -66.9464 52.9778	13-CR-12-01 Int.-Amp.b Parental -67.1728 52.8070	13-CR-12-02 Int.-Amp.b Evolved -67.1106 52.8531	13-CR-13-01 Low P-Zr Evolved -66.5401 53.0485	13-CR-14-01 Int.-Amp.b Evolved	13-CR-14-02 High P-Zr Evolved	AK-05-018A High P-Zr Evolved -66.2426 53.5963	AK-05-018B High P-Zr Evolved -66.2426 53.5963
Latitude	Wt.%	0.01	16.82	17.65	17.13	17.74	17.14	18.43	14.90	14.38	12.39	13.11
Al2O3	Wt.%	0.01	8.82	9.18	8.57	8.89	8.63	8.32	8.00	7.84	9.74	7.07
CaO	Wt.%	0.01	12.48	12.16	12.41	11.81	12.88	11.85	15.14	14.78	13.55	22.56
FeO	Wt.%	0.01	1.12	1.03	1.29	1.10	1.43	0.62	1.83	1.60	0.52	2.00
K2O	Wt.%	0.01	6.29	6.01	5.63	6.37	5.27	0.15	5.87	8.15	4.74	0.18
MgO	Wt.%	0.01	0.17	0.15	0.16	0.22	0.19	0.22	0.14	0.24	0.14	0.18
MnO	Wt.%	0.01	3.25	3.16	3.44	3.25	3.93	2.94	2.69	2.54	4.15	2.50
Na2O	Wt.%	0.01	0.71	0.75	0.65	0.64	0.73	0.21	0.93	0.88	1.78	0.71
P2O5	Wt.%	0.01	47.47	46.82	48.00	47.49	46.82	48.30	46.73	46.42	48.84	42.47
SiO2	Wt.%	0.01	2.85	3.09	2.72	2.49	2.97	1.43	3.70	3.27	4.06	2.66
TiO2	Wt.%	0.01	0.55	-0.13	0.31	0.28	0.91	0.21	0.54	0.67	1.56	9.26
LOI	Wt.%	0.01	548.0	547.0	688.0	585.0	668.0	301.0	540.0	476.0	167.5	531.0
Ba	ppm	0.5	70.0	73.3	66.9	67.0	76.5	28.0	89.0	95.5	130.0	67.6
Ce	ppm	0.5	48	45	34	45	37	58	48	62	27	200
Co	ppm	1	110	160	130	190	120	40	80	290	10	210
Cr	ppm	0.01	0.42	0.19	0.30	0.44	0.57	0.15	1.23	0.65	0.18	4.19
Cs	ppm	0.01	33	35	19	27	29	36	38	59	18	1850
Cu	ppm	1	6.63	6.76	6.93	5.76	6.60	3.61	8.67	6.83	12.50	6.18
Dy	ppm	0.05	3.49	3.53	3.73	3.29	3.90	2.10	4.96	3.62	6.54	3.37
Er	ppm	0.03	2.44	2.56	2.57	2.34	2.35	1.46	2.82	2.59	3.85	2.05
Eu	ppm	0.03	21.0	21.2	23.3	20.8	22.9	19.7	23.3	21.5	17.4	17.4
Ga	ppm	0.1	8.16	8.01	7.82	7.32	8.09	4.16	10.25	8.84	15.55	7.07
Gd	ppm	0.05	5.7	6.1	6.9	5.5	6.3	2.8	8.0	6.3	9.1	5.4
Hf	ppm	0.2	1.28	1.33	1.33	1.21	1.49	0.77	1.80	1.30	2.45	1.20
Ho	ppm	0.01	31.0	32.3	29.5	29.8	33.6	12.4	39.3	43.4	57.4	30.6
La	ppm	0.5	0.49	0.46	0.50	0.42	0.51	0.30	0.62	0.45	0.85	0.48
Lu	ppm	0.01	11.7	11.7	12.1	10.9	12.6	4.4	15.5	13.5	16.5	10.4
Nb	ppm	0.2	38.5	40.3	37.7	36.5	41.1	15.8	49.4	49.6	76.9	37.9
Nd	ppm	0.1	100	100	46	108	152	157	57	157	12	1540
Ni	ppm	1	14	4	7	14	3	<2	2	<2	6	10
Pb	ppm	2	9.28	9.67	8.84	8.74	9.98	3.77	11.70	12.15	17.50	8.77
Pr	ppm	0.02	21.7	21.5	27.6	23.1	29.0	11.1	42.8	37.6	11.5	59.7
Rb	ppm	0.3	21.00	19.00	21.00	18.00	20.00	13.00	29.00	23.00	37.00	22.00
Sc	ppm	1.00	7.70	7.94	8.23	7.48	8.46	3.78	10.15	9.92	16.55	8.19
Sm	ppm	0.03	362.0	376.0	357.0	426.0	414.0	331.0	275.0	197.5	215.0	270.0
Sr	ppm	0.1	0.6	0.6	0.6	0.6	0.7	0.3	0.8	0.6	1.0	0.6
Ta	ppm	0.1	1.20	1.24	1.17	1.12	1.17	0.65	1.52	1.28	2.09	1.06
Tb	ppm	0.01	2.85	2.67	3.34	2.95	3.19	1.21	3.74	3.58	5.22	3.03
Th	ppm	0.05	0.49	0.50	0.53	0.51	0.51	0.33	0.72	0.49	0.94	0.48
Tm	ppm	0.01	0.42	0.45	0.50	0.49	0.44	0.30	0.61	0.61	0.98	0.51
U	ppm	0.05	168	186	183	151	183	142	223	195	263	162
V	ppm	5	32.5	32.9	34.2	30.4	34.9	18.6	44.5	31.9	63.2	32.2
Y	ppm	0.5	3.21	3.44	3.62	3.14	3.69	2.12	4.42	3.08	5.43	3.03
Yb	ppm	0.03	147	126	133	139	138	110	171	137	144	132
Zn	ppm	2	266	275	314	240	291	106	348	286	407	245
Zr	ppm	2										

Sample Group	Unit	Limit	AK-05-018C Int.-Amp.b Evolved -66.2426 53.5963	AK-05-018D High P-Zr Evolved -66.2426 53.5963	AK-05-024A High P-Zr Evolved -66.0261 53.6404	AK-05-025B High P-Zr Evolved	AK-05-032 High P-Zr Evolved -65.9482 53.6533	AK-05-033 High P-Zr Evolved -65.9482 53.6555	AK-05-036 Low P-Zr Evolved -65.8425 53.6416	AK-05-047 High P-Zr Evolved -66.2406 53.5965	AK-05-049 Low P-Zr Evolved -66.2709 53.5936	AK-05-060 High P-Zr Evolved -66.0713 53.3783
Latitude	Wt.%	0.01	15.50	12.11	12.41	12.92	11.95	12.84	16.07	13.25	12.41	18.84
Al2O3	Wt.%	0.01	6.79	6.77	7.09	12.09	8.68	10.66	2.14	5.91	3.27	9.37
CaO	Wt.%	0.01	14.47	27.79	15.26	8.59	16.27	13.78	6.73	11.68	6.72	9.47
FeO	Wt.%	0.01	2.98	1.56	2.71	2.71	2.04	1.27	3.84	2.90	3.26	0.59
K2O	Wt.%	0.01	6.42	6.73	3.72	3.33	4.07	5.76	3.41	2.68	3.09	9.63
MgO	Wt.%	0.01	0.23	0.18	0.25	0.11	0.27	0.08	0.18	0.18	0.09	0.14
MnO	Wt.%	0.01	2.64	2.20	3.06	3.39	3.14	2.88	1.82	3.22	2.16	2.59
Na2O	Wt.%	0.01	0.84	0.88	1.69	1.43	1.65	0.62	0.26	1.09	0.45	0.16
P2O5	Wt.%	0.01	46.98	39.55	50.47	51.77	48.54	47.61	64.93	56.62	67.14	48.41
SiO2	Wt.%	0.01	3.16	2.43	3.35	3.66	3.39	4.37	0.71	2.47	1.40	0.80
TiO2	Wt.%	0.01	2.03	12.40	15.60	0.93	1.17	0.67	5.57	1.59	1.69	0.26
LOI	Wt.%	0.01	847.0	338.0	925.0	810.0	842.0	627.0	527.0	889.0	817.0	286.0
Ba	ppm	0.5	84.1	60.5	144.5	133.0	137.0	64.6	89.5	130.5	75.8	16.6
Ce	ppm	0.5	48	254	29	34	29	45	11	22	17	56
Co	ppm	1	160	210	<10	<10	<10	10	100	<10	80	80
Cr	ppm	0.01	2.23	3.21	1.22	0.11	1.13	0.43	7.84	1.46	1.26	0.17
Cs	ppm	0.01	44	2620	12	9	11	34	36	13	30	53
Cu	ppm	1	7.77	5.49	12.05	11.15	12.85	6.89	5.08	10.25	5.01	2.33
Dy	ppm	0.05	4.23	3.03	6.69	6.28	7.06	3.79	2.71	5.76	2.93	1.33
Er	ppm	0.03	2.50	1.79	3.75	3.73	3.89	2.33	1.43	3.15	1.53	0.88
Eu	ppm	0.03	22.0	15.5	20.8	25.9	21.6	18.0	20.0	16.0	16.0	13.6
Ga	ppm	0.1	9.33	6.39	14.10	12.65	14.65	7.54	6.00	11.65	5.69	2.33
Gd	ppm	0.05	7.0	4.7	10.6	9.8	8.9	5.4	4.1	9.5	5.2	1.6
Hf	ppm	0.2	1.57	1.12	2.39	2.18	2.53	1.34	0.95	2.03	1.00	0.49
Ho	ppm	0.01	38.4	27.5	64.6	58.9	59.9	28.7	45.1	59.2	36.2	7.5
La	ppm	0.5	0.60	0.40	0.93	0.83	0.91	0.51	0.37	0.78	0.42	0.21
Lu	ppm	0.01	13.0	9.0	20.4	19.2	17.0	9.6	12.6	18.4	12.2	1.5
Nb	ppm	0.2	47.2	33.4	76.9	68.5	75.0	37.1	40.7	66.5	36.1	9.8
Nd	ppm	0.1	96	2060	2	1	<1	26	45	3	26	296
Ni	ppm	1	5	7	6	8	11	9	17	12	11	2
Pb	ppm	2	11.10	7.94	18.15	16.50	17.60	8.49	10.65	16.10	9.24	2.19
Pr	ppm	0.02	100.5	46.1	72.2	35.1	45.4	25.2	144.5	76.4	89.0	7.7
Rb	ppm	0.3	28.00	19.00	29.00	32.00	41.00	52.00	15.00	25.00	16.00	11.00
Sc	ppm	1.00	9.95	7.15	15.35	14.20	15.85	8.11	7.79	13.55	7.29	2.39
Sm	ppm	0.03	222.0	219.0	199.0	357.0	255.0	279.0	208.0	207.0	209.0	413.0
Sr	ppm	0.1	0.8	0.5	1.1	1.0	0.9	0.5	0.9	1.1	0.8	0.1
Ta	ppm	0.1	1.31	0.92	2.08	1.87	2.18	1.14	0.89	1.74	0.83	0.38
Tb	ppm	0.01	3.81	2.97	6.80	6.60	5.27	2.73	12.40	8.55	7.83	0.42
Th	ppm	0.05	0.64	0.43	0.95	0.88	0.97	0.55	0.38	0.81	0.45	0.22
Tm	ppm	0.01	0.62	0.44	1.38	10.20	0.87	0.46	4.26	1.91	2.12	0.10
U	ppm	0.05	233	145	187	212	155	363	112	161	121	130
V	ppm	5	39.7	28.6	64.2	59.2	66.3	36.0	27.0	55.0	27.9	12.7
Y	ppm	0.5	3.99	2.85	5.99	5.65	6.18	3.58	2.45	5.39	2.69	1.26
Yb	ppm	0.03	176	138	161	46	235	157	84	241	145	74
Zn	ppm	2	319	212	444	415	369	219	137	392	200	53
Zr	ppm	2										

