A petrographic, geochemical and isotopic study of the 780 Ma Gunbarrel Large Igneous
Province, western North America

By

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Abstract

On the western margin of North America lie dykes, sills and volcanic rocks which define a magmatic episode at 780 Ma. These units have been collectively termed the Gunbarrel Large Igneous Province (LIP) and share remarkably similar petrographical, geochemical and isotopic signatures indicating a single homogeneous source. The Irene and Huckleberry metavolcanic rocks of Washington State were correlated to the Gunbarrel LIP based on similar ages, but were found to not be related based on geochemistry and isotopic analysis. The timing of the Gunbarrel LIP coincides with the break-up of Rodinia, and Gunbarrel samples were compared to coeval magmatism from South China to test the “Missing Link” reconstruction model. While some mafic dykes have similar Nd isotopic ratios, no definitive correlations could be found between the different magmatic events. Finally, LIPs play a key role in housing various economic deposits and the Gunbarrel magmas show potential for being a Ni-Cu-PGE target.

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Chapter 1: Introduction

1.1 Definition and importance of LIPs

Large Igneous Provinces (LIPs) were originally categorized in the early 1990s as large, predominantly mafic, magmatic provinces with areal extents $> 100,000 \text{ km}^2$, that were generated by means other than normal seafloor spreading (Coffin and Eldholm, 1991, 1992, 1993a, 1993b, 1994). Through years of investigative studies, the definition of LIPs has expanded to cover more criteria of identification. Bryan and Ernst (2008) revised the definition of a LIP to include the following: 1) they have areal extents $> 0.1 \text{ Mkm}^2$; 2) igneous volumes (including intrusive and extrusive components) $> 0.1 \text{ Mkm}^3$; 3) intraplate tectonic setting and geochemical affinities; 4) maximum lifespans of $\sim 50 \text{ Ma}$ but with short pulses ($1\text{-}5 \text{ Ma}$) in which large proportions ($> 75\%$) of material has been emplaced. LIPs punctuate the Earth's surface every few 10^7 's of millions of years and can form in continental or oceanic settings (Ernst, 2014). They are composed mainly of mafic magmatism but can also include ultra-mafic and silicic magmas and be associated with carbonatites and kimberlites. They consist of continental flood basalts, volcanic rifted margins, oceanic plateaus, ocean basin flood basalts, as well as dykes, sills, and layered intrusions that serve as the "plumbing system" of LIPs (Coffin and Eldholm, 1994, 2001; Ernst, 2014). There is still debate on assessing the origin of LIPs and there are essentially two stances: the plume model or plume alternatives (Ernst, 2014). The plume model suggests that LIP magmas are generated from anomalously hot mantle plumes that are generated deep within the mantle, and even possibly at the core-

mantle boundary (Ernst, 2014). Other theories state that LIP magmatism may be caused by lithospheric delamination, decompression melting during rifting, impact-induced melting, back-arc rifting, and shallow melting anomalies related to plate tectonic processes to name a few (Ernst, 2014).

LIPs have become major exploration targets over the last decade as many LIPs have been associated with various economic deposits (Ernst and Jowitt, 2013; Ernst, 2014). World class Ni-Cu-Platinum Group Elements (PGEs) and Fe-Ti-V deposits are often associated with the mafic-ultramafic LIPs such as the Noril'sk-Talnakh Ni-Cu-PGE deposits of the 251 Ma Siberian Trap LIP, or the Fe-Ti-V deposits of the Panzhihua intrusions of the 258 Ma Emeishan LIP of China and Vietnam (Lightfoot and Keays, 2005; Zhou et al., 2005; Ernst, 2014). Diamonds and Rare Earth Elements (REEs) can be associated with the kimberlite and carbonatite components of some LIP, such as diamond mines associated with the 360 Ma Yakutsk LIP of eastern Siberia and the Olympic Dam Cu-Au-Ag-U-REE deposits of the 1590 Ma Gawler Range LIP of Australia (Ernst and Jowitt, 2013; Ernst, 2014).

Due to their timing and size it is believed that LIPs have initiated and facilitated supercontinent break-ups throughout Earth's history (Courtillet et al., 1999; Park et al., 1995; Li et al., 2008; Ernst, 2014). Using precise U-Pb geochronology, paleomagnetism, and radiating dykes swarms (that are a common feature among continental LIPs) as "piercing points", supercontinent reconstruction models can be constructed (Bleeker and Ernst, 2006; Ernst, 2014).

1.2 Location of the Gunbarrel LIP

The Gunbarrel LIP is located along the western margin of North America and is comprised of diabase dykes, sills and volcanic rocks that span over 2500 km from the Yukon and Northwest Territories, Canada to Montana and Wyoming, United States (Fig. 1) (Park et al., 1995; Harlan et al., 2003; Buchan et al., 2010). The areal extent of the Gunbarrel is estimated to be $\sim 200,000 \text{ km}^2$ and the NNE to NW striking intrusions form a regionally radiating pattern known as a radiating dyke swarm (Park et al., 1995; Ernst and Buchan, 1997; Harlan et al., 2003; Buchan et al., 2010, www.largeigneousprovinces.org, January, 2014). These radiating dyke swarms are a common feature among continental LIPs and are seen on many continental blocks associated with supercontinent break-ups. The radiating nature of the intrusions makes it possible to extrapolate the strike back to a common intersecting point which is inferred to be the location of the plume head center. Extrapolating the Gunbarrel dykes back leads to an inferred plume head center offshore of Vancouver Island (Fig. 1) (Park et al., 1995; Harlan et al., 2003; Ootes et al., 2008; Buchan et al., 2010). Most Gunbarrel intrusions have seen low metamorphic conditions and fluid interaction, but overall Gunbarrel rocks preserve their igneous textures and show little to no deformation in the field.

Figure 1: Map of western North America showing general location of the 780 Ma Gunbarrel LIP including dykes (red), sills (green) and volcanic rocks (black). MM- Mackenzie Mountains. Red star is inferred location of plume head center. Modified from Buchan et al., (2010).

1.3 Previous Work

Due to the great areal extent of the Gunbarrel LIP, various studies have been carried out that have generally been more local and geographically small scale in nature (Wooden et al., 1978; Armstrong et al., 1982; LeCheminant and Heaman, 1994; Harlan et al., 1997; Sandeman et al., 2007; Harlan et al., 2008; Ootes et al., 2008). Much of the research, and one of the main ways LIPs are identified, has been through extensive geochronology using U-Pb from zircon and baddeleyite, as well as Ar-Ar, K-Ar and Sm-Nd isochrons using whole rock and mineral separates. Later geochemical and paleomagnetic studies have been carried out to test the relationships between the various units in different localities (Park et al., 1995; Harlan et al., 2003; Sandeman et al., 2014)

In the Mackenzie Mountains of northern Canada, dykes and sills intrude the carbonate-quartzite succession of the Mackenzie Mountain Supergroup (Armstrong et al., 1982, Harlan et al., 2003; Ootes et al., 2008). Armstrong et al. (1982) mapped and dated two diabase sills that intruded the Tsezotene Formation of the Mackenzie Mountain Supergroup by the Rb-Sr isochron method and obtained ages of 766 +/- 24 Ma and 769 +/- 27 Ma. Later, LeCheminant and Heaman (1994) re-dated the sills using the U-Pb method on baddeleyite and obtained an age of 779 +/- 2 Ma. Harlan et al. (2003) also dated the Concajou Canyon sill which intrudes the Tsezotene Formation at 779.5 +/- 2.3 Ma, again using the U-Pb method on baddeleyite. The top of the Mackenzie Mountain Supergroup is capped by the Little Dal Basalts which were too fine grained to be dated by U-Pb methods but have been correlated with the underlying 780 Ma dykes and sills as they share similar geochemical signatures (Narbonne and Aitken, 1995; Dudás and

Lustwerk, 1997).

To the east in the Slave Craton of the Northwest Territories, Canada, massive sills and dykes make up the Hottah Sheets (Fraser, 1964; Harlan et al., 2003; Ootes et al., 2008; Buchan et al., 2010). Samples from various sills of the Hottah Sheets were dated with the U-Pb method on baddeleyite by Harlan et al. (2003) and gave a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ date of $780.0 \pm 1\text{Ma}$. Sandeman et al. (2007), Ootes et al. (2008) and Sandeman et al. (2014) performed petrographical, geochemical and isotopic studies on the Faber Sill (from the Hottah Sheets) and Tsezotene dykes, sills and Little Dal Basalts from the Mackenzie Mountains and concluded they were indeed related and part of the same igneous event.

In northern British Columbia, Canada, LeCheminant and Heaman (1994) dated NE trending dykes that intrude the Muskwa assemblage. The Muncho Lake dykes were dated at $779 \pm 2\text{Ma}$ with U-Pb in baddeleyite (LeCheminant and Heaman, 1994; Ross et al., 2001).

Moving south to the Belt-Purcell Supergroup that spans from south eastern British Columbia to northern Idaho and Montana, multiple sills intrude its sedimentary succession. Burtis et al. (2007) mapped and dated multiple sills that intrude the Belt-Purcell stratigraphy, including the Holland Lake sill at $777.5 \pm 2.5\text{Ma}$, and Turah Sill at $772 \pm 10\text{Ma}$ using the U-Pb method on zircon. The Wolf Creek Sill was also dated by Harlan et al. (1997) and gave a hornblende $^{40}\text{Ar}/^{39}\text{Ar}$ date of $776 \pm 5\text{Ma}$.

Wooden et al. (1978) originally dated the dykes in the Tobacco Root Mountains in Montana, United States, with Rb-Sr whole rock isochrons and isolated 3 groups; Group A at $1455 \pm 125\text{Ma}$, Group B at $1120 \pm 185\text{Ma}$ and Group C was 1130 ± 130

Ma. Harlan (1993) re-dated many of these intrusions and found the Group B dykes to be 769 ± 7 Ma using the $^{40}\text{Ar}/^{39}\text{Ar}$ method and Harlan et al. (2003) obtained a U-Pb discordia upper intercept from two baddeleyite fractions of 782.4 ± 4.9 Ma and suggested this to be the best emplacement age estimate for the Group B dykes.

In the Beartooth Mountains of Montana and Wyoming, United States, are multiple generations of dykes. Mueller and Rogers (1973) dated multiple dykes with Rb-Sr and K-Ar whole rock methods and found apparent emplacement ages of 2.5 Ga, 1.3 Ga and 0.75 Ga. The youngest group (0.75 Ma) includes the Christmas Lake dyke which can be traced for 16 km along trend (Harlan et al., 1997). Harlan et al. (1997) also re-dated the Christmas Lake dyke and determined a $^{40}\text{Ar}/^{39}\text{Ar}$ date of 774 ± 4 Ma, and later a U-Pb date from Harlan et al. (2003) found a matching age of 779.5 ± 3 Ma. Sandeman et al. (2014) also correlated the Christmas Lake dyke with the northern Canada Gunbarrel exposures from the Mackenzie Mountains and Hottah Sheets based on geochemistry and Nd isotopic data.

Cutting the Teton Range in Wyoming, United States, is the Mount Moran dyke which was dated with the K-Ar whole rock method by Reed and Zartman (1973). Three different ages were given from different parts of the dyke. A whole rock chill margin gave an age of 775 ± 50 Ma with plagioclases from near the dyke center giving ages of 583 ± 8 Ma and 396 ± 6 Ma, respectively (Reed and Zartman, 1973; Harlan et al. 1997). Harlan et al. (1997) re-dated the Mount Moran dyke by the $^{40}\text{Ar}/^{39}\text{Ar}$ method and found it to be $765 \text{ Ma} \pm 5$ Ma. Harlan et al. (1997) and Harlan et al. (2008) performed a paleomagnetic study on the Mount Moran dyke, Christmas Lake dyke in the Beartooth Mountains, the Wolf Creek Sill which intrudes the Belt-Purcell Supergroup and multiple

dykes in the Tobacco Root Mountains. These studies showed that the intrusions from the Beartooth Mountains, Teton Range and Tobacco Root Mountains have similar paleomagnetic directions and virtual geomagnetic poles (VGPs) which plot in the western Pacific Ocean north of present day New Guinea (Harlan et al., 2008).

Park et al. (1995) first proposed a link between the NNE and NW trending intrusions along the western margin of North America based on matching 780 Ma age dates and the radiating pattern. Later authors have strengthened that link with paleomagnetism and geochemistry studies between intrusions in similar localities and across the margin of North America.

Other small volcanic packages proposed to be part of the Gunbarrel LIP event include the Irene and Huckleberry (I&H) metavolcanic rocks that are located in northeastern Washington State. Campbell and Loofbourow (1962) and Devlin et al. (1985, 1988) described and mapped the I&H metavolcanic rocks as fine grained, massive and often amygdaloidal metabasalts. Stoffel et al. (1991) also mapped the eastern quadrant of Washington State, including the Irene and Huckleberry metavolcanic rocks. The metavolcanic rocks were originally dated by Miller et al. (1973) using the K-Ar method on whole rock and mineral separates and proposed eruption ages between 827 and 918 Ma. Devlin et al. (1985, 1988) realized that the K-Ar and Rb-Sr isotopic systems were disturbed, likely due to metamorphism, and re-dated the I&H metavolcanic rocks with the Sm-Nd method. Devlin et al. (1988) obtained a Sm-Nd isochron with one whole rock sample and two pyroxene separates that gave a date of 762 $\pm$ 44 Ma. Geochemistry for I&H metavolcanic rocks was determined by Devlin et al. (1985) and found to be consistent with rift volcanism. Due to their similar age and close vicinity to Gunbarrel

intrusions, the I&H metavolcanic rocks were thought to be part of the Gunbarrel LIP as potential remnant continental flood basalts (Harlan et al., 2003).

1.4 Purpose of Study

While there have been a variety of geochronological and paleomagnetic studies which have identified components of the Gunbarrel LIP (Wooden et al., 1978; Armstrong et al., 1982; LeCheminant and Heaman, 1994; Park et al., 1995; Harlan et al., 1997, Harlan et al., 2003; Burtis et al., 2007; Harlan et al., 2008), only a few petrographical and geochemical studies have been conducted within local geographical areas (Wooden et al., 1978; Sandeman et al., 2007; Ootes et al., 2008). Apart from limited long-distance comparison in Sandeman et al. (2014), there have been few regionally extensive studies to compare the intrusive and extrusive components of the Gunbarrel LIP not only in age, but in geochemistry and isotopic signature.

This study has multiple purposes. The first is to compare the petrography, geochemistry and isotopic compositions of intrusions found in the various localities in order to identify if and how the intrusions are related to one another. Secondly, mantle source(s) and magma evolution will also be characterized to see if there are one or multiple sources of melt generation and whether the magma feeding the intrusions underwent similar or different evolutionary paths. Thirdly, the I&H metavolcanic rocks of northeastern Washington State and south central British Columbia have been correlated to the Gunbarrel LIP based on an imprecise Sm-Nd whole rock and mineral isochron. This study will also complete a petrographical, geochemical and isotopic

analysis of the I&H metavolcanic rocks to determine whether they were fed from nearby Gunbarrel intrusions and are, in fact, related to the Gunbarrel LIP. Fourth, many LIPs have world class economic deposits associated with them, including the Ni-Cu-PGE Muskox layered intrusion of the 1270 Ma Mackenzie LIP of the N.W.T., Canada, or Ni-Cu-PGE Noril'sk deposits of the 250 Ma Siberian Traps (Ernst and Jowitt, 2013). Ni-Cu-PGE analyses will be completed on selected Gunbarrel intrusions to test the economic potential of the Gunbarrel LIP. Finally, LIPs have been associated with the break-up of supercontinents throughout time. The timing of the Gunbarrel LIP coincides with the breakup of the Proterozoic supercontinent Rodinia (Park et al., 1995; Li et al., 1995; Harlan et al., 2003; Li et al., 2008; Evans, 2009). There are multiple models and thoughts regarding the assembly of Rodinia, one of which places South China in between Laurentia and Australia during that time (Li et al., 1995; Li et al., 2008). The geochemical and isotopic “fingerprint” of the Gunbarrel LIP obtained through this study will be compared to coeval magmatism on the South China Block to see if there are any petrogenetic linkages between the different events.

Chapter 2: Regional Geology

2.1: General Geology

Gunbarrel dykes and sills, which have been dated using various methods and by various authors, are found along the western margin of North America and intrude a variety of localities and country rocks (Park et al., 1995; Buchan and Ernst 2004, 2013). Herein are brief regional descriptions of the different localities where samples or data have been obtained through field work and published data.

2.1.1 Mackenzie Mountains, Yukon-N.W.T., Canada

In the Mackenzie Mountains, Northwest Territories and Yukon Territory, Canada, the Concajou Canyon Sill, Tsezotene sills and rare dykes intrude the Mackenzie Mountain Supergroup (Narbonne and Aitken, 1995, Ootes et al., 2008). The Mackenzie Mountains Supergroup is an epicratonic platform sequence of 1080 Ma age and consists mainly of shallow water siliciclastic and carbonate rocks (Jefferson and Parish, 1988; Narbonne and Aitken, 1995). The 4-6 km succession is divided into the H1 unit at the base followed by Tsezotene Formation, Katherine Group and Little Dal Group (Jefferson and Parish, 1988; Narbonne and Aitken, 1995). The Mackenzie Mountain Supergroup is then overlain by the Coates Lake Group in the east and the Windermere Supergroup in the west (Jefferson and Parish, 1988; Ootes et al., 2008). The N-NE trending Tsezotene dykes and sills intrude all units of the Mackenzie Mountain Supergroup and the Little Dal Basalts lie stratigraphically above the intrusions at the top of the Little Dal Group (Park

et al., 1995; Narbonne and Aitken, 1995; Ootes et al., 2008; Buchan et al., 2010). The Little Dal Basalts have been correlated to the intrusions based on stratigraphy and geochemical similarities (Ootes et al., 2008). The Tsezotene sills range from 10-50 m in thickness and outcrop for over 250 km along strike, and the Tsezotene dykes are up to 60 m wide (Ootes et al., 2008).

2.1.2 Wopmay Orogen, N.W.T., Canada

Further east in the Slave craton are the Hottah Sheets, which consist of gently dipping, NE striking/trending dykes and sills that intrude the Archean to Paleoproterozoic rocks of the Wopmay Orogen (Fraser, 1964; Harlan et al., 2003; Sandeman et al., 2007; Buchan et al., 2010). The Wopmay orogeny is a north trending, 1.95-1.84 Ga orogenic belt in the western part of the Slave craton and consists of three constituents 1) the Coronation Margin 2) the Great Bear Magmatic zone and 3) the 2.4-2.0 Ga Hottah Terrane (Ault et al., 2009). The Coronation Margin consists of rift-related volcanic rocks and sediments overlain by siliciclastic and carbonate rocks. The Hottah Terrane consists of sedimentary and igneous rocks that have been metamorphosed to amphibolite facies that are then overlain by 1.9 Ga basaltic to intermediate volcanic rocks (Ault et al., 2009). Finally, the Great Bear Magmatic Zone represents a continental arc and comprises of calc-alkaline intrusive and extrusive rocks of 1.88-1.84 Ga age (Ault et al., 2009). The Gunbarrel, Calder, Faber Lake, Margaret and Hardisty Sheets are composed of shallow-dipping sills ranging from a few kilometers to >2 km in width and 10-200m in thickness and are collectively termed the Hottah Sheets (Fraser, 1964; Harlan et al., 2003; Sandeman et al., 2007).

2.1.3 Canadian Rockies, British Columbia, Canada

In northeastern British Columbia, Canada, the Muncho Lake dykes intrude strata of the Muskwa assemblage which is situated in the Canadian Rockies (Ross et al., 2001). The Muskwa assemblage is a 6 km-thick succession of relatively unmetamorphosed fine grained dolostones, limestones, sandstones, calcareous mudstones and mudstones (Ross et al., 2001). U-Pb dates and Sm-Nd data from units in the assemblage place it in Succession A (ca. 1700-1100 Ma) of the Precambrian stratigraphic subdivisions of Young et al. (1979). In the east the Muskwa assemblage is unconformably overlain by strata of Cambrian through Devonian age, while in the west the assemblage and 25-30 m wide Muncho Lake dykes are unconformably overlain by the Windermere Supergroup (Ross et al., 2001).

2.1.4 Belt-Purcell Supergroup, Idaho-Montana, USA

The Mesoproterozoic Belt-Purcell Supergroup is a 20 km-thick sedimentary succession of fluvial-alluvial to subaqueous lacustrine deposits that cover areas in British Columbia, Canada to Washington, Idaho and Montana, United States (Sears, 2007b). Multiple sills intrude the sedimentary strata of the Belt-Purcell Supergroup in northern Idaho and northwestern Montana. These sills intrude Archean basement, quartzite and turbidites of the Lower Belt-Prichard Formations, to the argillite sandstones of the Garnet Range Formation and are unconformably overlain by the Cambrian Flathead Sandstone (Harlan et al., 1997; Burtis et al., 2007; Sears, 2007b). The sill collected in this study is vertically dipping, intrudes the feldspathic sandstones of the Mount Shields Formation

and is truncated by the Blackfoot Thrust Fault (Winston and Sears, 2013).

2.1.5 Tobacco Root Mountains, Montana, USA

The Tobacco Root Mountains of south-central Montana host multiple, sub-parallel, northwest trending dykes dated at 780 Ma and ~1460 Ma (Harlan et al., 1997; Harlan et al., 2008). These dykes intrude Precambrian basement-cored uplifts at the intersection of two Laramide age tectonic provinces: the Rocky Mountain uplifts and Helena salient of Cordilleran thrust (Harlan et al., 2008). The basement rocks in the Tobacco Root Mountains are composed of three distinct suites which include quartzofeldspathic gneisses and metamorphosed supracrustal rocks of the Indian Creek and Pony-Middle Mountain Metamorphic suites, and amphibolites with lesser quartzites and aluminous schists of the Sphuler Peak Metamorphic suite (Harlan et al., 2008). The Tobacco Root Mountain dykes range from 5 m to >75 m in width.

2.1.6 Beartooth Mountains, Montana-Wyoming, USA

The Beartooth Mountains of south-central Montana and northwestern Wyoming host multiple generations of dykes that generally trend northwest, with some trending northeast, that intrude the Archean crystalline basement that makes up the cored uplifts of the mountains (Harlan et al., 1997). The Christmas Lake dyke is a 10-15 m wide dyke that can be traced up to 16 km along trend and is one of the main Gunbarrel intrusions in the Beartooth Mountains (Harlan et al., 1997).

2.1.7 Teton Range, Wyoming, USA

In northwestern Wyoming, Gunbarrel dykes intrude deformed gneisses, amphibolites, and discordant plutons of the Archean crystalline basement which makes up the Teton Range (Harlan et al., 1997). The Tetons are part of a Laramide-aged structural block which has been deformed by north-striking normal faults of Pliocene age along its eastern edge (Harlan et al., 1997). The most spectacular of these northwest trending intrusions is the Mount Moran dyke, which is 30 m wide and has over 1500 m of vertical exposure (Reed and Zartman, 1973; Harlan et al., 1997).