Sample Group	Unit	Limit	AK-05-063 Low P-Zr Parental -65.9584 53.4119	AK-05-070 High P-Zr Evolved -66.7608 52.9273	AK-05-071 Low P-Zr Parental -66.6285 53.0656	AK-05-072 Low P-Zr Evolved -66.4870 53.0930	AK-05-080 Low P-Zr Evolved -66.2888 53.1417	AK-05-081 Int-Amp.b Parental -66.2993 53.6183	AK-05-082 High P-Zr Evolved	AK-05-092 Int-Amp.b Evolved -65.1186 53.7306	AK-05-097 High P-Zr Evolved -65.1255 53.4698	AK-05-102 High P-Zr Evolved -64.7549 53.4516
Magma Longitude	Wt.%	0.01	17.51	9.66	18.20	14.55	17.58	15.64	13.08	14.52	21.34	18.19
	Wt.%	0.01	9.37	6.65	9.72	7.94	10.76	5.80	7.39	7.98	10.77	9.72
	Wt.%	0.01	10.87	13.68	10.41	14.93	8.41	13.35	14.46	14.32	6.53	9.15
	Wt.%	0.01	0.83	2.11	0.57	0.51	0.63	4.08	2.45	1.43	0.23	0.37
	Wt.%	0.01	7.79	17.66	6.48	10.17	5.30	6.11	3.42	4.28	10.62	9.26
	Wt.%	0.01	0.17	0.24	0.15	0.24	0.14	0.22	0.22	0.22	0.09	0.14
	Wt.%	0.01	2.87	1.57	3.06	2.53	3.64	2.36	3.04	3.44	2.23	2.85
	Wt.%	0.01	0.24	0.30	0.30	0.28	0.23	0.72	1.64	0.49	0.08	0.11
	Wt.%	0.01	49.16	47.32	49.45	47.27	52.03	49.12	51.08	50.71	47.69	49.62
	Wt.%	0.01	1.21	1.61	1.65	1.61	1.28	2.61	3.21	2.60	0.40	0.58
	Wt.%	0.01	0.65	0.32	1.27	0.37	0.17	0.55	3.33	3.86	0.82	0.58
	ppm	0.5	479.0	1775.0	314.0	274.0	338.0	1585.0	957.0	612.0	128.0	186.5
	ppm	0.5	33.3	23.7	36.0	32.2	31.6	94.6	157.0	70.6	10.0	13.8
	ppm	1	53	72	46	74	31	37	28	42	52	60
	ppm	10	120	1110	110	120	190	370	10	110	710	180
	ppm	0.01	0.48	7.78	0.08	0.16	0.21	1.28	3.63	1.09	<0.01	0.21
	ppm	1	86	58	32	46	38	4	13	66	19	64
	ppm	0.05	4.31	2.06	4.77	4.47	4.76	7.35	13.10	8.24	1.24	1.97
	ppm	0.03	2.52	1.14	2.75	2.72	2.65	4.10	7.40	4.87	0.68	1.03
	ppm	0.03	1.49	1.97	1.57	1.42	1.62	2.79	3.98	2.39	0.59	0.81
	ppm	0.1	18.6	10.9	19.7	18.7	21.1	21.7	22.3	23.9	13.5	15.3
	ppm	0.05	4.30	2.73	4.84	4.57	4.73	8.35	15.20	8.47	1.23	1.97
	ppm	0.2	2.5	2.0	3.3	3.5	3.2	6.8	11.5	6.0	0.8	1.1
	ppm	0.01	0.86	0.42	0.94	0.93	0.95	1.50	2.58	1.68	0.25	0.39
	ppm	0.5	15.2	10.5	16.1	14.1	14.2	43.2	69.5	31.8	4.6	6.3
	ppm	0.01	0.35	0.15	0.37	0.38	0.37	0.58	0.98	0.67	0.11	0.15
	ppm	0.2	6.2	2.4	5.1	5.0	4.2	13.0	22.9	8.9	1.1	1.6
	ppm	0.1	19.7	13.9	20.6	19.0	19.1	48.8	85.6	39.7	5.6	8.1
	ppm	1	197	262	88	116	35	65	5	21	363	138
	ppm	2	3	6	2	2	3	35	7	8	<2	3
	ppm	0.02	4.50	3.19	4.76	4.31	4.24	11.80	19.90	9.28	1.31	1.86
	ppm	0.3	12.9	68.5	9.5	10.4	10.3	107.0	115.5	35.3	3.0	4.8
	ppm	1.00	19.00	37.00	22.00	20.00	29.00	19.00	29.00	36.00	7.00	14.00
	ppm	0.03	4.65	3.04	4.80	4.64	4.56	9.79	17.70	8.95	1.21	1.98
	ppm	0.1	494.0	190.5	352.0	289.0	360.0	348.0	332.0	268.0	357.0	335.0
	ppm	0.1	0.2	0.1	0.3	0.3	0.2	0.7	1.3	0.5	0.1	0.1
	ppm	0.01	0.68	0.37	0.75	0.72	0.74	1.27	2.27	1.32	0.19	0.31
	ppm	0.05	0.97	1.23	1.29	1.57	1.20	4.75	7.68	3.39	0.33	0.50
	ppm	0.01	0.36	0.15	0.39	0.39	0.40	0.60	1.02	0.70	0.10	0.16
	ppm	0.05	0.20	0.60	0.22	0.40	0.28	1.04	1.86	0.60	0.11	0.17
	ppm	5	246	229	220	242	241	203	232	300	60	104
	ppm	0.5	22.7	11.2	25.1	24.6	25.5	39.7	70.4	44.8	6.6	10.3
	ppm	0.03	2.28	1.05	2.58	2.47	2.53	3.82	6.55	4.42	0.64	1.03
	ppm	2	102	113	102	136	77	365	147	166	55	80
	ppm	2	85	71	129	124	118	285	484	227	27	37