2.1.8 Northeast Washington, USA

In northeastern Washington, USA and south central British Columbia, Canada, are the Irene and Huckleberry (I&H) metavolcanic rocks. Field work for this study focused on the Washington State side. The Irene and Huckleberry metavolcanic rocks are part of the Huckleberry Formation, which contains two members: the lower conglomerate member and upper greenstone member which extend from the northern end of the Magnesite Belt to the southward vicinity of Deer Trail Monitor (Devlin et al., 1985). The lower unit is a schistose conglomerate composed of angular to subrounded clasts of slate, phyllite, argillite, limestone, dolomite and quartzite, and range in size of a few centimeters to several inches. Sorting is poor but alignment of clasts is striking (Devlin et al., 1985, 1988). The greenstone member is resistant to weathering and outcrops are numerous. Bennett (1941) and Campbell and Loofbourow (1962) estimated a thickness of 3000 ft (915 m) for the unit, although attitudes and elevations are hard to distinguish. The greenstone gradually thins to the north and south. Although many lithology types have been identified, the majority of the unit appears to consist of fine grained and massive

metabasalts. None of the units can be traced laterally and flow banding has not been recognized. The greenstone member likely reflects an accumulation of basaltic flows (Devlin et al., 1985, 1988).

Chapter 3: Methods

3.1 Field Methods

Two consecutive field seasons were conducted in the summers of 2012 and 2013. From July 11th - July 14th, 2012, samples were collected from the Tobacco Root Mountains (TRM), Montana corresponding to Wooden et al. (1978) Group B dykes. Using road maps from Wooden et al. (1978) and GPS coordinates from Harlan et al. (2008) samples were located on roadside outcrops and through short traverses. The Group B dykes represent the 780 Ma Gunbarrel LIP. Samples were collected from dyke centers and margins where available. In poor exposures, samples were collected from float and scree slopes with clear indications of belonging to the dyke outcrops. Sample locations are presented in Figure 2.

From July 15th – July 17th, 2012, samples were collected from the Irene and Huckleberry metavolcanic rocks in northeastern Washington, USA. Sample sites corresponded to the Zmv unit of Stoffel et al. (1991) and were located using the geological map of northeastern Washington from Stoffel et al. (1991) and a road map of Washington State. Samples were collected from outcrops and float where exposures were poor or insufficient. Sample locations are presented in Figure 3. Samples collected from this first field season are listed as 12-MT-01 to 12-MT-27.

From July 6th – July 31st, 2013, samples were collected from the Beartooth Mountains, Tobacco Root Mountains, Wolf Creek Sill and a sill that intrudes the Mount Shields Formation (likely linked to the Turah Sill from Burtis et al., (2007)) in the Belt-

Purcell Supergroup, Montana. In the Beartooth Mountains, the 780 Ma Christmas Lake dyke was located through satellite images, field guides and generalized geological map from Harlan et al. (1997). Sample locations are presented in Figure 4. In northern Montana, samples were collected from the Wolf Creek Sill which was located by aerial photos and geological maps from papers with GPS coordinates. Sample locations are presented in Figure 5. The Tobacco Root Mountain dykes were revisited and more samples were collected and locations are presented in Figure 2. During a field trip for the Belt Symposium V and 34th annual Tobacco Root Geological Society meeting, a sample from a sill that intrudes the Mount Shields Formation in the Belt Basin was collected. Burtis et al. (2007) dated a sill in the area which he termed the Turah Sill at 772 +/- 10 Ma with U-Pb in zircons which is ~6 km north of the samples taken from the Mount Shields Formation. It is likely that the sample obtained during the field trip is part of the Turah Sill. The Turah sill is situated in the Blackfoot thrust fault and samples were collected from the fault scarp and a less deformed area along the sill. Sample numbers from this field season are listed as 13-AM-01 to 13-AM-26. All samples obtained during the second field season were also tested with a hand held magnetic susceptibility metre to further categorize the Gunbarrel intrusions. Measurements are listed in Table 1.

Three samples from the Muncho Lake dyke, and two samples from the Mount Moran dyke were provided by Dr. Anthony LeCheminant and samples from Tobacco Root Mountain dykes TR-45 and TR-62 were provide by Dr. Steven Harlan. Data for Tsezotene dykes, sills, Little Dal Basalts and Hottah Sheets were obtained from Ootes et al. (2008) and Ernst and Buchan (2010). Most of these additional samples already had high quality full spectrum geochemical analyses and were not reanalyzed for this study.

At all localities GPS coordinates using NAD27 were recorded. All sample coordinates are listed in Appendix B.

Figure 2: Simplified map of the Tobacco Root Mountains with the sample locations. Green and blue dykes correspond to Wooden et al. (1978) Group A and B dykes respectively and red dykes correspond to Harlan et al. (2008) R magnetization. Modified from Harlan et al. (2008).

Figure 3: Simplified map of northeastern Washington State showing location of the Monk Formation (Zmm), Irene and Huckleberry Formation's greenstone member (Zmv) and conglomerate member (Zcg) and sample locations. Modified from Stoffel et al. (1991).

- Paleozoic sedimentary rock
- Middle and Late Proterozoic dikes
- Archean metadolerite dikes
- Archean crystalline basement
- Lake
- BT-8 Paleomagnetic site
- Sample locations

Figure 4: Simplified geological map showing location of Archean and Proterozoic dykes in the Beartooth Mountains and sample locations for the Christmas Lake dyke. Modified from Harlan et al. (1997).

EXPLANATION

	Tertiary-Cretaceous dike		Late Proterozoic gabbro sill
	Cretaceous intrusions		Middle Proterozoic-Empire and Spokane Formations (undivided)
	Upper Cretaceous and Paleocene sedimentary strata		Middle Proterozoic Empire Formation
	Upper Cretaceous Two Medicine Formation		Thrust fault - teeth on upper plate
	Upper Cretaceous sandstone and shale		Sample location
	Paleozoic sedimentary strata		

Figure 5: Simplified geological map showing location of the Wolf Creek Sill in northwest Montana and sample location. Modified from Harlan et al. (1997).

3.2 Petrography

All samples collected were cut and made into either standard or polished thin sections. Polished thin sections were used for mineral analysis by Electron Microprobe. Samples from the Mount Moran and Muncho Lake dykes provided by Dr. LeCheminant were also made into thin sections. Thin sections were also provided by Dr. Steven Harlan for samples TR-45 and TR-62.

Thin section preparation involved cutting hand samples with a diamond tipped rock saw into 1cm thick slabs of varying lengths. Three slabs were cut, one for thin section preparation and two were crushed for geochemical analysis (see below). Standard thin section pucks (27 mm x 46 mm) were cut with a trim saw. Pucks were then smoothed on a rock polisher using a series of 300 and 600 grit sand. Thirty five thin sections were prepared and examined using a petrographic microscope in both plain and cross polarized light on 4x, 10x and 20x magnification. Petrographic analyses are summarized in section 4.3 and Appendix C.

3.3 Major, trace element and isotope geochemistry powder preparation

Two slabs for each sample were cut from hand samples using a diamond tip rock saw. Edges of the slabs were cut using a trim saw to remove all weathered surfaces. Slabs were then polished with a rock polisher using 300 grit sand to remove saw marks and contaminants potentially left from the rock saws. Slabs were washed, dried and then wrapped in a plastic bag and hit with a hammer to break the slabs into small pieces.

Those pieces were then crushed using a steel-plated Braun Chipmunk. To avoid cross contamination from samples, before and after each sample, the Chipmunk was cleaned using a steel brush, air gun and wiped down with ethanol. Also, each time the collection trap was washed with soap and water, air dried and wiped down with ethanol. A small fraction of each sample would be run through the Chipmunk and then disposed of as a pre-contamination step. The Braun Chipmunk would render rocks fragments <1mm to 1 cm in size. Samples were then powdered using a Rock Labs ringmill. Samples 12-MT-01 to 12-MT-27, 91LAAT2-1, 91LAAT2-2, 91LAAT2-3, 94LAAT1-2A, and 94LAAT003-1A were powdered using a chrome-steel head for approximately 45 seconds on high speed until a very fine powder was achieved. Samples 13-AM-01 to 13-AM-26B were crushed using the Braun Chipmunk and then passed through a 2 mm mesh separator. The separator was cleaned before and in between samples with soap and water, air dried and wiped down with ethanol. A small fraction of each sample was run through the separator to coat it and then disposed as a pre-contamination run. The <2mm crushed material was then powdered using an agate head Ringmill on slow speed for approximately 3 minutes until a very fine powder was achieved. The ring mill components were cleaned before and in between each sample. Components were washed with soap and water, air dried and wiped down with ethanol. A small portion of crushed material was first added and then disposed of as a pre-contamination run. Quartz sand was run through the ring mill to clean it at the start of use, after every ~5 samples, and at the end of use. The steel Braun Chipmunk crusher and steel ring mill head likely added small amounts of Fe and Cr to the samples, however, comparisons with Gunbarrel intrusions powdered in the agate ringmill, which should have negligible contamination, are comparable and thus it is

thought that the Fe and Cr contamination are insignificant to this study. Two ~30 ml vials were filled with the powder material for each sample. One vial was sent to the Ontario Geological Survey (OGS), Sudbury, Ontario, for major element oxide and trace element geochemistry by XRF and ICP-MS respectively, and one vial stayed at Carleton University for isotope geochemistry analysis. Six selected samples (12-MT-01, 91LAAT2-2, 94LAAT1-2A, 13-AM-01, 13-AM-11 and 13-AM-26B) had a third vial filled and sent to ActLabs for Platinum Group Element (PGE) analysis.

3.4 Major and trace element geochemistry

Thirty one powdered samples were sent to the Ontario Geological Survey's Geo Labs in Sudbury, Ontario and major elements were analysed by x-ray fluorescence (XRF) techniques. The powdered samples are first run for loss on ignition (LOI) in an oven at 100°C under nitrogen atmosphere and then 1000°C under oxygen atmosphere until a constant weight is maintained to yield lost on ignition (LOI) data. The sample is then fused with a borate flux to produce a glass bead. The glass bead is then analysed using an x-ray fluorescent spectrometer where the sample is hit with an x-ray incident beam exciting the atoms in the sample causing them to release energy spectra specific to each element. Intensities of the different spectra are proportional to element abundance in the sample and converted to oxide wt%. SiO_2 , Al_2O_3 , CaO , FeO^T , K_2O , MgO , MnO , Na_2O , P_2O_5 , TiO_2 were determined. The thirty one samples were run with an internal standard to determine precision and accuracy of results. Data and standards are listed in Appendix D.

Trace elements were determined for thirty one samples by inductively coupled plasma mass spectrometry (ICP-MS) at the Ontario Geological Survey's GeoLabs in Sudbury, Ontario. Powdered samples were dissolved in an open vessel and calibrated using a certified reference material (CRM). The samples were run with an internal standard to ensure precision of results. In the ICP-MS, samples are introduced to argon plasma that dissociates the molecules and creates charged atoms. These ions then passed through magnetic fields and filtered/separated based on mass. When the ions hit a detection plate the energy becomes an electronic pulse which is amplified and the intensities are compared to a standard curve and concentrations are determined. Data and standards are listed in Appendix D. In some cases, Ti for samples measured using ICP-MS exceeded the upper detection limit (UDL). In these circumstances, Ti concentrations in ppm were calculated using the TiO₂ wt% determined by XRF analysis by the equation

$$\text{Ti (ppm)} = \text{TiO}_2 \text{ wt\%} \times 0.5993\% \text{ (percent of Ti in TiO}_2\text{)} \times 10000.$$

All iron was presented as FeO^T. Any data that was gathered from other sources in which iron was reported as Fe₂O₃^T was converted to FeO^T by the equation

$$\text{FeO}^{\text{T}} \text{wt\%} = \text{Fe}_2\text{O}_3^{\text{T}} \text{wt\%} / 1.1111 \text{ (weight ratio between Fe}_2\text{O}_3 \text{ and FeO)}$$

It was noted for the Irene and Huckleberry (I&H) metavolcanic rocks that all samples had extremely low Zr concentrations after analysis was done with ICP-MS.

Therefore, four representative samples: 12-MT-19, 12-MT-22, 12-MT-24 and 12-MT-25 and internal standard 10-LT-05 were sent to ALS Laboratories in North Vancouver, BC, and reanalyzed for trace elements by ICP-MS following sintering with a flux and a multiple acid dissolution. The four samples were chosen as representative samples with the largest to smallest negative Zr anomalies. It was found that Zr and many other light to heavy rare earth elements (LREE - HREEs) were significantly different in abundances in all re-analyzed samples from ALS. 12-MT-19 and 12-MT-25 showed the most consistency in original values vs. re-analyzed samples with many trace element abundances being within 95% of each other and some element abundances within 90% or <90%. 12-MT-22 and 12-MT-24 had many more trace element abundances lower than 95% confidence between the original and reanalysed samples. Elements such as Er, Hf, Ho, Li, Lu, Th, Tm, V, U, Yb and Zr showed the largest differences with samples being <90% within confidence. This inconsistency may be due to a number of reasons. Technician error may have played a role including variable powder size or inconsistent digestion. Mineral phases may not have been dissolving completely in the ICP-MS dissolution process done at the OGS but likely did in the ALS sintering and dissolution method. Due to this variability between trace element abundances from the different laboratories, only the 4 re-analyzed samples of I&H metavolcanic rocks will be used in geochemical plots. This inconsistency only appears to have affected the volcanic rocks and not the Gunbarrel intrusions as geochemical analyses for intrusions in this study compare extremely well with data from other studies and the internal standard was run with all the samples and came back with good results. Data and standards are listed in Appendix D.

3.5 Platinum Group Element (PGE) analysis

Six samples were sent to ActLabs, Ancaster, ON, for platinum group element (PGE) analyses determined by lead sulphide fire assay ICP-MS. The procedure is as follows: the sample is mixed with a borate flux and Ag as a collector to concentrate the desired elements. Then the mixture is placed in a clay crucible and heated at steps of 850°C, 950°C and 1060°C for 60 minutes. The molten mixture of lighter elements is discarded, leaving a Pb button, which is then placed in a preheated crucible at 950°C that absorbs the Pb, leaving a Ag, Au and PGE bead. The bead is then digested at 95°C in HCl+HNO₃, cooled for 2 hours and then analysed using an ICP-MS. Au, Pt, and Pd abundances were determined. These data were combined with 8 PGE analysis from (Ernst and Buchan, 2010) performed on samples from the Hottah Sheets in the Wopmay Orogen, northern Canada. Data are presented in Table 3.

3.6 Electron Probe Micro-Analysis (EPMA)

Minerals in selected polished thin sections from the different localities were analysed using a Cameca Cambax MBX electron microprobe at Carleton University. Carbon-coated thin sections were placed in a vacuum sample chamber and selected mineral phases were bombarded with a focused electron beam. The electron beam excites electrons of the elements in the mineral phase causing them to “jump” orbital fields and upon falling back into original orbital fields secondary electrons and x-rays are emitted which have a characteristic energy for each element. Multiple detectors collect the

secondary x-rays from the sample. The Cameca PAP matrix correction program converted the raw x-ray data into major element oxide weight%. Natural and synthetic phases were used as standards. Digital back-scatter electron (BSE) images were taken with an Electron Optic Services digital imaging system. Mineral data are presented in Appendix E.

3.7 Geothermometry and oxybarometry

Mineral chemistry data from coexisting ilmenite-titano magnetite phases in selected thin section were analysed using the electron microprobe discussed in 3.6. Mineral chemistry data for ilmenite-magnetite pairs were input to the ILMAT: A magnetite-ilmenite geothermobarometry program (version 1.20) spreadsheet constructed by Luc D. Lepage at Queens University, Kingston, Ontario. It utilizes the geothermometer and oxybarometer calculation methods of Powell and Powell (1977), Spencer and Lindsley (1981) and Anderson and Lindsley (1985), giving individual temperatures and oxygen fugacities from each method as well as an average temperature and oxygen fugacity for all methods. Data and values are presented in Table 2.

3.8 Isotope Geochemistry

Twenty four samples were analysed for isotopic composition. Gunbarrel intrusions and 12-MT-17, 12-MT-20 and 12-MT-21 (I&H metavolcanic rocks) were analysed for Pb, Sr, and Nd isotopic compositions. The rest of the I&H metavolcanic

rocks were solely analysed for Nd isotopic ratios. All forms of preparation and analysis were conducted at the Isotope Geochemistry and Geochronology Research Center (IGGRC) at Carleton University, Ottawa, Canada. Due to the age of Gunbarrel rocks, samples needed to be spiked for Nd and Sm (^{148}Nd - ^{149}Sm) so precise measurements of Nd and Sm concentrations could be calculated. The required powder weight and spike weight for each sample was calculated using an Excel spreadsheet based on the concentration (ppm) of Nd in the sample from the ICP-MS analysis. Powdered sample and spike were then added to a 15 ml Teflon screw-cap vial and dissolved using 2-3 ml of 50% HF:16N HNO_3 , 1 ml of 7N HNO_3 , and 2 ml 6N HCL. Samples were dried down in between each step.

For Pb analysis, the samples needed to run in two passes through 200-400 mesh AG1-X8 anion resin columns. For the first pass the sample was taken up in 3 ml of HBr, centrifuged and run through 0.6 ml of anion resin. To start anion columns were washed twice with 2 ml of 6N HCl, once with 0.5 ml ultra-pure H_2O , and twice with 2 ml 1N HBr. Sample was then added and the columns were washed twice with 2 ml 1N HBr, 0.5 ml 1.5N HCl and then Pb was stripped from the column with 5 ml of 6N HCl that was collected in a clean snap cap beaker, dried down, and the residue was then taken up in 1 ml 1N HBr. The first 2 ml of HBr was collected for Sr and Nd isotopes. The 2 ml Sr-REE HBr solution was dried down and a ~0.5 ml of 7N HNO_3 was added to drive off bromides and re-dissolve the sample. The solution was dried down and taken up in 1.5 ml 2.5N HCl.

For the second pass for Pb, 0.2 ml of anion resin was added to the columns and washed with ultra-pure H_2O , twice with 1 ml 6N HCl, once with 0.5 ml ultra-pure H_2O ,

and twice with 1 ml 1N HBr. The sample taken up in 2.5N HCl was then added to the column and washed twice with 1 ml 1N HBr, once with 0.2 ml 1.5N HCl and 3 ml of 6N HCl was added to strip Pb and was dried down.

For Sr separation, samples were run through Dowex 50-X8 cation resin columns. Dissolved samples were centrifuged and added to the columns. The sides of the columns were then washed with ~1 ml of 2.5N HCl to ensure the entire sample had collected at the resin. 18 ml of 2.5N HCl was then added to the columns to drain through and then 6 ml of 2.5N HCl was collected in snap cap beakers with the Sr-fraction and dried down. Then 3.5 ml of 6N HCl was added to the columns to drain through and then 9ml of 6N HCl was added to strip the REE and was dried down for the Sm-Nd isotopes (next paragraph). When dry, 0.5 ml of 0.26N HCl was then added to the REE residue and left at room temperature for at least 30 minutes.

For Sm-Nd separation, samples were run through Eichrom Nd columns. The dissolved sample (described above) was added to the columns and the columns were washed with 6.5 ml of 0.26 N HCl in 0.5 ml stages. 4.5 ml of 0.26 N HCl was added to strip Nd, collected and dried down. The columns were then washed with 2 ml of 0.5N HCl in 0.5ml stages. 4 ml of 0.5 N HCl was then added to strip Sm, collected and dried down.

All columns were cleaned after use and blanks were run through the columns alongside samples to ensure contamination was negligible.

Each isotope separation and blanks were analysed at Carleton University on a Triton Multi-collector Thermal Ionization Mass Spectrometer (MC-TIMS). All isotope residues were taken up in 4 μ l of H₃PO₄. 2 μ l of solution was loaded onto a rhenium

single filament with silica gel for Pb and tantalum single filament for Sr, and one side of a double rhenium filament assembly for Sm and Nd. 3 μ l of silica gel was also added to the Pb filaments. The filaments were then heated using a current between 1.9 and 2.1 Amperes to dry down the sample. Filaments were then loaded onto a 21-position sample wheel and isotopic ratios were analysed using the MC-TIMS. Sm and Nd concentrations, as well as initial Nd isotopic ratios, epsilon values, and depleted mantle model ages were calculated using an offline Excel program written by George Tilton and Brian Cousens. Initial Pb and Sr ratios were calculated using Rb, Sr, Th, U, and Pb concentrations from the ICP-MS data. All samples were corrected for post-crystallization decay using an age of 780 Ma.

Chapter 4: Field and petrography descriptions, mineral chemistry, geothermometry and oxybarometry

4.1 Introduction

This chapter is dedicated to the physical description of the Gunbarrel intrusions and Irene and Huckleberry (I&H) metavolcanic rocks collected in this study, supplemented with descriptions from previous work done on Gunbarrel intrusions and the Little Dal Basalts by other authors. Field and petrographic linkages and or differences can help determine the relationship between the various units as well as their mode of formation and emplacement/eruption histories.

4.2 Field descriptions

Gunbarrel dykes and sills were commonly sampled at large roadside outcrops where samples were collected from the freshest material (Fig. 6a). Gunbarrel dykes occur as 10-70 meter-wide, sub-vertical intrusions. The Gunbarrel sills are 10-50 meters thick. The dykes and sills are often highly fractured and show a rusty-red weathering colour in outcrop. Contacts with country rocks are often sharp where they could be observed, with no country rock xenoliths appearing within the margins (Fig. 6b). Gunbarrel intrusions are predominantly medium-grained plagioclase, pyroxene, Fe-Ti oxide diabase with fine grained chill margins (Fig. 6c). Some veining of calcite and quartz are present in the fractures of some outcrops. Magnetic susceptibility meter readings gave ranges of 0.8-2.6 $\times 10^{-3}$ SI, which were much higher than surrounding country rocks, likely due to a higher

presence of magnetite in samples (Table 1). Harlan et al. (2003), Sandeman et al. (2007) and Ootes et al. (2008) describe the intrusions from northern Canada (the Hottah Sheets and the Mackenzie Mountain intrusions) as having the same mineral assemblage as listed above but with medium to coarse grained members. Local low grade metamorphic conditions have affected some samples but overall Gunbarrel intrusions in northern Canada are relatively pristine. Dykes and sills from the Mackenzie Mountains and Wopmay Orogen range from 5 to over 100 m in thickness/width (Sandeman et al., 2007; Ootes et al., 2008).

Table 1: Magnetic Susceptibility readings across outcrops for Gunbarrel intrusions

Sample	Location	Magnetic Susceptibility Readings $\times 10^{-3}$ SI						Average
13-AM-01	Beartooth Mtns	0.68	2.25	2.14	2.98	1.34	0.783	1.70
13-AM-03	Beartooth Mtns	1.57	2.33	2.76	2.62	1.36		2.13
13-AM-11	Wolf Creek Sill	1.24	1.34	0.96	1.43	1.25	1.5	1.29
13-AM-12	Wolf Creek Sill	0.146	1.19	0.645	0.598	1.34	0.983	0.82
13-AM-13	TRM	2.48	2.64	2.79	2.41			2.58
13-AM-14	TRM	1.98	1.51	1.89	2.34	1.88		1.92
13-AM-15	TRM	2.73	1.25	1.78	2.33	1.43	1.29	1.80

TRM – Tobacco Root Mountains, Mtns – Mountains

The I&H metavolcanic rocks of Washington State were mapped by Campbell and Loofbourow (1962). They are large flow units that are resistant to weathering and have numerous large outcrops. It is estimated that the cumulative maximum thickness of the flows is 3000 ft (~915 m) thick, with the unit thinning to the north and south (Campbell and Loofbourow, 1962). The metavolcanic rocks were observed as large, roadside outcrops and some smaller, bulbous outcrops (Fig. 7a, b). The I&H metavolcanic rocks observed in the field displayed at least three lithological units which were greenstone,

phyllitic and brecciated tuff units. The greenstone member appears dark green in outcrops. It is fine grained with remnant phenocrysts or amygdules in filled with chlorite, quartz, epidote or calcite (Fig. 7c). In thin section they are mostly porphyritic metabasalts. There are large flows 30 meters thick and some smaller-scale flows that are largely covered by overburden and growth. Secondary epidote veining and calcite veins are present in many outcrops (Fig. 7d). The second member was a fine grained, greyish-green phyllite and the third was a brecciated tuff composed of mm – cm scale clasts of fine grained basalt and what appears to be fine grained argillite (Fig. 7e). Samples from the I&H metavolcanic rocks were taken from the freshest material at the surface. Magnetic susceptibility readings on some revisited outcrops in the summer of 2013 showed uniformly low magnetic susceptibility readings of $0.031 - 0.617 \times 10^{-3}$ SI.