Sample Group	Unit	Limit	CG79-391C Low P-Zr Evolved -57.4536 54.4443	CG79-400B Int.-Amp.b Parental -58.5304 54.5638	CG79-637B High P-Zr Evolved -58.0175 54.4025	CG79-658 High P-Zr Evolved -58.4275 54.3169	CG79-673 High P-Zr Evolved -58.1114 54.2841	CG80-035 High P-Zr Parental -58.4473 54.2357	CG80-046 High P-Zr Evolved -58.4492 54.2303	CG80-561 High P-Zr Evolved	CG80-574 High P-Zr Evolved	CG80-580 High P-Zr Evolved -58.7964 54.2566
Longitude	Wt.%	0.01	15.52	17.75	14.70	19.63	18.83	15.65	16.12	22.76	20.90	17.96
Al2O3	Wt.%	0.01	8.06	8.06	8.19	9.54	8.86	8.44	8.50	10.66	9.38	8.38
CaO	Wt.%	0.01	15.82	11.94	15.44	12.14	10.87	15.49	14.59	7.32	9.70	12.03
FeO	Wt.%	0.01	1.19	1.31	1.22	0.64	0.51	1.04	0.99	0.57	0.57	0.52
K2O	Wt.%	0.01	6.13	6.26	6.15	5.68	9.51	6.88	6.74	4.37	6.48	10.17
MgO	Wt.%	0.01	0.22	0.17	0.22	0.15	0.15	0.22	0.21	0.10	0.13	0.16
MnO	Wt.%	0.01	2.93	3.19	2.90	3.04	2.67	2.90	2.97	3.46	3.05	2.60
Na2O	Wt.%	0.01	0.48	0.62	0.92	0.39	0.31	0.90	0.87	0.28	0.30	0.33
P2O5	Wt.%	0.01	46.85	48.69	46.90	46.76	47.24	45.27	45.95	49.14	48.27	46.59
SiO2	Wt.%	0.01	2.80	2.01	3.36	2.03	1.06	3.21	3.06	1.34	1.23	1.27
TiO2	Wt.%	0.01	0.38	0.33	0.01	0.49	0.01	0.28	0.23	0.06	0.01	0.01
LOI	Wt.%	0.01	517.0	558.0	653.0	360.0	288.0	577.0	543.0	318.0	325.0	298.0
Ba	ppm	0.5	66.1	61.2	73.9	32.7	26.6	71.1	67.1	25.3	27.3	28.6
Ce	ppm	0.5	65	58	55	57	76	64	62	42	63	78
Co	ppm	1	110	90	160	120	60	100	80	180	260	160
Cr	ppm	0.01	0.53	0.41	0.41	0.50	0.12	0.34	0.24	0.19	0.87	0.32
Cs	ppm	0.01	39	34	23	32	17	48	42	21	22	21
Cu	ppm	1	7.15	5.46	8.44	3.71	2.81	8.02	7.00	2.60	2.82	3.04
Dy	ppm	0.05	3.93	3.09	4.59	1.96	1.44	4.34	4.22	1.29	1.64	1.81
Er	ppm	0.03	2.31	1.97	2.69	1.41	1.10	2.50	2.45	1.23	1.21	1.18
Eu	ppm	0.03	25.5	22.5	25.1	21.2	16.9	25.0	23.4	20.7	20.1	17.7
Ga	ppm	0.1	7.59	6.06	8.81	3.59	2.92	7.90	8.25	2.77	2.68	3.23
Gd	ppm	0.05	6.1	5.3	7.0	3.0	2.4	6.2	5.7	2.0	2.4	2.4
Hf	ppm	0.2	1.52	1.16	1.76	0.80	0.57	1.64	1.49	0.56	0.57	0.61
Ho	ppm	0.01	29.8	28.1	32.2	14.7	12.0	31.2	30.5	11.8	12.8	13.1
La	ppm	0.5	0.59	0.44	0.63	0.31	0.21	0.63	0.56	0.20	0.22	0.24
Lu	ppm	0.01	9.0	8.8	12.6	5.3	3.9	11.5	11.1	4.0	4.4	4.4
Nb	ppm	0.2	37.5	33.0	43.3	18.4	14.7	41.4	38.1	14.4	15.4	16.1
Nd	ppm	0.1	80	114	47	93	250	104	96	97	114	261
Ni	ppm	1	4	<2	<2	<2	<2	<2	<2	<2	<2	<2
Pb	ppm	2	8.45	7.61	9.62	4.10	3.30	9.22	8.76	3.20	3.53	3.66
Pr	ppm	0.02	23.6	25.0	23.6	9.5	6.9	17.2	17.2	6.9	7.7	7.8
Rb	ppm	0.3	28.00	19.00	32.00	17.00	10.00	29.00	27.00	11.00	9.00	11.00
Sc	ppm	1.00	8.02	6.93	9.16	4.03	2.88	8.04	8.40	2.68	3.09	3.25
Sm	ppm	0.03	281.0	362.0	271.0	378.0	360.0	290.0	306.0	484.0	404.0	338.0
Sr	ppm	0.1	0.6	0.9	1.1	0.7	0.7	0.9	1.2	0.7	0.9	0.7
Ta	ppm	0.1	1.27	1.00	1.47	0.62	0.45	1.35	1.27	0.45	0.47	0.52
Tb	ppm	0.01	2.66	2.39	2.26	0.82	0.69	1.97	1.77	0.65	0.67	0.69
Th	ppm	0.05	0.61	0.45	0.68	0.25	0.22	0.64	0.55	0.20	0.21	0.24
Tm	ppm	0.01	0.45	0.58	0.69	0.10	0.11	0.30	0.30	0.07	0.09	0.11
U	ppm	0.05	271	152	243	196	77	216	200	121	99	98
V	ppm	5	38.7	30.1	43.6	19.2	14.0	40.8	37.1	13.8	14.4	15.7
Y	ppm	0.5	3.58	2.84	4.17	1.90	1.29	4.04	3.56	1.30	1.39	1.48
Yb	ppm	0.03	174	131	168	112	110	175	158	74	93	112
Zn	ppm	2	255	218	293	124	97	264	243	86	95	97
Zr	ppm	2										

Sample Group	Unit	Limit	CG81-634 High P-Zr Evolved -56.9954 53.9229	CG82-020 Low P-Zr Evolved -58.9279 54.6200	CG82-023 Low P-Zr Evolved -58.8380 54.6484	CG82-025 Low P-Zr Parental Evolved -59.1328 54.5433	CG82-026 Low P-Zr Evolved -59.2066 54.6326	CG82-028 Low P-Zr Evolved -57.2313 54.4496	CG82-029A Low P-Zr Evolved -57.2267 54.4433	CG82-029B Low P-Zr Parental Evolved -57.2267 54.4433	CG82-030 Low P-Zr Evolved -57.1935 54.4446
Longitude											
Latitude											
Al2O3	Wt.%	0.01	18.54	17.44	16.94	18.82	15.90	15.75	15.98	14.66	15.64
CaO	Wt.%	0.01	8.85	7.96	8.09	8.94	8.17	8.04	8.71	8.04	8.34
FeO	Wt.%	0.01	11.62	12.69	13.72	11.88	15.82	14.38	14.05	15.83	14.47
K2O	Wt.%	0.01	1.25	1.32	1.33	1.34	1.21	1.20	1.24	1.48	1.19
MgO	Wt.%	0.01	4.89	5.51	4.94	5.08	5.75	6.19	5.85	5.73	6.70
MnO	Wt.%	0.01	0.16	0.18	0.19	0.17	0.21	0.21	0.21	0.23	0.21
Na2O	Wt.%	0.01	3.04	3.23	3.10	3.08	3.06	2.99	3.06	2.91	2.91
P2O5	Wt.%	0.01	0.77	0.38	0.42	0.37	0.49	0.43	0.44	0.49	0.42
SiO2	Wt.%	0.01	48.20	49.21	48.80	48.32	46.44	48.00	47.88	47.69	47.72
TiO2	Wt.%	0.01	2.68	2.07	2.48	2.00	2.95	2.46	2.58	2.93	2.40
LOI	Wt.%	0.01	0.27	0.29	0.14	0.46	0.01	0.04	0.57	0.08	0.12
Ba	ppm	0.5	548.0	526.0	534.0	508.0	548.0	524.0	529.0	603.0	505.0
Ce	ppm	0.5	57.1	58.1	62.1	62.8	66.9	62.8	63.8	71.8	60.7
Co	ppm	1	59	61	46	49	62	56	61	55	59
Cr	ppm	10	90	80	50	190	50	130	130	120	130
Cs	ppm	0.01	0.38	0.33	0.46	0.63	0.28	0.38	0.80	0.44	0.32
Cu	ppm	1	35	33	28	39	46	45	53	51	44
Dy	ppm	0.05	6.15	6.09	6.55	5.95	7.63	7.04	7.36	8.19	7.01
Er	ppm	0.03	3.32	3.14	3.63	3.15	4.07	3.91	3.86	4.43	3.82
Eu	ppm	0.03	2.08	1.87	1.92	1.94	2.39	2.07	2.11	2.56	2.14
Ga	ppm	0.1	23.2	24.7	24.6	24.4	26.0	24.4	25.2	26.0	23.5
Gd	ppm	0.05	6.45	6.27	7.13	5.99	8.36	7.47	7.33	8.14	7.46
Hf	ppm	0.2	5.5	5.6	5.5	4.9	6.4	6.0	6.1	7.1	5.8
Ho	ppm	0.01	1.33	1.26	1.39	1.23	1.60	1.44	1.45	1.68	1.44
La	ppm	0.5	24.1	27.0	28.4	24.9	29.8	28.4	32.0	32.0	27.3
Lu	ppm	0.01	0.50	0.53	0.52	0.45	0.58	0.59	0.58	0.65	0.56
Nb	ppm	0.2	10.1	7.8	9.2	7.6	9.2	8.6	8.5	9.7	8.0
Nd	ppm	0.1	32.1	31.9	33.9	29.6	38.6	35.7	36.3	40.2	34.2
Ni	ppm	1	65	80	45	72	66	90	95	63	103
Pb	ppm	2	<2	3	<2	<2	<2	<2	4	3	<2
Pr	ppm	0.02	7.25	7.49	7.94	6.95	8.67	7.96	8.19	9.31	7.81
Rb	ppm	0.3	27.1	26.1	26.9	37.6	24.3	23.8	26.0	35.3	24.3
Sc	ppm	1.00	24.00	22.00	25.00	21.00	30.00	29.00	30.00	33.00	29.00
Sm	ppm	0.03	6.81	7.14	7.47	6.65	8.40	7.50	8.27	8.78	7.96
Sr	ppm	0.1	363.0	354.0	333.0	378.0	302.0	281.0	284.0	265.0	270.0
Ta	ppm	0.1	1.5	0.9	0.8	0.6	0.6	0.6	0.8	0.7	0.6
Tb	ppm	0.01	1.06	1.03	1.13	1.05	1.31	1.19	1.22	1.42	1.20
Th	ppm	0.05	1.55	2.85	2.68	2.57	2.85	2.71	2.74	3.05	2.64
Tm	ppm	0.01	0.48	0.48	0.53	0.48	0.62	0.60	0.58	0.65	0.57
U	ppm	0.05	0.28	0.62	0.56	0.33	0.48	0.51	0.47	0.50	0.43
Y	ppm	5	188	209	234	203	296	249	255	237	296
Yb	ppm	0.5	32.5	31.4	34.3	30.6	39.5	37.0	37.9	43.3	35.4
Zn	ppm	0.03	3.08	3.00	3.38	2.99	3.68	3.55	3.76	4.05	3.64
Zr	ppm	2	128	141	147	130	180	156	170	172	152
		2	233	230	241	200	264	241	244	281	229