Figure 6: A) Outcrop photo of a typical dyke in the Tobacco Root Mountains. Location of 12-MT-02. B) Photo of typical sharp contact of Gunbarrel dykes (dark grey-left) and country rock (light beige-right) often seen in the Tobacco Root Mountains. Location of 13-AM-14. C) Photo of typical Gunbarrel intrusion showing uniform, medium grained diabase with rusty red weathering on outer surface. Sample 13-AM-11 from the Wolf Creek Sill.

Figure 7: A) large roadside flow outcrops. Sample locality of 12-MT-18. B) Smaller bulbous outcrop. Sample location of 12-MT-27. C) Greenstone member of showing vesicles in filled with chlorite/chloritoid. Sample 12-MT-18. D) Near sample 12-MT-18. Part of the outcrop showing cm scale epidote veins carbonate blebs forming on the surface of the outcrop. E) brecciated tuff member showing cm scale clasts. Sample 12-MT-17.

4.3 Petrography

4.3.1 Gunbarrel Intrusions

Petrographically, the Gunbarrel intrusions from all of the localities have remarkably similar mineral assemblages, with varying degrees of alteration in mineral phases such as plagioclase and clinopyroxene. Petrographic descriptions for Gunbarrel samples collected in this study are summarized below and in Appendix C. Comparative outcrop photos and photomicrographs of intrusions from the various locations are also shown in Figures 8 through 13.

In general, the mineral assemblage shared by all Gunbarrel intrusions is an medium grained plagioclase (40-70%) + clinopyroxene (12-40%) + magnetite/ilmenite (2-12%) diabase with minor amounts of quartz (interstitial and intergrown with alkali feldspar in granophyre) + biotite + amphibole and chlorite with an ophitic to sub-ophitic texture. Accessory and trace minerals commonly include apatite, zircon, baddeleyite, rutile and rare, small disseminated pyrite and chalcopyrite grains.

Plagioclase often occurs as elongated laths or euhedral prisms (0.5 – 7 mm) that are lightly to highly sericitized, with some samples having plagioclase almost completely replaced. Most plagioclase grains show albite twinning and some show rare zonation in thin section.

Clinopyroxene appears as anhedral to euhedral crystals (0.2-4 mm) sometimes altered at the rim to blue-green or brown amphibole. Upon investigation with the electron microprobe, the pyroxenes have extremely fine exsolution lamellae of clinopyroxene and

orthopyroxene (Figure 17a). However, upon analysing a number of pyroxenes with the electron microprobe, the orthopyroxene lamellae are too fine to analyze accurately, and mineral chemistry for spot analysis uniformly compute as clinopyroxene. Clinopyroxene often have amphibole and plagioclase inclusions.

The Fe-Ti oxides in various thin sections occur in a number of morphologies including euhedral to anhedral prisms, globular and skeletal and can be <0.1-2 mm. Upon investigation with the electron microprobe, it was seen that many of the oxides present in Gunbarrel intrusions are titanomagnetite – ilmenite exsolutions (Fig. 17b). Mineral chemistry was analyzed for ilmenite-titanomagnetite phases within the same crystal to use in geothermobarometric calculations in section 4.4.

Biotite often occurs as small (<0.5 mm) tabular flakes and some samples show varying degrees of alteration to pale green chlorite. Interstitial quartz grains are commonly pitted and have small inclusions of apatite, rutile or both, whereas some quartz is intergrown with alkali feldspar in granophyre.

Some opaques in thin sections are small (<0.5 mm) cubic or globular grains and upon using reflective light microscopy it was found that these were disseminated pyrite and chalcopyrite. Small subhedral to euhedral zircons (10-20 μm) were commonly found in biotite or near the rims of amphibole. Small blades of baddeleyite (8-25 μm) were found in granophyre and in amphibole rims.

4.3.2 Irene and Huckleberry Metavolcanic Rocks

The samples collected from the I&H metavolcanic rocks from northeast Washington, USA are not as uniform petrographically as the Gunbarrel intrusions. There are at least 3 distinct lithological units seen in hand sample and thin sections: 1) a greenstone unit, 2) a more phyllitic unit, and 3) a brecciated tuff unit. All the I&H metavolcanic rocks have undergone significant greenschist facies metamorphic conditions and many appear to have seen fluid activity from the presence of significant calcite and quartz veining in many outcrops. The greenstone unit is mainly schistose. Below is a brief description of the 3 units with individual petrographic descriptions in Appendix C. Photos of the different units are shown in Figures 14-16.

The Greenstone unit

The majority of I&H metavolcanic rock samples taken during this study are represented by the greenstone unit. Samples are predominately fine grained (Fig. 14c, f) or porphyritic (Fig. 14a, b, e) and often amygdaloidal. Rare samples are more medium grained and preserve relict igneous textures such as interstitial and sub-ophitic (Fig. 14d, h). Phenocrysts include plagioclase laths and needles 0.3-1.5 mm (5-10%), euhedral to anhedral clinopyroxene 0.2-0.8 mm (2-10%), euhedral to sub-hedral amphibole prisms 0.3-3 mm (3-5%) and sub-hedral epidote grains 0.3-0.6 mm (2-8%).

Vesicles are in-filled with one or more minerals including calcite, quartz, large chlorite sheets, epidote, and Fe-Ti oxides (Fig. 14g). Vesicles are up to 1 mm in diameter, have rounded or flattened morphologies and can make up to 10% of the rock.

The groundmass in most samples is composed of fine grained chlorite, amphibole (occur as separate grains or intergrown with chlorite), plagioclase, quartz and opaques in varying percentages. Opaques include Fe-Ti oxides and disseminated sulphides such as chalcopyrite and pyrite. Trace minerals include apatite, alkali feldspar, titanite, xenotime, and zircon.

One sample, 12-MT-27, is more of a biotite schist than greenstone. Fine grained biotite, Fe-Ti oxides, quartz and plagioclase define a strong foliation that wraps around large clasts (1.5 cm) containing acicular anthophyllite, quartz, plagioclase, biotite and Fe-Ti oxides (Fig. 14i).

Phyllitic unit

Light grey in hand sample, with a slight sheen to the surface and brown weathering. The unit is fine grained and has small fractures. It is composed of fine grained plagioclase, carbonate, Fe-Ti oxides, chlorite, quartz, epidote, with minor amounts of amphibole, biotite and trace amounts of apatite (Fig. 15).

Tuff unit

This unit is a brecciated tuff with clasts that can get up to several centimeters in size. Samples are light green in hand sample and contain semi-rounded to angular clasts of different materials. Some clasts contain spheroids (0.5 mm) of either calcite, chlorite, clays, or a fine grained unknown mineral or mixture of minerals that are set in a matrix of

semi-opaque to opaque glass with microphenocrysts (0.1-0.5 mm) of euhedral clinopyroxenes and plagioclase laths forming a trachytic texture. Other clasts have large sheets of chlorite and small euhedral epidote grains while a third type of clast is composed of large (up to 3 mm), euhedral plagioclase laths that are highly altered to sericite and larger white mica grains. Plagioclase and clinopyroxene phenocrysts are relatively pristine and can make up 25% of the rock. The remainder of the rock is composed of fine grained chlorite, amphibole, and clays (Fig. 16).

Figure 8: A) Outcrop picture of sample location 12-MT-02 in the Tobacco Root Mountains. B) Photomicrograph in XPL of 12-MT-02 displaying common mineral assemblage, lightly to highly altered plagioclase, clinopyroxenes with alteration rims of amphibole and sub-ophitic texture. C) Photomicrograph in XPL of 12-MT-09 from the Tobacco Root Mountains displaying common mineral assemblage, skeletal oxides, highly altered plagioclase and ophitic texture. Field of view is 3.5 mm for B and C. Amph- amphibole, bt-biotite, cpx - clinopyroxene, gphyr – granophyre, plag – plagioclase, ox – F-Ti oxides, qtz- quartz.

Figure 9: A) Roadside outcrop of the Christmas Lake dyke and sample 13-AM-01 in the Beartooth Mountains showing typical rusty red weathering, backpack for scale. B) Photomicrograph in XPL of sample 13-AM-01 showing lightly to moderately altered plagioclase and ophitic texture. Field of view is 3.5 mm Cpx - clinopyroxene, plag – plagioclase, ox – Fe-Ti oxides.

Figure 10: Photomicrograph in XPL of sample 94LAAT003-1A from Mount Moran in the Teton Range. Field of view is 3.5 mm. Cpx - clinopyroxene, gphyr – granophyre, plag – plagioclase, ox – Fe-Ti oxides.

Figure 11: Photomicrograph in XPL of sample 91LAAT2-2 from the Muncho Lake dyke in northern British Columbia. Field of view is 3.5 mm. Cpx – clinopyroxene, plag – plagioclase, ox – Fe-Ti oxide.

Figure 12: A) Outcrop photo of Wolf Creek Sill in northeastern Montana and sample location of 13-AM-11. B) Photomicrograph of 13-AM-11 in XPL displaying pristine plagioclases and clinopyroxenes with a sub-ophitic texture. Field of view is 3.5 mm. Cpx – clinopyroxene, plag – plagioclase.

Figure 13: A) Outcrop picture of Turah Sill in the Belt Supergroup and sample location 13-AM-26B. B) Photomicrograph in XPL of sample 13-AM-26B displaying more alteration and slight deformation than other Gunbarrel intrusions. Plagioclases are almost completely replaced by sericite and larger white mica grains and chlorite is present often replacing biotites and clinopyroxenes. Field of view is 3.5 mm. Amph-amphibole, bt-biotite, cpx - clinopyroxene, ox - Fe-Ti oxides, chl - chlorite, WM - white mica.

Figure 14: Photomicrographs of the greenstone unit from the Irene and Huckleberry metavolcanic rocks. A) 12-MT-18 in XPL B) 12-MT-19 in XPL C) 12-MT-21 in PPL D) 12-MT-22 in PPL. Field of view is 3.5 mm.

Figure 14 cont'd: Photomicrographs of the greenstone unit from the Irene and Huckleberry metavolcanic rocks. E) 12-MT-23 in XPL F) 12-MT-24 in PPL G) 12-MT-25 in XPL H) 12-MT-26 in PPL. Field of view is 3.5 mm.

Figure 14 cont'd: Photomicrographs of greenstone unit of Irene and Huckleberry metavolcanic rocks. I) Sample 12-MT-27 in PPL. Field of view is 3.5 mm. Amph- amphibole, plag – plagioclases, carb – carbonate, ox – Fe-Ti oxides, chl – chlorite, ep – epidote, qtz – quartz.

Figure 15: Photomicrographs of sample 12- MT-20 in XPL representing the phyllitic unit of the Irene and Huckleberry metavolcanic rocks. Field of view is 3.5 mm. Plag – plagioclase, carb – carbonate, ox – Fe-Ti-oxides.

Figure 16: Photomicrograph of sample 12-MT-17 in XPL representing the tuff unit of the Irene and Huckleberry metavolcanic rocks. Field of view is 3.5 mm. Plag – plagioclase, cpx – clinopyroxene.

4.4 Mineral Chemistry

Multiple thin sections were analysed using the electron probe at Carleton University and individual mineral analyses were collected for plagioclase, pyroxene, amphibole and Fe-Ti oxide minerals. Data for mineral chemistry analyses are presented in Appendix E.

The main pyroxene in all samples was augite. Upon investigation with BSE images, it was found that most pyroxenes in Gunbarrel intrusions were composed of ultra-fine orthopyroxene-clinopyroxene lamellae, however, when analysed using the electron probe compositions were uniformly clinopyroxene (Fig. 17a). All I&H metavolcanic pyroxenes, cores and rims, were high Mg and in some cases high Ca augites. All Christmas Lake pyroxenes probed are augites. In the Tobacco Root Mountains and Mount Moran samples, all pyroxene cores were augite in composition with most of the rims decreasing in Ca and having a composition of pigeonite. The Wolf Creek Sill has more variation in pyroxene composition compared to the other localities, with cores and rims plotting as augites, pigeonites, and clinoferrosilites (Fig. 18).

For plagioclase, the Tobacco Root Mountain samples have a large spread in compositions from labradorite to almost pure albite for one sample. Samples from the Christmas Lake and Mount Moran dykes have more uniform analyses that plot in the labradorite field, with a rim for Mount Moran plotting as andesine. All I&H metavolcanic rock plagioclases are almost pure albite in composition, with the exception of 12-MT-27 having a plagioclase with the composition of andesine (Fig. 19).

The Fe-Ti oxides in the Gunbarrel intrusions were often exsolutions of titanomagnetite and ilmenite, with smaller grains usually being entirely one or the other mineral (Fig. 17b). Fe-Ti oxides in the I&H metavolcanic rocks were predominately ilmenite, with little magnetite seen.

Amphibole analyses were also conducted for the Gunbarrel intrusions and I&H metavolcanic rocks. Amphibole compositions for Gunbarrel intrusions were predominately hornblende with some minor actinolite seen, while amphibole analyses for the I&H metavolcanic rocks were actinolite. For sample 12-MT-27, the acicular amphibole in thin section was determined to be anthophyllite.

Figure 17: A) Backscatter electron (BSE) image of common orthopyroxene-clinopyroxene lamellae. Sample 12-MT-02 from the Tobacco Root Mountains. B) BSE image showing common ilmenite-titano-magnetite exsolutions. Lighter sections are titanomagnetite and darker sections are ilmenite. Sample 94LAAT003-1A from the Teton Range.

Figure 18: Mineral chemistry data for pyroxenes in selected thin sections in the enstatite (En) – Forsterite (Fs) – Wollastonite (Wo) system. Filled in symbols represent core analyses and empty symbols represent rim analyses. TRM – Tobacco Root Mountains, I&H – Irene and Huckleberry metavolcanic rocks, X-Mas Lake – Christmas Lake.

Figure 19: Mineral chemistry data for plagioclases in selected thin sections. Same legend as in Figure 18. Filled in symbols represent core analyses and empty symbols represent rim analyses.

4.5 Ilmenite-magnetite geothermometer and oxybarometer

Upon investigation with the EMPA, many Gunbarrel intrusion Fe-Ti-oxides appeared to be ilmenite-Ti-magnetite exsolutions. The coexistence of these two phases allows for determination of temperature and oxygen fugacity using the FeO-Fe₂O₃-TiO₂ system and magnetite-ulvöspinel and hematite-ilmenite solid-solutions and equations 1 and 2 (Powell and Powell, 1977, Hammond and Taylor, 1982).

Often, the temperatures calculated for rocks are lower than one would expect for magmatic magnetite crystallization and thus likely represent re-equilibrium through slow cooling (Hammond and Taylor, 1982). Caution must be used in applying the ilmenite-titano-magnetite geothermometer and oxybarometer on the fact that while the magnetite is being oxidized and the ilmenite is being reduced, the internal composition of Fe and Ti must remain unchanged and cannot experience loss or gain along grain boundaries to external mineral phases (Hammond and Taylor, 1982). This may only be plausible in hypabyssal and extrusive environments, and thus may lead to some uncertainty in the results (Powell and Powell, 1977; Hammond and Taylor, 1982).

Seven ilmenite-titano-magnetite analyses were conducted on 4 thin sections from the Tobacco Root Mountains, Christmas Lake and Mount Moran dykes. Values for

calculated temperatures and fO_2 are listed in Table 2. Values for temperature ranged significantly depending on which method was used, with the Powell and Powell (1977) method yielding the highest temperature values and the Spencer and Lindsley (1981) method yielding the lowest temperature values for the same ilmenite-titano-magnetite pairs. Oxygen fugacity did not tend to vary as much between Fe-Ti oxides depending on what method was used, however there was a large spread among values from different samples. Temperature ranges for the Powell and Powell (1977) method were 613-843°C (mean = 703°C). Temperature and $\log_{10}fO_2$ ranges for the Spencer and Lindsley (1981) method were 517-734°C (mean= 591°C) and -17 to -26 (mean = -22.59). For the Anderson and Lindsley (1985) method, the temperature and $\log_{10}fO_2$ ranges were 544-756°C (mean= 622°C) and -17 to -25 (mean = -21.71). The two ilmenite-titano-magnetite pairs from the Christmas Lake dyke in the Beartooth Mountains were consistent with each other and gave the highest temperatures and lowest oxygen fugacities. The sample from the Mount Moran dyke in the Teton Range and the two samples from dykes in the Tobacco Root Mountains shared similar temperatures and oxygen fugacities with each other and among different oxide pairs.

Table 2: Geothermobarometry data for selected Gunbarrel intrusions.

Sample	Location	Powell & Powell (1977)		Spencer & Lindsley (1981)		Anderson & Lindsley (1985)		Average	
		Temp (°C)	$\log_{10}fO_2$	Temp (°C)	$\log_{10}fO_2$	Temp (°C)	$\log_{10}fO_2$	Temp (°C)	$\log_{10}fO_2$
12-MT-02	TRM	670	-	540	-25	577	-23	596	-24
12-MT-09-1	TRM	613	-	543	-24	572	-23	576	-24
12-MT-09-2	TRM	628	-	557	-24	586	-23	590	-23
94LAAT003-1A-1	Teton Rnage	653	-	517	-26	554	-25	574	-25
94LAAT003-1A-2	Teton Rnage	704	-	563	-23	601	-22	623	-23
13-AM-01-1	Beartooth Mtns	843	-	734	-17	756	-17	778	-17
13-AM-01-2	Beartooth Mtns	810	-	682	-19	711	-18	734	-19

TRM – Tobacco Root Mountains, Mtns – Mountains

Chapter 5: Major, minor and trace element geochemistry of Gunbarrel intrusions and Irene and Huckleberry metavolcanic rocks and Ni-Cu-PGE assessment of the Gunbarrel LIP

5.1 Introduction

The purpose of this chapter is to determine and compare lithogeochemical signatures of the Gunbarrel intrusions from all localities with each other and to the Little Dal Basalts and Irene and Huckleberry (I&H) metavolcanic rocks to determine if (and how) they are related, their tectonic setting and source magma(s) characteristics. This will then provide a robust geochemical “fingerprint” for the entire Gunbarrel LIP. Ni-Cu-PGE deposit potential will also be assessed through major and trace element geochemistry.

5.2 Major, minor and trace element geochemistry

5.2.1 Gunbarrel Intrusions

Despite the vast distances between units, Gunbarrel intrusions share remarkably similar geochemical signatures. In an AFM diagram Gunbarrel intrusions from all localities plot in a tight group as Fe-tholeiites (Fig. 20). In a standard total-alkalis vs. silica (TAS) plot Gunbarrel samples span between basalts to basaltic andesites (LeBas et al., 1986) (Fig. 21). However, some samples have moderate LOI of up to 1.58 wt% (Appendix B) and alteration is apparent in plagioclase and clinopyroxene in thin sections, indicating that some mobilization of major elements such as K and Na may have occurred. To mitigate this effect all samples were plotted on a Pearce (1996) Nb/Y vs. Zr/Ti which utilizes incompatible and less mobile element and the Gunbarrel rocks plot

solely as basalts (Fig. 22a). In a Y/15 - Nb/8 - La/10 tectonic setting diagram (Cabanis and Lecolle, 1989), samples plot within the “Continental Tholeiites” field (Fig. 22b) and in a Ti/100-Zr-Y*3 after Pearce and Cann (1973) plot, Gunbarrel rocks straddle the line between “Ocean Floor” and “Within Plate” basalts, although the southern samples from the United States tend to be more on the Within Plate boundary and northern samples from Canada tend to be more within the “Ocean Floor” field. The two samples from the Turah Sill are the lone exceptions, plotting in the “Island Arc Field” (Fig. 22c). This deviation is believed to be attributed to insufficiently dissolved minerals such as zircon and baddeleyite retaining zirconium which yielded lower values for the Turah sills. In other geochemical diagrams that utilize Ti, Y, and other rare earth elements, the Turah sills plot consistently with the other Gunbarrel samples. Most Gunbarrel samples have Ti/V ratios <50 and plot within the “Continental Flood Basalt” field, with the exception of a few Wopmay and a Mackenzie Mountains samples which have Ti/V ratios >50 and plot in the “Alkali” field in a Ti/1000 vs. V plot (Fig. 23). To look more into source characteristics, samples were plotted in a Th/Yb vs. Nb/Yb diagram from Pearce (2008) where Th/Yb ratios are used as proxies for crustal contamination. Again, all Gunbarrel intrusions plot in a tight group above the E-MORB part of the mantle array (Fig. 24). Gunbarrel intrusions have Mg#s between 0.27-0.46 and high FeO^T wt% of 12-18% along with high TiO₂ wt% of 1.5-3.5%, making them high Fe and Ti tholeiites. Selected major, compatible and incompatible trace elements were then plotted against Mg# [atomic Mg²⁺/Mg²⁺ + Fe²⁺] to look for patterns between samples (Fig. 25).

Figure 20: AFM diagram from Irvine and Baragar, (1971) for Gunbarrel rocks for various location showing high Fe-tholeiite compositions. Alk – alkalis ($\text{Na}_2\text{O} + \text{K}_2\text{O}$), FeO^* - $\text{FeO} + \text{Fe}_2\text{O}_3$. TRM – Tobacco Root Mountains, I&H – Irene and Huckleberry metavolcanic rocks. References are listed for data from the Mackenzie Mountains, Wopmay Orogen and Little Dal Basalts. Coloured symbols represent work done in this study, black symbols represent previous work by other authors.

Figure 21: Total Alkali vs. Silica (TAS) plot from LeBas et al. (1986) for Gunbarrel rocks from various localities. TRM-Tobacco Root Mountains, Mtns – Mountains.

Figure 22: Classification diagrams for Gunbarrel intrusions and volcanic rocks. A) Nb/Y vs. Zr/Ti classification diagram after Pearce (1996) (after Winchester and Floyd, 1977). Alk. – alkalic, bas. – basalt, trach. – trachyte, andes. – andesite. B) Nb/8-La/10-Y/15 diagram after Cabanis and Lecolle (1989). VAT – volcanic arc tholeiite, Cont. – continental basalt, EMORB – enriched mid-ocean ridge basalt, NMORB – normal mid-ocean ridge basalt. C) Y*3-Zr-Ti/100 diagram after Pearce and Cann (1973). TRM – Tobacco Root Mountains, I&H – Irene and Huckleberry volcanic rocks.