Sample Group	Unit	Limit	CG82-031A Low P-Zr Evolved -57.2453 54.4644	CG82-031B Low P-Zr Evolved -57.2453 54.4644	CG82-034B High P-Zr Evolved	CG82-035 High P-Zr Evolved -59.3568 54.5253	CG82-036 Low P-Zr Parental -59.3568 54.6160	CG83-006 Low P-Zr Parental -59.3568 54.4951	CG83-013 Low P-Zr Evolved	CG83-017A High P-Zr Evolved -59.3503 54.4177	CG83-020 High P-Zr Evolved	CG83-085 Low P-Zr Evolved -59.2736 54.2361
Magma Longitude	Wt.%	0.01	15.80	15.22	19.31	16.63	17.54	14.81	12.58	16.57	21.23	15.19
Al2O3	Wt.%	0.01	8.41	8.14	9.25	8.49	7.90	7.62	6.36	8.74	9.56	8.06
CaO	Wt.%	0.01	14.29	14.71	9.97	12.16	10.80	16.84	18.40	14.34	9.74	15.66
FeO	Wt.%	0.01	1.11	1.12	0.48	0.50	1.38	1.19	0.38	0.80	0.49	1.19
K2O	Wt.%	0.01	6.39	7.50	10.08	10.86	4.01	7.76	14.68	8.26	6.56	5.87
MgO	Wt.%	0.01	0.21	0.21	0.13	0.15	0.15	0.23	0.18	0.18	0.21	0.21
MnO	Wt.%	0.01	2.92	2.81	2.55	2.42	3.41	2.76	1.89	2.56	3.00	3.09
Na2O	Wt.%	0.01	0.41	0.41	0.25	0.28	0.25	0.42	0.14	0.56	0.31	0.49
P2O5	Wt.%	0.01	48.06	47.50	47.10	47.01	52.53	45.84	44.07	45.92	47.65	47.52
SiO2	Wt.%	0.01	2.39	2.38	0.87	1.49	2.03	2.55	1.27	2.08	1.35	2.71
TiO2	Wt.%	0.01	0.01	0.01	1.07	0.01	0.42	0.01	0.01	0.01	0.13	0.10
LOI	Wt.%	0.01	515.0	509.0	261.0	293.0	495.0	538.0	209.0	434.0	317.0	559.0
Ba	ppm	0.5	61.1	60.8	22.8	27.8	46.1	66.3	18.3	47.1	28.1	70.0
Ce	ppm	0.5	59	65	68	78	47	80	134	82	65	81
Co	ppm	1	130	120	70	120	50	120	790	180	100	70
Cr	ppm	0.01	0.38	0.40	0.10	0.11	0.22	0.46	0.07	0.39	0.20	0.31
Cs	ppm	0.01	46	40	16	21	30	37	61	38	20	44
Cu	ppm	1	6.84	6.91	2.13	2.92	4.24	7.26	2.29	4.65	2.90	7.85
Dy	ppm	0.05	3.55	3.68	1.18	1.51	2.39	3.87	1.38	2.55	1.53	4.24
Er	ppm	0.03	2.16	1.95	0.92	1.12	1.61	2.34	0.83	1.60	1.26	2.45
Eu	ppm	0.03	24.4	23.4	16.9	17.0	22.8	24.1	16.1	21.2	19.7	26.3
Ga	ppm	0.1	7.26	7.19	2.37	3.02	4.90	7.65	2.33	5.38	2.97	8.63
Gd	ppm	0.05	5.8	5.7	1.8	2.4	3.9	6.2	1.9	3.9	2.2	6.4
Hf	ppm	0.2	1.38	1.44	0.41	0.60	0.90	1.47	0.48	1.01	0.54	1.64
Ho	ppm	0.01	27.7	27.6	10.5	12.6	21.6	30.1	8.1	20.9	12.9	32.0
La	ppm	0.5	0.56	0.50	0.19	0.23	0.38	0.57	0.22	0.38	0.20	0.63
Lu	ppm	0.01	8.2	8.2	3.1	4.8	6.5	9.3	2.9	7.4	4.4	9.8
Nb	ppm	0.2	34.5	33.6	12.3	15.3	24.2	37.2	10.6	27.3	16.1	39.4
Nd	ppm	0.1	106	142	279	253	48	117	334	172	135	69
Ni	ppm	1	<2	2	<2	<2	2	<2	<2	<2	<2	<2
Pb	ppm	2	7.72	7.85	2.82	3.56	5.64	8.48	2.35	6.11	3.57	8.95
Pr	ppm	0.02	22.0	22.5	5.9	7.0	25.8	23.1	5.9	12.8	6.4	24.1
Rb	ppm	0.3	29.00	27.00	9.00	14.00	21.00	28.00	9.00	17.00	12.00	31.00
Sc	ppm	1.00	7.24	7.72	2.40	3.04	5.27	8.29	2.33	5.55	3.30	8.68
Sm	ppm	0.03	283.0	273.0	387.0	335.0	376.0	274.0	229.0	315.0	410.0	284.0
Sr	ppm	0.1	0.7	0.6	0.3	0.6	0.7	1.5	1.2	1.4	1.3	1.6
Ta	ppm	0.1	1.17	1.19	0.39	0.48	0.79	1.24	0.40	0.85	0.49	1.34
Tb	ppm	0.01	2.68	2.52	0.60	0.77	2.87	2.78	0.68	1.16	0.71	2.99
Th	ppm	0.05	0.55	0.56	0.15	0.25	0.36	0.59	0.17	0.41	0.25	0.62
Tm	ppm	0.01	0.44	0.48	0.08	0.12	0.98	0.46	0.08	0.22	0.09	0.53
U	ppm	0.05	238	235	67	122	234	239	191	164	104	276
V	ppm	5	36.2	35.9	11.0	15.2	23.0	37.9	12.3	25.1	14.6	40.4
Y	ppm	0.5	3.45	3.51	1.07	1.55	2.31	3.59	1.22	2.36	1.43	3.95
Yb	ppm	0.03	156	155	100	116	125	182	160	92	179	275
Zn	ppm	2	228	229	63	97	144	247	69	166	91	275
Zr	ppm	2										

Sample Group	Unit	Limit	CG83-115 High P-Zr Evolved	CG83-229 Low P-Zr Evolved -59.5229 54.4197	CG83-234 High P-Zr Parental -59.7318 54.4106	CG83-237 Low P-Zr Evolved -59.8840 54.4024	CG83-239 Low P-Zr Evolved -59.8213 54.3901	CG83-240 High P-Zr Parental -59.7737 54.3824	CG83-246 High P-Zr Evolved -59.8331 54.3450	CG83-250A High P-Zr Evolved	CG83-261 High P-Zr Evolved -59.8210 54.2682	CG83-280 High P-Zr Evolved
Magma Longitude Latitude												
Al2O3	Wt.%	0.01	20.25	9.35	20.09	8.50	18.26	17.50	22.44	19.35	17.05	20.42
CaO	Wt.%	0.01	9.11	4.44	9.84	4.42	9.15	8.26	10.17	8.75	9.16	9.49
FeO	Wt.%	0.01	9.07	19.93	10.74	20.25	12.15	13.20	8.07	12.06	13.20	9.68
K2O	Wt.%	0.01	1.54	0.88	0.58	0.43	0.81	1.30	0.53	0.53	1.50	0.53
MgO	Wt.%	0.01	8.25	19.39	5.92	21.20	6.82	7.24	5.05	7.68	3.45	7.73
MnO	Wt.%	0.01	0.12	0.24	0.14	0.24	0.13	0.10	0.15	0.15	0.12	0.12
Na2O	Wt.%	0.01	2.92	1.74	3.04	1.47	3.21	2.99	3.38	2.80	3.26	3.06
P2O5	Wt.%	0.01	0.28	0.31	0.49	0.24	0.28	0.64	0.27	0.35	1.11	0.36
SiO2	Wt.%	0.01	47.43	42.56	47.32	42.01	48.67	46.61	48.90	46.91	48.21	47.48
TiO2	Wt.%	0.01	1.04	1.34	1.83	1.23	0.51	2.09	1.14	1.41	2.87	1.14
LOI	Wt.%	0.01	1.24	0.01	0.04	0.01	0.70	0.87	0.12	0.01	0.08	0.01
Ba	ppm	0.5	290.0	319.0	380.0	245.0	331.0	519.0	310.0	379.0	769.0	314.0
Ce	ppm	0.5	25.7	38.0	40.8	30.8	39.4	28.4	24.6	28.4	101.0	27.8
Co	ppm	1	66	151	59	151	57	60	51	73	44	73
Cr	ppm	10	60	420	70	1050	180	100	150	140	50	60
Cs	ppm	0.01	3.00	0.17	0.25	0.12	0.67	1.41	0.40	0.12	0.48	0.15
Cu	ppm	1	11	22	26	29	9	25	13	19	41	20
Dy	ppm	0.05	2.43	4.21	4.15	3.36	4.32	5.36	2.22	2.70	9.91	2.70
Er	ppm	0.03	1.18	2.23	2.28	2.12	2.72	3.02	1.42	1.50	6.00	1.63
Eu	ppm	0.03	1.03	1.23	1.50	1.12	1.71	2.06	1.27	1.39	3.46	1.29
Ga	ppm	0.1	17.6	14.7	20.4	13.0	21.5	20.3	19.6	19.3	27.4	17.8
Gd	ppm	0.05	2.52	4.19	4.43	3.82	5.46	6.05	2.78	3.29	11.45	3.20
Hf	ppm	0.2	1.9	3.7	3.1	3.2	3.3	4.0	2.2	2.3	8.7	2.4
Ho	ppm	0.01	0.50	0.83	0.86	0.73	1.00	1.05	0.49	0.59	2.13	0.57
La	ppm	0.5	12.1	17.4	18.4	14.4	17.7	22.8	11.6	13.5	45.3	12.5
Lu	ppm	0.01	0.19	0.32	0.31	0.30	0.37	0.40	0.19	0.23	0.89	0.24
Nb	ppm	0.2	3.3	4.9	6.1	4.0	6.7	8.6	3.9	4.7	15.9	4.4
Nd	ppm	0.1	13.9	20.8	23.2	16.5	22.2	28.2	13.1	16.0	56.9	15.2
Ni	ppm	1	219	483	124	531	146	131	88	134	186	186
Pb	ppm	2	<2	<2	<2	<2	<2	<2	<2	<2	2	<2
Pr	ppm	0.02	3.22	4.93	5.24	3.86	5.02	6.45	3.11	3.72	13.00	3.60
Rb	ppm	0.3	77.1	13.4	9.5	11.3	21.6	37.0	8.6	8.1	31.9	7.4
Sc	ppm	1.00	8.00	15.00	15.00	14.00	23.00	19.00	8.00	10.00	30.00	10.00
Sm	ppm	0.03	2.86	4.73	4.69	3.87	5.08	6.30	2.93	3.41	12.10	3.44
Sr	ppm	0.1	363.0	175.5	396.0	150.5	327.0	332.0	462.0	390.0	352.0	415.0
Ta	ppm	0.1	0.7	0.8	1.2	0.7	0.7	0.8	1.3	1.3	1.7	1.5
Tb	ppm	0.01	0.42	0.69	0.71	0.61	0.80	0.90	0.42	0.53	1.78	0.51
Th	ppm	0.05	0.67	1.55	1.06	1.60	1.69	1.48	0.76	0.72	3.26	0.74
Tm	ppm	0.01	0.19	0.34	0.33	0.27	0.34	0.40	0.17	0.22	0.82	0.22
U	ppm	0.05	0.09	0.23	0.13	0.22	0.48	0.21	0.13	0.10	0.59	0.07
V	ppm	5	68	118	130	157	176	142	88	122	81	14.6
Y	ppm	0.5	12.4	21.9	21.1	17.7	23.4	27.4	12.2	14.7	53.8	14.6
Yb	ppm	0.03	1.08	2.09	2.14	1.89	2.30	2.56	1.10	1.33	5.61	1.37
Zn	ppm	2	77	191	109	178	125	148	72	112	148	94
Zr	ppm	2	74	147	126	120	130	174	88	90	371	96