Figure 23: Classification diagram of Ti/1000 vs. V after Shervais (1982) for Gunbarrel intrusions and volcanic rocks. CFB – continental flood basalts, IAT – Island arc tholeiites, OFB – ocean floor basalts, TRM – Tobacco Root Mountains, Mtns. – Mountains, I&H –Irene and Huckleberry.

Figure 24: Classification diagram of Nb/Yb vs. Th/Yb after Pearce (2008) for Gunbarrel intrusion and volcanic rocks. NMORB – normal mid-ocean ridge basalt, EMORB – enriched mid-ocean ridge basalt, OIB – ocean island basalt.

There does appear to be slight variations among samples from the different localities in which different signatures and slopes are displayed, which can be attributed to varying degrees of crystal fractionation. Plotted against Mg#, SiO₂ for intrusions from the TRMs, Christmas Lake dyke, Mount Moran and Muncho Lake dykes have a negative correlation, while rocks from the Mackenzie Mountains, Hottah Sheets, Wolf Creek and Turah sills have a relatively flat slope. For TiO₂, with a few exceptions from the Mackenzie Mountains and Mount Moran dyke, there is a positive correlation against Mg#. For Al₂O₃, many of the Mackenzie Mountain samples appear to display a negative slope while intrusions from the other localities cluster together. When plotted against FeO, with a few exceptions from the Mackenzie Mountains, Wopmay Orogen and Little Dal Basalts, all samples show a positive correlation against Mg#. For V, all samples have a positive slope except for the Hottah Sheets which display a flat slope. With Ni all samples show a positive slope and for CaO samples show a negative correlation with Mg# with the exception of the Little Dal Basalts. Nb shows a very shallow negative slope and Th and Yb have negative slopes. Finally, Sc shows a strong positive correlation with Mg# (Fig. 25).

In a REE plot normalized to chondrite from Sun and McDonough (1989), the Gunbarrel intrusions from the Mackenzie Mountains, Yukon, Canada to the Beartooth Mountains in Wyoming, USA, display a very tight, overlapping pattern with a slight elevation in light rare earth elements (LREEs), a small negative Eu anomaly and a moderate slope from the light to heavy rare earth elements (LREEs to HREEs) (Fig. 26). In a primitive mantle normalized multi-element plot, normalized to the values of Sun and McDonough (1989), samples from all localities again show remarkably similar,

overlapping patterns with larger enrichments in the LREEs, moderate Th-U, K and large Pb peaks with small Nb-Ta troughs, large Sr depletions and small Eu negative anomalies in the range of 0.72-0.99, mean = 0.79 using $\text{Eu}/\text{Eu}^* [\text{Eu}/(\text{Sm}_N + \text{Gd}_N)/2]$ and normalization values from Sun and McDonough, (1989) for an average E-MORB source (Winter, 2008). Gunbarrel intrusions also display a moderate slope from the middle to heavy REEs which is used to infer approximate melting depth (Fig. 27).

The Little Dal Basalts (LDBs) are found at the top of the Little Dal Group and stratigraphically above the Tsezotene dykes and sills in the Mackenzie Mountains, Canada and are believed to represent a small portion of the continental flood basalts of the Gunbarrel LIP. The LDBs are slightly less evolved than the Gunbarrel intrusions having Mg#s between 0.32-0.46. The LDB have FeO^T contents of 14.61-20.82 wt%, TiO_2 contents of 1.76-2.20 wt% and high LOI contents of 3.8-6.0 wt%. The LDBs plot as tholeiitic basalts, and in a TAS diagram the LDBs plot as trachy-basalts to basaltic trachy andesites (Fig. 21). However, in a Pearce (1996) Zr/Ti vs. Nb/Y diagram they all plot solely in the basalt field (Fig. 22a). In a Cabanis & Lecolle (1989) diagram, the LDBs plot as continental tholeiites (Fig. 22b) whereas in a Pearce and Cann (1973) diagram they plot as ocean floor basalts (Fig 22c). In a Pearce (2008) diagram the LDBs plot along with the Gunbarrel intrusions above the ocean basalt array around E-MORB (Fig. 24). In a chondrite-normalized REE plot, the LDBs have a slight LREE enrichment, a small positive Eu anomaly of around 1, and a slightly flatter MREE to HREE slope compared to Gunbarrel intrusions but still show similar values (Fig. 26). In a primitive mantle normalized multi-element plot, the LDBs share the same pattern as the Gunbarrel intrusions, with LREE enrichments, a moderate Nb-Ta depletion, large K and Pb peaks,

large Sr depletions, with the exception of having a flatter MREE to HREE slope and slightly positive Eu anomaly (Fig. 27).

Figure 25: Selected major oxide, minor and trace elements from Gunbarrel rocks plotted against atomic Mg# to display how samples evolved from high to lower Mg concentrations. Major oxides presented in wt% and minor and trace elements presented in parts per million (ppm).

Figure 25 cont'd: Selected major oxide, minor and trace elements from Gunbarrel rocks plotted against atomic Mg# to display how samples evolved from high to lower Mg concentrations. Major oxides presented in wt% and minor and trace elements presented in parts per million (ppm). TRM – Tobacco Root Mountains. Plots with no error bars indicate 2σ fit within symbols.

Figure 26: Chondrite normalized rare earth element (REE) plot for Gunbarrel intrusions and Little Dal Basalts. Normalization values from Sun and McDonough (1989).

Figure 27: Primitive mantle normalized multi-element distribution plot for Gunbarrel intrusions and Little Dal Basalts. Normalization values from Sun and McDonough (1989).

5.2.2 Irene and Huckleberry metavolcanic rocks

The Irene and Huckleberry (I&H) metavolcanic rocks have undergone metamorphism and alteration as is apparent through petrographical investigation (section 4.3.2) and large LOI contents seen in Appendix B (ranging from 0.88-14.6 wt%, mean = 6.0 wt%), and many of the major elements were likely mobile and untrustworthy for geochemical classification. As stated in section 3.4, OGS dissolution processes were likely unsuccessful in dissolving all minerals phases which appear to retain many trace elements. Reanalysis was performed on four representative samples 12-MT-19, 12-MT-22, 12-MT-24 and 12-MT-25. The values obtained for Zr and other HREEs appear to correspond better with published data for the I&H metavolcanic rocks and thus the reanalyzed values using the dissolution method from ALS Laboratories will be taken as more accurate and only these four samples will be used in the geochemical plots.

I&H metavolcanic rocks appear to be slightly less evolved than the Gunbarrel rocks with Mg#s between 0.40-0.52. FeO^{T} content is lower ranging from 6-14wt% and TiO_2 content is 1.16-3.23 wt%. In an AFM diagram the I&H metavolcanic rocks plot near but slightly below the Gunbarrel intrusions in the “Tholeiitic” field (Fig. 21). In a Pearce (1996) diagram, they plot as basalts (Fig. 22a) and in a Pearce and Cann (1973) diagram they plot in the “Within Plate” basalt field except for 12-MT-22 which plots as calc-alkaline (Fig. 22c). In a Cabanis and LeColle (1989) diagram, the volcanic rocks plot in a group along the boundary between “E-MORB” and “Continental” basalt fields, with 12-MT-20, 12- MT-21 and MT-26 being more within the “Continental” field (Fig. 22b). In a Ti/1000 vs. V plot, the I&H metavolcanic rocks have Ti/V ratios <50 and plot within the “Continental Flood Basalt” field (Fig. 23). In a Pearce (2008) plot, the I&H

metavolcanic rocks plot along the ocean basalt array around E-MORB, however, unlike the Gunbarrel intrusions and LDBs the I&H metavolcanic rocks do not plot above the array (Fig. 24). In a chondrite normalized REE plot, the I&H metavolcanic rocks display similar trends to Gunbarrel intrusions. There is enrichment in the LREE, a small negative Eu anomaly ranging from 0.77-0.89, and a moderate slope from the MREE to HREE (Fig. 28). In a primitive mantle normalized multi element plot, 12-MT-19 and 12-MT-24 have higher enrichment in Rb and Ba than 12-MT-22 and 12-MT-25. All four samples have flat slopes from Th to Ta, large K depletions, and moderate Sr depletions, except for 12-MT-25 which has a small Sr enrichment. 12-MT-19 and 12-MT-25 have comparable, moderate slopes from the MREE to HREE as the Gunbarrel intrusions while 12-MT-22 and 12-MT-24 have slightly shallower slopes (Fig. 29).

Figure 28: Chondrite normalized REE plot for the 4 re-analysed Irene and Huckleberry metavolcanic rocks (green triangles) plotted against one representative Gunbarrel intrusion (red circle). Normalization values from Sun and McDonough (1989).

Figure 29: Primitive Mantle normalized multi-element plot with Irene and Huckleberry metavolcanic rocks (green triangles) plotted against one representative Gunbarrel sample (red circle). Normalization values from Sun and McDonough (1989).

5.3 Ni-Cu-PGE potential of the Gunbarrel LIP

As mentioned in section 1.1, many LIPs have been associated with world class economic deposits (Ernst and Jowitt, 2013, Jowitt and Ernst, 2013, Ernst, 2014). Six samples collected for this study from the different geographical areas (Tobacco Root Mountains, Beartooth Mountains, Teton Range, Belt Basin, Wolf Creek, and Muskwa Range), have been supplemented with data from Ernst and Buchan (2010) of four dykes and three sill from the Hottah Sheets, Wopmay Orogen to examine most of the Gunbarrel LIP for Ni-Cu-PGE potential. Au, Pt, and Pd have been analysed and combined with Ni and Cu data from trace element analysis and are used to provide a preliminary geochemical assessment of the economic potential of the Gunbarrel LIP. To aid in evaluating the economic potential, the Gunbarrel LIP samples will be compared with

Canadian LIPs of known Ni-Cu-PGE deposits from Jowitt and Ernst (2013). These include the 2445-2490 Ma Matachewan LIP which has the PGE-rich East Bull Lake intrusions, the 1870 Ma Chukotat magmatism which hosts the Cape Smith Ni-Cu-PGE deposits and is part of the Circum-Superior LIP, and the 1270 Ma Mackenzie LIP which is associated with the Muskox Layered Cu-Ni-PGE intrusion (Jowitt and Ernst, 2013, and references therein). Data for Ni, Cu and selected PGE element values are reported in Table 3.

The thirteen samples from the Gunbarrel LIP have low Ni (22-69 ppm), high Cu (102-319 ppm) compared to primitive mantle values, and variable Au (2-92 ppb), Pd (0.2-20.7 ppb) and Pt (0.2-17.9). These values were plotted against a number of compatible and incompatible trace elements to determine if any trends could be discerned.

Table 3: Ni, Cu, Pt, Pd and Au analysis for selected Gunbarrel samples

Sample	Location	Ni	Cu	Au	Pt	Pd
		ppm	ppm	ppb	ppb	ppb
12-MT-01	TRM, MT	37	255	6	11.4	10.2
91LAAT2-2	Muskwa Ranges, BC	50	159	2	< 0.1	0.2
94LAAT1-2A	Teton Range, MT-WY	62	255	10	13.6	20
13-AM-01	Beartooth Mtns, MT	25	278	6	11.7	8.6
13-AM-11	Wolf Creek, MT	69	285	13	17.9	18
13-AM-26B	Belt Basin, ID-MT	67	319	7	17.3	20.7
HD1*	Wopmay Orogen, N.W.T	29	102	92	0.5	-0.5
HD2*	Wopmay Orogen, N.W.T	28	103	5	0.7	-0.5
HD3*	Wopmay Orogen, N.W.T	28	102	-1	0.2	-0.5
HD4*	Wopmay Orogen, N.W.T	22	111	5	0.3	-0.5
HS1*	Wopmay Orogen, N.W.T	42	258	4	3	1.6
HS2*	Wopmay Orogen, N.W.T	59	278	2	7.3	6.6
HS3*	Wopmay Orogen, N.W.T	40	159	2	0.2	-0.5

Notes: HD - Hottah Dyke, HS - Hottah Sheet, TRM - Tobacco Root Mountains, MT - Montana, BC - British Columbia, WY - Wyoming, ID - Idaho, N.W.T. - Northwest Territories. *samples obtained from Ernst and Buchan (2010).