Sample Group	Unit	Limit	CG83-283 High P-Zr Evolved Parental -59.9355 54.2291	CG83-288 High P-Zr Parental -59.8473 54.2236	CG83-427 Low P-Zr Parental -59.2663 54.6338	CG83-429 High P-Zr Evolved	CG83-462 High P-Zr Parental -59.8255 54.1362	CG83-469C High P-Zr Parental -59.8348 54.0925	CG83-545 Low P-Zr Parental -59.9399 54.3475	CG83-628a High P-Zr Parental	CG84-172E High P-Zr Parental -56.9264 53.8827	DJ-90-2302 Low P-Zr Parental
Longitude												
Latitude												
Al2O3	Wt.%	0.01	14.46	18.52	18.72	18.69	17.47	16.09	19.44	17.93	15.86	21.01
CaO	Wt.%	0.01	7.90	8.73	8.73	8.57	8.97	8.17	9.48	8.82	8.77	9.81
FeO	Wt.%	0.01	16.79	11.87	11.59	10.60	13.01	14.58	10.76	12.85	14.44	8.59
K2O	Wt.%	0.01	1.17	0.37	1.18	1.12	0.89	1.55	0.50	1.12	1.13	0.42
MgO	Wt.%	0.01	7.53	7.41	4.30	8.02	5.64	7.54	7.59	5.29	5.29	7.24
MnO	Wt.%	0.01	0.21	0.15	0.15	0.14	0.18	0.21	0.18	0.18	0.12	0.12
Na2O	Wt.%	0.01	2.30	3.00	3.36	2.88	3.11	1.87	2.84	3.34	3.13	3.23
P2O5	Wt.%	0.01	0.86	0.51	0.38	0.37	0.77	0.81	0.22	0.78	0.90	0.11
SiO2	Wt.%	0.01	45.76	47.50	49.49	48.33	47.15	46.28	47.74	46.91	46.71	48.65
TiO2	Wt.%	0.01	3.01	1.94	2.09	1.30	2.81	2.89	1.28	3.57	3.57	0.67
LOI	Wt.%	0.01	0.01	0.01	0.87	1.21	0.15	0.79	0.51	-	0.01	0.79
Ba	ppm	0.5	607.0	413.0	498.0	344.0	546.0	455.0	340.0	481.0	592.0	233.0
Ce	ppm	0.5	70.0	43.0	53.7	32.9	64.6	59.2	33.4	60.3	71.7	15.3
Co	ppm	1	79	70	45	56	59	68	64	44	71	39
Cr	ppm	10	210	110	40	140	120	120	230	270	90	44
Cs	ppm	0.01	0.47	0.24	0.26	1.68	0.47	8.19	0.49	0.33	0.29	BD
Cu	ppm	1	48	30	23	34	42	44	33	39	47	36
Dy	ppm	0.05	7.39	4.29	5.85	3.34	6.74	6.18	4.03	6.61	8.02	1.84
Er	ppm	0.03	4.27	2.61	3.26	1.68	3.66	3.56	2.06	3.52	4.63	0.95
Eu	ppm	0.03	2.54	1.77	2.14	1.38	2.48	2.29	1.48	2.48	2.62	0.77
Ga	ppm	0.1	22.8	20.9	24.3	19.1	22.3	22.4	20.4	23.0	24.3	BD
Gd	ppm	0.05	8.71	4.91	6.75	3.41	7.67	7.42	4.10	7.42	8.87	1.77
Hf	ppm	0.2	6.9	3.5	5.1	2.7	5.5	5.2	3.1	5.2	6.1	1.2
Ho	ppm	0.01	1.55	0.91	1.24	0.65	1.36	1.28	0.79	1.34	1.65	0.36
La	ppm	0.5	32.4	19.6	24.7	15.2	30.0	28.1	15.3	27.5	32.3	6.9
Lu	ppm	0.01	0.60	0.36	0.44	0.24	0.51	0.51	0.30	0.55	0.67	0.14
Nb	ppm	0.2	11.0	7.1	7.7	4.5	12.2	10.5	4.6	10.6	12.8	2.0
Nd	ppm	0.1	40.5	24.0	29.2	18.5	37.8	35.4	18.8	35.4	41.4	8.1
Ni	ppm	1	119	149	44	144	84	126	200	79	59	152
Pb	ppm	2	<2	<2	<2	2	<2	<2	<2	<2	<2	BD
Pr	ppm	0.02	9.34	5.46	6.98	4.13	8.45	7.95	4.28	7.83	9.38	1.90
Rb	ppm	0.3	23.2	11.3	24.6	34.2	19.1	73.8	13.9	22.0	20.9	10.0
Sc	ppm	1.00	27.00	18.00	20.00	12.00	25.00	25.00	16.00	24.00	30.00	BD
Sm	ppm	0.03	8.61	5.45	6.62	3.91	7.76	7.77	4.16	7.52	9.13	1.90
Sr	ppm	0.1	244.0	382.0	375.0	381.0	334.0	205.0	356.0	331.0	298.0	343.0
Ta	ppm	0.1	1.5	1.3	0.8	0.6	1.4	1.4	0.9	0.6	2.2	0.1
Tb	ppm	0.01	1.35	0.80	1.04	0.57	1.17	1.18	0.67	1.16	1.45	0.28
Th	ppm	0.05	1.81	1.19	2.61	1.02	1.82	1.57	1.32	1.80	2.09	0.49
Tm	ppm	0.01	0.60	0.34	0.48	0.24	0.52	0.46	0.29	0.50	0.62	0.14
U	ppm	0.05	0.36	0.17	0.66	0.20	0.32	0.92	0.16	0.29	0.41	BD
V	ppm	5	245	137	189	112	189	33.1	135	181	219	BD
Y	ppm	0.5	38.4	23.2	29.9	16.8	34.8	33.1	19.6	33.7	40.6	9.7
Yb	ppm	0.03	3.96	2.24	3.06	1.55	3.48	3.40	1.94	3.36	4.25	0.79
Zn	ppm	2	183	125	131	91	147	188	107	142	165	69
Zr	ppm	2	278	147	205	115	229	223	124	224	260	49

Sample Group	Unit	Limit	FA68-002-02 Low P-Zr Evolved -57 2260 54.4660	FA68-005-01 Low P-Zr Evolved -57 6540 54.4520	FA68-008-05 High P-Zr Evolved -58 4300 54.3300	FA69-057-01 Low P-Zr Parental -57 1890 54.4440	FA69-064-01 Low P-Zr Parental -57 2430 54.4690	FA71-001-05 Low P-Zr Evolved -60 4970 54.3700	FA71-002-06 Low P-Zr Evolved -59 8090 54.3960	FA71-003-05 High P-Zr Evolved -59 8340 54.3430	FA71-004-02 Low P-Zr Parental -57 8340 54.3000	FA71-005-01 Low P-Zr Parental -58 6090 54.3770
Magma Longitude	Wt.%	0.01	14.05	17.69	20.06	15.73	15.63	16.98	18.34	20.74	12.94	17.84
Al2O3	Wt.%	0.01	7.10	8.33	9.59	8.88	8.55	9.18	9.71	9.71	7.22	9.84
CaO	Wt.%	0.01	16.52	11.07	9.90	13.50	13.42	11.51	11.28	9.20	15.16	11.07
FeO	Wt.%	0.01	1.16	0.37	0.66	1.03	1.15	1.19	0.78	0.52	1.68	0.66
K2O	Wt.%	0.01	8.35	9.17	5.99	6.61	6.14	5.11	6.99	3.75	3.75	7.29
MgO	Wt.%	0.01	0.23	0.15	0.13	0.19	0.27	0.16	0.14	0.12	0.23	0.15
MnO	Wt.%	0.01	2.77	2.74	3.06	2.98	3.29	3.17	2.95	3.11	3.39	2.92
Na2O	Wt.%	0.01	0.39	0.09	0.56	0.39	0.42	0.44	0.26	0.27	0.51	0.21
P2O5	Wt.%	0.01	47.27	48.38	48.48	48.52	48.64	49.92	48.50	48.30	52.49	48.59
SiO2	Wt.%	0.01	2.17	1.02	1.57	2.17	2.49	2.34	1.32	1.04	2.63	1.43
TiO2	Wt.%	0.01	-0.50	-0.50	0.00	-0.30	0.70	0.00	-0.40	0.00	-0.10	0.10
LOI	Wt.%	0.01	520.0	190.0	400.0	500.0	460.0	460.0	380.0	280.0	600.0	330.0
Ba	ppm	0.5	64.0	12.0	42.0	62.0	64.0	63.0	41.0	25.0	74.0	35.0
Ce	ppm	0.5	77	67	49	62	54	50	62	53	45	56
Co	ppm	1	221	118	69	145	143	111	270	174	48	242
Cr	ppm	0.01	0.29	0.06	0.22	0.28	0.78	0.49	0.15	0.25	1.30	0.27
Cs	ppm	0.01	49	67	28	44	54	29	31	21	35	26
Cu	ppm	1	6.80	2.10	4.10	6.80	7.00	7.00	4.10	2.40	12.00	4.30
Dy	ppm	0.05	3.60	1.20	2.10	3.60	3.80	3.70	2.40	1.30	7.00	2.40
Er	ppm	0.03	2.20	0.92	1.80	2.30	2.40	2.20	1.60	1.20	2.80	1.50
Eu	ppm	0.03	21.0	16.0	19.0	22.0	23.0	23.0	20.0	17.0	24.0	19.0
Ga	ppm	0.1	7.50	2.20	5.00	7.70	7.90	7.80	4.60	2.60	12.00	4.60
Gd	ppm	0.05	5.3	1.1	2.5	4.6	4.1	4.9	3.1	1.6	7.2	2.9
Hf	ppm	0.2	1.40	0.42	0.81	1.30	1.40	1.40	0.86	0.48	2.50	0.88
Ho	ppm	0.01	29.0	5.1	19.0	27.0	30.0	29.0	20.0	12.0	34.0	17.0
La	ppm	0.5	0.55	0.19	0.31	0.55	0.58	0.55	0.35	0.20	1.10	0.36
Lu	ppm	0.01	9.7	2.3	7.3	8.9	9.6	11.0	5.8	3.8	14.0	5.2
Nb	ppm	0.2	34.0	7.2	23.0	33.0	33.0	34.0	23.0	14.0	44.0	20.0
Nd	ppm	0.1	104	103	122	102	84	65	165	144	21	153
Ni	ppm	1	7	3	4	6	10	7	4	2	9	4
Pb	ppm	2	8.10	1.60	5.40	7.90	8.10	8.10	5.50	3.40	10.00	4.80
Pr	ppm	0.02	25.0	3.9	9.6	23.0	35.0	29.0	16.0	7.2	54.0	12.0
Rb	ppm	0.3	24.00	20.00	14.00	29.00	29.00	29.00	15.00	11.00	41.00	25.00
Sc	ppm	1.00	7.60	1.90	4.90	7.50	7.80	7.60	4.60	2.70	11.00	4.30
Sm	ppm	0.03	239.0	347.0	402.0	275.0	291.0	300.0	332.0	415.0	224.0	336.0
Sr	ppm	0.1	0.5	0.2	0.4	0.5	0.5	0.6	0.3	0.2	0.7	0.3
Ta	ppm	0.1	1.20	0.35	0.73	1.20	1.20	1.20	0.70	0.41	1.90	0.73
Tb	ppm	0.01	2.70	0.44	0.93	2.60	3.00	2.90	1.70	0.63	3.70	1.40
Th	ppm	0.05	0.54	0.18	0.31	0.53	0.59	0.54	0.33	0.19	1.00	0.34
Tm	ppm	0.01	0.52	0.09	0.17	0.44	0.61	0.62	0.30	0.10	0.88	0.25
U	ppm	0.05	219	113	88	226	237	219	135	83	215	165
V	ppm	5	39.0	12.0	23.0	39.0	41.0	40.0	24.0	14.0	68.0	25.0
Y	ppm	0.5	3.70	1.30	2.10	3.70	3.80	3.70	2.20	1.30	6.90	2.30
Yb	ppm	0.03	174	90	101	147	175	125	128	102	181	124
Zn	ppm	2	215	41	115	204	230	202	133	69	274	113
Zr	ppm	2										

Sample Group	Unit	Limit	FA71-021-05 High P-Zr Parental -57.0080 53.8050	FA71-022-01 High P-Zr Parental -56.9650 53.8360	FA71-029-01 Low P-Zr Parental -59.1730 54.5110	FA71-030-04 Low P-Zr Parental -59.7590 54.5630	FA71-032-03 Low P-Zr Parental -60.3167 54.2333	SW10-65-55 Int.-Amp.b Parental -66.9726 53.0443	W3-11-71-25 Int.-Amp.b Evolved -66.9411 52.9814	W3-11-71-40 Int.-Amp.b Parental -66.9411 52.9814	W3-11-71-60 Int.-Amp.b Evolved -66.9411 52.9814	W6-10-129-235 Low P-Zr Evolved -66.9063 53.0039
Latitude	Wt.%	0.01	17.08	17.00	14.08	16.84	18.42	14.67	14.06	14.39	14.40	15.64
Al2O3	Wt.%	0.01	9.00	8.86	7.56	7.90	8.72	7.99	7.95	7.95	8.19	6.16
CaO	Wt.%	0.01	12.76	12.90	15.74	11.57	11.14	14.56	16.04	13.76	15.96	10.11
FeO	Wt.%	0.01	1.07	1.19	1.12	1.49	0.68	1.27	1.69	2.21	1.74	2.04
K2O	Wt.%	0.01	4.59	4.83	8.61	4.96	8.26	8.58	5.17	5.38	5.52	5.53
MgO	Wt.%	0.01	0.18	0.17	0.22	0.16	0.38	0.22	0.38	0.50	0.45	0.25
MnO	Wt.%	0.01	3.21	3.28	2.48	3.37	2.87	3.48	3.25	3.65	2.74	2.84
Na2O	Wt.%	0.01	0.79	0.77	0.38	0.36	0.25	0.73	0.90	0.96	0.94	0.17
P2O5	Wt.%	0.01	48.35	48.03	47.51	51.42	48.31	45.74	46.70	47.08	45.96	56.65
SiO2	Wt.%	0.01	2.99	2.97	2.30	1.94	1.22	2.75	4.04	4.12	4.11	0.60
TiO2	Wt.%	0.01	0.20	0.10	0.60	-0.10	0.20	0.81	1.19	2.36	1.08	3.44
LOI	Wt.%	0.01	540.0	580.0	480.0	540.0	360.0	784.0	636.0	701.0	728.0	995.0
Ba	ppm	0.5	66.0	68.0	56.0	63.0	36.0	69.2	90.8	103.0	91.4	33.4
Ce	ppm	0.5	51	52	77	51	63	58	61	45	48	48
Co	ppm	1	69	72	431	59	314	230	60	50	70	70
Cr	ppm	10	0.31	0.39	0.38	0.49	0.20	0.36	1.76	3.91	1.01	0.91
Cs	ppm	0.01	40	43	56	30	31	37	64	29	53	2
Cu	ppm	1	7.60	7.60	6.50	6.40	3.90	6.39	9.23	10.80	9.42	2.66
Dy	ppm	0.05	4.20	4.40	3.70	3.50	2.20	3.46	5.36	6.17	6.05	1.84
Er	ppm	0.03	2.40	2.50	2.10	2.20	1.50	2.34	2.94	3.67	2.91	1.19
Eu	ppm	0.03	22.0	22.0	21.0	22.0	19.0	18.7	25.1	24.4	24.9	17.7
Ga	ppm	0.1	8.10	8.50	6.90	7.10	4.20	7.47	10.80	11.75	10.40	2.73
Gd	ppm	0.05	4.6	5.9	4.5	5.1	2.8	5.9	8.6	8.8	8.6	1.8
Hf	ppm	0.2	1.60	1.60	1.40	1.30	0.81	1.30	2.10	2.24	2.01	0.53
Ho	ppm	0.01	31.0	31.0	26.0	31.0	17.0	31.2	43.0	50.3	42.5	16.8
La	ppm	0.5	0.63	0.67	0.55	0.53	0.33	0.47	0.71	0.72	0.72	0.22
Lu	ppm	0.01	12.0	13.0	9.2	10.0	5.9	11.0	15.7	17.5	15.5	3.9
Nb	ppm	0.2	38.0	38.0	31.0	33.0	20.0	38.1	50.8	57.0	51.1	17.4
Nd	ppm	0.1	39	51	164	63	187	166	39	31	45	17
Ni	ppm	1	6	6	6	10	4	16	BD	3	5	11
Pb	ppm	2	9.10	9.20	7.60	8.30	4.70	9.28	12.05	13.35	12.35	4.37
Pr	ppm	0.02	23.0	28.0	25.0	34.0	13.0	25.0	45.4	72.0	41.4	47.4
Rb	ppm	0.3	28.00	27.00	26.00	22.00	14.00	21.00	29.00	29.00	29.00	21.00
Sc	ppm	1.00	7.90	8.20	6.70	7.30	4.30	7.91	10.30	11.85	10.25	3.10
Sm	ppm	0.03	318.0	318.0	251.0	337.0	335.0	406.0	232.0	283.0	239.0	743.0
Sr	ppm	0.1	0.7	0.7	0.5	0.6	0.3	0.6	1.2	1.2	0.9	0.5
Ta	ppm	0.1	1.30	1.30	1.10	1.10	0.68	1.17	1.60	1.86	1.59	0.44
Tb	ppm	0.01	1.90	2.00	2.40	3.60	1.50	2.79	4.26	4.37	4.15	2.23
Th	ppm	0.05	0.62	0.63	0.53	0.50	0.31	0.51	0.66	0.80	0.85	0.20
Tm	ppm	0.01	0.37	0.43	0.47	1.00	0.28	0.49	0.60	0.60	0.53	0.73
U	ppm	0.05	191	184	224	181	118	159	291	264	273	199
V	ppm	5	44.0	45.0	38.0	36.0	23.0	32.3	50.9	59.8	53.6	13.6
Y	ppm	0.5	4.10	4.40	3.60	3.50	2.10	3.41	4.93	5.20	5.42	1.54
Yb	ppm	0.03	154	158	176	138	121	262	82	135	123	67
Zn	ppm	2	194	244	190	210	126	267	370	384	349	64
Zr	ppm	2										

Appendix 3.2: Fenner diagrams for 3 geochemical groups in Eastern Laurentia.

Figure A3.2-1: Fenner plots of low P-Zr Group.

Figure A3.2-2: Fenner plots of Intermediate-Amphibolite P-Zr Group.

Figure A3.2-3: Fenner plots of low P-Zr Group.

Appendix 4.1: Table of Samples.

OZCHEM Database

Sample	Groups	Easting	Northing	Zone	Age (Ma)
1699644	CUR-1	462979	6768172	53	1580
1699638	CUR-1	480706	6765492	53	1580
1700898	CUR-2	485454	6765897	53	1580
1700899	CUR-2	485454	6765897	53	1580
1699642	CUR-3	420820	6557153	54	1585
40013	CUR-3	420820	6557153	54	1585
40002	CUR-3	390306	6458015	54	1585
586119	CUR-3	385814	6457143	54	1585
1699624	CUR-3	462979	6768172	53	1580
586118	CUR-3	462979	6768172	53	1580
45446	GR-1				
1840385	GR-2				
1840382	GR-2				
1840379	GR-2	524658	6541315	53	1592
44427	GR-2	524684	6540575	53	1592
44422	GR-2	524682	6540897	53	1592
1840384	GR-2	524687	6540897	53	1592
1840527	GR-2	521183	6543465	53	1592
1840370	GR-3	521595	6543277	53	1592
1840369	GR-3	521209	6543377	53	1592
1840367	GR-3	521563	6543233	53	1592
1840365	GR-3	521873	6543606	53	1592
1840805	GR-3	521269	6542876	53	1592
1840813	GR-3	520029	6544024	53	1592
1840524	GR-3	520254	6544419	53	1592
1840543	GR-3	524790	6541349	53	1592
1840519	GR-3	492498	6489397	53	1592
1840811	GR-3	520748	6543498	53	1592
1840363	GR-3	519798	6544748	53	1592

Appendix 5.1 Conference Abstracts.

Newly recognized 1550-1590 Ma Tobacco Root -Western Channel LIP, and further evidence for bringing South Australia back home to Western Laurentia.

Rogers, C.¹, Ernst, R.E.¹, Cousens, B.¹, Soderlund, U.², Hamilton, M.³, Harlan, S.⁴

¹ Carleton University, Ottawa, ON, ² Lund University, Sweden, ³ University of Toronto, Toronto, ON, ⁴Division of Earth Sciences, National Science Foundation, Arlington, VA

Large Igneous Provinces (LIPs) have become increasingly important in both continental reconstructions and the understanding of continental breakup. Mafic dyke swarms, in particular, are proving valuable in providing geochronological and geochemical correlations between formerly adjacent crustal blocks. Recently we have identified multiple discrete geochemical signatures within a previously defined ca.1460 Ma Moyie-Purcell event along the western Laurentia margin using (La/Sm)_{PM} and (Gd/Yb)_{PM} ratios. Two of these distinct geochemical groups in the Tobacco Root Mountains have been recently dated by baddeleyite U-Pb techniques and are termed the 1590 ± 3 Ma Mammoth and the 1550.6 ± 5.2 Ma Ramshorn events. These newly identified events have an intraplate geochemical signature, and they provide a potential detrital zircon source to the Belt-Purcell basin from the presumed eroded remnant of the corresponding LIP felsic volcanic packages. Thus, ending the requirement of an off craton source to supply the Belt-Purcell basin with 1550-1590 Ma detrital zircons that lie within the age range of the former "North American Magmatic Gap".

Furthermore, the ca.1590 Ma Mammoth Group dykes in the Tobacco Root Mountains can be geochemically and geochronologically correlated with the ca.1590 Ma Western Channel Diabase (WCD) in northern Canada, and the ca.1550 Ma Ramshorn Creek dykes can be geochemically matched with an undated sill from the WCD. Based on these correlations, we postulate a 1550-1590 Ma Tobacco Root - Western Channel Diabase (TR-WCD) LIP that extends 2000 km along the western margin of Laurentia, from the Wyoming Craton in Montana, USA, to the Great Bear Lake region and Yukon Territory in Canada. A new geochemical connection between the 1590 Ma, bimodal Gawler Range magmatism of the South Australian craton and the 1590 Ma WCD of NW Laurentia, combined with the previously established: 1) geochronological match 2) reconstruction link based on paleomagnetism and 3) correlating age-equivalent Wernecke breccias in the Wernecke and Ogilvie Mountains (Yukon), with Olympic Dam breccias in Gawler craton, extends the combined ca.1590-1550 Ma TR-WCD-Gawler Range LIP event to over 2500 km in length.

GAC-MAC Whitehorse, YT Canada, June 1-3
Phosphorous and Potassium enrichment in the Michael-Shabogamo magmatic event of eastern Laurentia; can intense mantle metasomatism be responsible?

Rogers, C.¹, Ernst, R.E.¹, Cousens, B.¹, Soderlund, U.², Gower, C.³

¹Carleton University, Ottawa, ON, ² Lund University, Sweden, ³Newfoundland Geological Survey

Traditionally, intrusions that outcrop in eastern Canada between Labrador City and Rigolet, Labrador, have been mapped as two groups: the Shabogamo Gabbros that outcrop west of Churchill Falls, and the Michael Gabbros that outcrop east of Churchill Falls. New U-Pb ages and detailed geochemical analysis of the Michael and Shabogamo events show that both are related, as others have previously proposed based on sparse U-Pb ages. Geochemically, most of the Michael and Shabogamo Gabbros are trachybasalt to basalt, and alkaline to sub-alkaline in composition with complicated evolutionary histories, involving: high P₂O₅ (~2 wt.%) and K₂O (~4.9%) values, evidence of cumulate (1.1 <Eu/Eu*), residual (0.9 >Eu/Eu*) and undifferentiated (0.9 >Eu/Eu* > 1.1) subsets.

We define four geochemical groups on the basis of [P₂O₅*1000]/Zr ratios (P-Zr) that also correspond to the different ages of Michael-Shabogamo Gabbros: 1) 1450 Ma group - 6.19-2.77 P-Zr ratio; 2) 1430-1435 Ma group (preliminary ages) - 2.74-2.01 P-Zr ratio; 3) 1425 Ma group - 2.00-1.03 P-Zr ratio; and 4) an undated group - 1.08-0.45 P-Zr ratio. The positive slope of the P-Zr ratio indicates that apatite melting was a dominant process in the generation of the magmas for the Michael-Shabogamo Gabbros. For each of these groups, the P-Zr slope is inversely correlated with degree of partial melting, a lower degree of partial melt represents a higher P-Zr ratio. Additionally, plotting (P₂O₅/Nd)_{PM} and Nb/Y, the proxy for alkalinity in potentially altered rocks, further supports higher P₂O₅ values representing lower degrees of partial melt.

Enrichment of P₂O₅ and K₂O of the Michael-Shabogamo Gabbros indicate that the source of the magma was from metasomatized subcontinental lithospheric mantle, probably from a late Paleo- to early Mesoproterozoic phosphate-rich sedimentary source subducted by the closing of the basin that existed between the Molson Lake and Lac Joseph terrains at ca.1650 Ma. Mafic intrusions of the 1647 ± 3 Ma Ossokmanuan event help constrain the timing of metasomatism of the mantle as the Ossokmanuan intrusions do not show similar P-Zr ratios, to the Michael-Shabogamo Gabbros, indicating that the proposed mantle metasomatism must have occurred after emplacement of the ca.1650 Ma dykes. On the other hand, the emplacement of the ca.1290-1280 Ma Nain HP and LP dykes show similar geochemical trends as the Michael-Shabogamo event. The ca.1100 Ma Aillik dykes (also in the area) do show enriched P-Zr ratios but

the slopes of those ratios are negative indicating that apatite fractionation had a dominant role not mantle melting of apatite. The high P-Zr ratios indicate that a metasomatized mantle may have persisted beneath Eastern Laurentia for at least ca.350 Ma from <1650 Ma to at least ca.1300 Ma over multiple distinct melting events.

Abstracts with Program AESRC Ottawa Canada April 1-3
Persistent Proterozoic Metasomatized Mantle Produces the Phosphorous-Potassium Enriched Michael-Shabogamo Gabbros, Seal Lake Dykes and Aillik Dykes of Eastern Laurentia

Rogers, C.¹, Ernst, R.E.¹, Cousens, B.¹, Soderlund, U.², Gower, C.³

¹Carleton University, Ottawa, ON, ²Lund University, Sweden, ³Newfoundland Geological Survey

Mafic intrusions that are exposed in eastern Canada between Labrador City and Rigolet, Labrador, were originally mapped as two groups: the Shabogamo Gabbros that outcrops west of Churchill Falls, and the Michael Gabbros that outcrops east of Churchill Falls. New U-Pb ages and detailed geochemical analysis of the Michael and Shabogamo events show both are related, as others have previously proposed based on sparse U-Pb ages. Geochemically, most of the Michael and Shabogamo Gabbros are trachybasalt to basalt, and alkaline to sub-alkaline in composition with complicated evolutionary histories, including: high P₂O₅, up to 2 wt.% and K₂O, up to 4.9%, evidence of cumulate (1.1 < Eu/Eu*), residual (0.9 > Eu/Eu*) and undifferentiated (0.9 > Eu/Eu* > 1.1) subsets.

We define four geochemical groups on the basis of [P₂O₅*1000]/Zr ratios (P-Zr) that correspond to the different ages of Michael-Shabogamo Gabbros: 1) 1450 Ma group - 6.19-2.77 P-Zr ratio 2) 1430-1435 Ma group (preliminary ages) - 2.74-2.01 P-Zr ratio 3) 1425 Ma group - 2.00-1.03 P-Zr ratio and 4) an undated group - 1.08-0.45 P-Zr ratio. The positive slope of the P-Zr ratio indicates that apatite melting was a dominant process in the generation of the magmas for the Michael-Shabogamo Gabbros. The different P-Zr slope for each of these groups represents different degrees of partial melting and/or mantle heterogeneity.

Enrichment of P₂O₅ and K₂O of the Michael-Shabogamo Gabbros indicate that the magma was generated from low degree partial melting of metasomatized subcontinental lithospheric mantle. Metasomatism probably occurred as a result a late Paleo- to early Mesoproterozoic phosphate-rich sedimentary source subducted by the closing of the basin that existed between the Molson Lake and Lac Joseph terrains at ca. 1650 Ma. Sm-Nd and Rb-Sr isotopes demonstrate that the mantle producing the Michael-Shabogamo gabbros was enriched by an older crustal source. The low P₂O₅ and K₂O values of the ca. 1647 ± 3 Ma Ossokmanuan mafic magmatism constrains the timing for metasomatism to after ca. 1650 Ma. The high P-Zr ratios of the younger Nain HP, Nain, LP and Aillik dykes indicate that metasomatized mantle persisted beneath Eastern Laurentia for at least ca. 300 Ma and over multiple distinct melting events.

Newly discovered 1550 Ma mafic magmatism in the Tobacco Root Mountains, MT USA: An end to the North American Magmatic Gap?

Authors: C. Rogers¹, R.E. Ernst¹, B. Cousens¹, and S. Harlan²

¹Department of Earth Sciences, Carleton University, Ottawa, ON

²Division of Earth Sciences, National Science Foundation, Arlington, VA

A new baddeleyite U-Pb age of 1550.6 ± 5.2 Ma for a dyke in the Tobacco Root Mountains (TRM) falls in the middle of a “magmatic gap” that was previously noted to exist between 1500 and 1600 Ma in western North America (Ross et al. 2003) based on the detrital zircon record of Proterozoic sedimentary rocks (Finney et al. 2005). Dykes of this age offer a potential local source for ca. 1550 Ma detrital zircons found within the Belt-Purcell Basin. The 1552 Ma age is significantly older than 1470-1430 Ma U-Pb mafic sills within the Belt-Purcell Supergroup and is unknown elsewhere in the Wyoming craton. The new U-Pb age for these intra-plate mafic dykes indicate that this magmatic event may have preceded 1470 to 1400 Ma extension and deposition of the Belt-Purcell Supergroup.

In the TRM, Proterozoic mafic dykes are subvertical, strike NW, and cut foliation of the Archean basement. Geochemical analyses of mafic dykes from the southern TRM and the Ruby Range (RR) by Wooden et al. (1978) identified distinct geochemical groups that they termed A, B, and C. We concur that there are three distinct groups of dykes within the TRM and RR. However, we revised the original groups based on more extensive and modern geochemical analysis. We propose A, B and C group dykes be renamed the Ramshorn Creek Group (RCG; 1552 Ma date applies), 780 Ma Gunbarrel dykes, and the yet undated Mammoth Group (MG), respectively. The very similar geochemical signatures of the RCG and MG dykes indicate deeper melting, more lithospheric contribution and different source(s) than the Gunbarrel dykes.

Paleomagnetic studies by Harlan and others (2005, 2008) yielded dual polarity magnetizations for both the RCG and MG dykes that are supported by both normal and reverse polarity baked contact tests. The definition of a 1550 Ma RCG pole from the southern TRM dykes would contribute to enhanced definition of the Laurentian apparent polar wander path during the Mesoproterozoic.

GSA Vancouver Canada October 19-22

Sm-Nd isotopic, and geochemical characterization of mafic magmatism in the Belt-Purcell and Wyoming Basins, comparing the single pulse ca. 780 Ma Gunbarrel and the multiple pulses of the Moyie-Purcell ca. 1460 Ma intraplate magmatic events.

Authors: C. Rogers, A. Mackinder, R. Ernst and B. Cousens
Department of Earth Sciences, Carleton University, Ottawa, ON

Meso- and Neoproterozoic intraplate magmatism exposed along the western side of the Laurentian margin between southern British Columbia, Canada, and the Montana-Wyoming border (MWB), USA can be divided into at least 12 geochemical groups, 9 of which group into two Large Igneous Provinces (LIPs): 8 in the ca. 1460 Ma Moyie-Purcell LIP (MPL) which consists of *i*) the Purcell lavas and other dykes and sills in the USA, *ii*) the gabbroic Moyie sills and dykes in Canada. This event is composed of tholeiitic basalts and basaltic andesites. The ca. 780 Ma Gunbarrel LIP (GL) is 1 geochemical group, extends from Yukon Territories in Canada to the MWB in the USA, although herein we focus on tholeiitic basalt to basaltic andesite dykes, sills and volcanic rocks from MWB to Idaho. We integrate new geochemical and isotopic data with previous studies to model the MPL in terms of mantle source, interactions with lithosphere (mantle and crust) and fractionation, and contrast these results with the GL.

The MPL and GL have distinct geochemical fingerprints. Some units of both LIPs exhibit a negative Nb-Ta anomaly interpreted to reflect interaction with subduction-modified lithospheric mantle. The MPL consistently plot with lower $(\text{Gd/Yb})_{\text{PM}}$ (1.5-1.0) than the GL which has a higher ratio (1.8-1.4), indicating different depths of melting above and below, but adjacent to the garnet-spinel transition. $(\text{La/Sm})_{\text{PM}}$ for the MPL (3.1-1.2) have much more variable crustal and lithospheric mantle contribution compared to the more tightly constrained slope (2.3-1.4) of the GL. Sm-Nd isotopic analyses show a single GL pulse but at least 4 distinct isotopic signatures within the 8 geochemical MPL pulses, indicating mantle melting at or near the garnet-spinel transition with contributions from crustal and lithospheric mantle sources. Samples from the northern Belt-Purcell basin have tightly constrained $\text{eNd}_{(i)} \sim (-1)$ compared to highly positive $\text{eNd}_{(i)}$ (0 to +7) values from those in the southern Belt-Purcell and Wyoming basins. GL dykes have a positive $\text{eNd}_{(i)}$ of $\sim (+1)$. There are 3 geochemical groups of dykes of unknown age within the Wyoming basin that have low $\text{eNd}_{(1460\text{Ma?})}$ of $(-8 \text{ to } 0)$, indicating greater crustal contribution or a different magmatic source.

**GSA Rocky Mountain/Cordilleran Joint Sections, 19–21 May, Bozeman,
Montana**

**Geochemical and geochronological characterization of multiple
generations of mafic magmatism in the Belt-Purcell and Wyoming Basins,
focusing on the Moyie-Purcell ca. 1460 Ma intraplate magmatic event.**

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Mesoproterozoic and Neoproterozoic intraplate magmatism that is exposed along the western side of the Laurentian margin between Kimberley BC and north of Yellowstone National Park in Wyoming can be divided into at least two Large Igneous Provinces: 1) The ca. 1460 Ma Moyie-Purcell event consists of *i)* the Purcell lavas and other dykes and sills in the USA, *ii)* the gabbroic Moyie sills of the Belt-Purcell basin and associated dykes. This magmatism is composed of tholeiitic basalts and basaltic andesites. 2) The ca. 780 Ma Gunbarrel LIP consists of dykes, sills and volcanic rocks and is also comprised of tholeiitic basalts and basaltic-andesites.

Until this research the Moyie-Purcell event has not been geochemically characterized. We are integrating our new geochemistry with that of previous studies to model and characterize the Moyie-Purcell event in terms of mantle source, interactions with lithosphere (mantle and crust) and fractionation. These results will be contrasted with those of a parallel study on the Gunbarrel event (see Mackinder, et al. this session).

The Moyie-Purcell and Gunbarrel magmatic events each have distinct geochemical fingerprints. For instance there is a difference in rare-earth slopes between the two events (*i.e.* the Moyie-Purcell event consistently plots with a shallower slope). Some units of both events exhibit a negative Nb-Ta anomaly thought to reflect interaction with subduction modified lithospheric mantle. Trace element geochemistry is consistent with petrography that indicates at most minor alteration of primary igneous petrology. From our geochemical modelling we aim to assess the origin of the magmatism: that may include one or more the following: *a)* plume(s), *b)* subduction-back arc, and/or *c)* decompressing associated with rifting.

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Geochemistry and Geochronology of ca. 1460 Ma Mafic Magmatic Nodes Of
Beneath the Laurentian Craton: Characterization of Plume and Lithosphere
Activity Below Laurentia

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Ca. 1460 Ma intraplate magmatism (mainly mafic dykes and sills) that are exposed on the eastern and western margins of Laurentia (North America) are each interpreted to be parts of a Large Igneous Province (LIP): that of the western margin (British Columbia, Montana, Idaho and Colorado), and that of eastern margin (Labrador) are herein called the Western Laurentia Node (WLN) and the Eastern Laurentia Node (ELN), respectively. LIPs are identified as intraplate magmatism that consists of large volumes of magma ($>0.1\text{Mkm}^3$) emplaced in a very short period of time ($<1\text{-}5\text{Ma}$) over a large area ($>0.1\text{Mkm}^2$). The WLN contains the gabbroic Moyie Sills of the Belt-Purcell basin that are associated with a number of mineral deposits including the world class Sullivan Pb-Zn deposit. Dykes in the Wyoming craton are also linked with the WLN. The ELN consists of the non-mineralized Michael-Shabogamo Gabbros.

The goals of this project are to geochemically and isotopically: 1) characterize and model the ca. 1460 Ma magmatism of each node in terms of source and subsequent differentiation processes, 2) develop criteria to distinguish 1460 Ma units of the WLN from intermixed swarms of different ages (including dykes of the 780 Ma Gunbarrel LIP) 3) compare the petrogenesis of the two nodes of 1460 Ma magmatism to test three hypotheses for their origin: *i)* a single superplume model, *ii)* multiple plume model or *iii)* variable tectonic setting model that include a different origin of magmatism for each node, including one or more of the following: *a)* plume, *b)* subduction-back arc, and/or *c)* intra-continental rift basins. to assess the plausibility and/or validity of each of these hypotheses the following questions will be addressed: *i)* what geochemical variations exist within and among each ca. 1460 Ma node? *ii)* What is the origin (source, tectonic setting) of the mafic-ultramafic magmatism