Similar to the Gunbarrel LIP, the three economic LIPs discussed here are tholeiitic, with the Chukotat LIP being tholeiitic-komatiitic, in composition and show continental flood basalt signatures (Jowitt and Ernst, 2013). Plotting the various chalcophile elements against MgO wt% will show how the various elements react to changing magma conditions. Ni (ppm) in all LIPs plot along the within plate basalt array of Keays and Lightfoot (2007) with a positive correlation, with the Gunbarrel, Mackenzie and Matachewan data having lower and more clustered values than the Chukotat LIP (Fig. 30a). The Gunbarrel and Mackenzie LIPs show large variations in Cu content over the MgO wt% range whereas the Chukotat and Matachewan data are much more uniform over their MgO wt% contents (Fig. 30b). For Pd the Gunbarrel, Matachewan and Chukotat data show slightly positive correlation with MgO wt%, with Pd values for the Chukotat LIP levelling out at higher MgO content and the Mackenzie LIP appears to be consistently high in Pd (Fig. 30c). Finally for Pt, the Gunbarrel, Mackenzie and Matachewan LIPs show similar spread in values while the Chukotat magmatism displays a positive correlation at lower MgO wt % and again levels out in Pt content at higher MgO wt% (Fig. 30d).

Next the LIPs are plotted on discriminatory diagrams that look into crustal contamination and chalcophile element enrichment and depletion relative to primitive mantle. On a (Cu/Zr)_{PM} vs. (Th/Yb)_{PM} diagram all LIPs display a negative slope of (Cu/Zr)_{PM} towards higher (Th/Yb)_{PM} values with the majority of samples plotting between 0.2 and 1 and showing variable depletion of chalcophile elements. A few samples from the Chukotat and Matachewan LIPs and potentially 1 sample from the Gunbarrel LIP have >1 (Cu/Zr)_{PM} values indicating slightly chalcophile enriched magmas (Fig.

Figure 30: Chalcophile element variations within the Chukotat, Matachewan, Mackenzie and Gunbarrel LIPs (A) Ni, (B) Cu, (C) Pd, and (D) Pt plotted against MgO wt%. Data for Chukotat, Matachewan and Mackenzie LIPs from Jowitt and Ernst (2013). Dashed line in (A) is the within plate basalt array from Keays and Lightfoot (2007).

31). When plotting (Pd/Yb)PM against (Th/Yb)PM all four LIPs tend to have the majority of samples with <1 values and only a few >1 and above the Primitive Mantle line (Fig. 32). Finally, by plotting Cu/Pd vs. Pd and Cu vs. Pd, sulphide accumulation and removal can be graphed by utilizing the different partitioning coefficient of Cu and Pd into sulphide melts. Most of the samples from the four LIPs tend to plot above the Primitive Mantle value line except for a few samples from the Chukotat and one sample from the Matachewan LIPs and all samples display trends consistent with sulphide removal from their magmas (Figs. 33, 34). In a (Th/Yb)PM vs. (Nb/Th)PM plot the Matachewan and Chukotat LIPs define nice mixing trends between a mantle component (N-MORB) and crustal component (upper continental crust (UCC)) (Fig. 35). The Gunbarrel LIP plots in between the two end members on the mixing line with a slight spread while the Mackenzie LIP data do not define a mixing trend (Fig. 35).

Figure 31: Variations in (Cu/Zr)PM vs. (Th/Yb)PM as a proxy for crustal contamination for the Chukotat, Matachewan, Mackenzie and Gunbarrel LIPs. Ratios have been normalized to Primitive Mantle values of McDonough and Sun (1995). Chukotat, Matachewan and Mackenzie LIP data from Jowitt and Ernst (2013).

Figure 32: Variation in $(\text{Pd}/\text{Yb})_{\text{PM}}$ vs. $(\text{Th}/\text{Yb})_{\text{PM}}$ as a proxy for crustal contamination for the Chukotata, Matachewan, Mackenzie and Gunbarrel LIPs (2013). Ratios have been normalized to Primitive Mantle values from McDonough and Sun (1995). Data for Chukotat, Matachewan and Mackenzie LIPs from Jowitt and Ernst (2013). Same legend as Figure 31.

Figure 33: Variation of Cu/Pd ratios plotted against Pd concentration for the Chukotat, Matachewan, Mackenzie and Gunbarrel LIPs. Dashed line represents a modeled magma with ~ 10 ppb Pd and ~ 100 ppm Cu undergoing equilibrium fractionation and removal of immiscible sulphides. Solid line in the middle right correspond to R -factors (Campbell and Naldrett, 1979) or 100, 1000 and 10, 000 and samples the plot on these lines have accumulated sulphides under these R factor conditions. Data for Chukotat, Matachewan and Mackenzie LIPs from Jowitt and Ernst (2013).

Figure 34: Variation diagram plotting Pd concentrations against Cu concentrations for the Chukotat, Matachewan, Mackenzie and Gunbarrel LIPs. Also plotted are the fields for the PGE –depleted Siberian Trap (Nd1-Nd3) basalts and PGE-undepleted Siberian Trap Tk+Mk+Sm basalts from Keays and Lightfoot (2010) and mid ocean ridge basalt (MORB) field from McDonough and Sun (1995). Dashed line is from Vogel and Keays (1997) and separates the S-undersaturated and S-saturated fields.

Figure 35: Variation of (Th/Yb)PM vs. (Nb/Th)PM for the Chukotat, Matachewan, Mackenzie and Gunbarrel LIPs. Ratios are normalized to Primitive Mantle values of McDonough and Sun (1995). N-MORB composition from Hofmann (1988) and average upper continental crust (UCC) composition is from Taylor and McLennan (1985). Data for the Chukotat, Matachewan and Mackenzie LIPs from Jowitt and Ernst (2013).

Chapter 6: Radiogenic isotopes of the Gunbarrel intrusions and Irene and Huckleberry metavolcanic rocks

6.1 Introduction

This chapter focuses on the radiogenic isotope composition of the Gunbarrel intrusions from the multiple localities and Irene and Huckleberry (I&H) metavolcanic rocks (this study) and comparing them with each other and to published work on the northern Canada Gunbarrel intrusions. Pb, Sr and Sm-Nd isotope work was completed at Carleton University and these isotopes will be able to further show whether all the intrusions from the Gunbarrel LIP are from the same mantle source, and what source that may be. Also, even if the metamorphic conditions experienced by the I&H metavolcanic rocks in northeast Washington State affected their geochemical signatures and disturbed their Pb and Sr isotopes (Devlin et al., 1985), isotopes such as Sm-Nd should remain more robust even under greenschist metamorphic conditions (Faure and Mensing, 2005) and will provide insight as to whether the I&H metavolcanic rocks are related to and fed by the Gunbarrel intrusions.

6.2 Pb isotopes

Pb isotopic ratios for thirteen Gunbarrel intrusions and three I&H metavolcanic rocks are listed in Appendix F. Due to the mobility of Pb the I&H metavolcanic rocks will not be plotted. Representative samples from each locality were chosen to provide an overview of the entire Gunbarrel LIP. Correcting to $t=780$ Ma, initial ratios for

$^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ were calculated. The majority of Gunbarrel intrusions have similar Pb isotopic ratios with $^{207}\text{Pb}/^{204}\text{Pb}$ values between 15.53-15.60, with samples from Muncho Lake dyke, a Christmas Lake dyke and the Turah sill having elevated values of 15.72, 15.97, and 15.82 respectively. Similarly, the majority of $^{206}\text{Pb}/^{204}\text{Pb}$ ratios lie between 17.34-18.32 and the same Christmas Lake dyke and Turah sill samples have elevated ratios of 19.15 and 20.58 respectively. Finally, $^{208}\text{Pb}/^{204}\text{Pb}$ ratios are mostly between 36.91-37.82 with the same Christmas Lake dyke and Turah sill samples having larger ratios of 39.60 and 40.43, respectively. Plotting these ratios against each other, most of the Gunbarrel intrusions plot closely to each other with a slight positive trend (Fig. 36a, b).

6.3 Sr isotopes

Thirteen Gunbarrel intrusions and three I&H metavolcanic rocks were analyzed for Sr isotopes. Data are listed in Appendix F. Initial $^{87}\text{Sr}/^{86}\text{Sr}$ values show a bit of spread throughout the Gunbarrel LIP and range from 0.706-0.711 (mean = 0.707) (Fig. 37). $^{87}\text{Rb}/^{86}\text{Sr}$ ratios were calculated using ICP-MS data and range from 0.636-1.371. The Christmas Lake dyke and Mount Moran dyke have the highest Sr isotopic ratios at 0.711 and 0.710, respectively, while dykes in the Tobacco Root Mountains have the lowest Sr values at 0.706. The three I&H metavolcanic rocks have lower initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios at 0.703, 0.704 for 12-MT-17, 12-MT-21 and a comparable Sr ratio of 0.706 for 12-MT-20 (Fig. 37).

Figure 36: Initial $^{208}\text{Pb}/^{204}\text{Pb}$ (A) and $^{207}\text{Pb}/^{204}\text{Pb}$ (B) plotted against initial $^{206}\text{Pb}/^{204}\text{Pb}$ for selected Gunbarrel intrusions plotted with known mantle reservoirs and present day mid-ocean ridge basalts (MORB) from (Zindler and Hart, 1986 & Winter, 2001). EMI, EMII – enriched mantle, PREMA – prevalent mantle, DMMa, b – depleted mantle, BSE – bulk silicate Earth, HIMU – high μ . Errors within $\pm 2\sigma$ fit within symbols. TRM – Tobacco Root Mountains.

6.4 Sm-Nd isotopes

Thirteen Gunbarrel intrusions from the various localities and eleven I&H metavolcanic samples were analyzed for Sm-Nd isotope ratios and data are listed in Appendix F. All the data have been time corrected ($t=780$ Ma). All Gunbarrel intrusions show very similar age-corrected present day $^{143}\text{Nd}/^{144}\text{Nd}$ ratios between 0.5124-0.5126 (mean=0.5125), initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of 0.51172-0.51182 (mean =0.51172), and $\epsilon\text{Nd}(t)$ values of +1.7 to + 3.6. These data correspond well with new Sm-Nd isotopic data from Sandeman et al. (2014) for samples from the Faber Sheet, Tsezotene sills and Tsezotene dyke from the Wopmay orogeny and Mackenzie Mountains, respectively. The northern samples gave time corrected initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios between 0.511702-0.511717 and $\epsilon\text{Nd}(t)$ values of +1.4 to +1.7. The Gunbarrel intrusions also have calculated T_{DM} ages between 1409 Ma – 1572 Ma using the depleted mantle model of DePaolo (1981). The $\epsilon\text{Nd}(t)$ values were plotted against SiO_2 and Th/Yb to investigate potential crustal contribution to Gunbarrel magmas. While there is no correlation observed between $\epsilon\text{Nd}(t)$ values and SiO_2 , there is a slight negative correlation between $\epsilon\text{Nd}(t)$ values and Th/Yb (Figs. 38 a, b).

The I&H metavolcanic rocks have initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios comparable to slightly higher than the Gunbarrel intrusions, ranging from 0.51178 to 0.51196 (mean = 0.51190). Their $\epsilon\text{Nd}(t)$ ($t=780$ Ma) values are higher at +2.9 to + 6.4 and T_{DM} ages are lower at 996 – 1210 Ma (Fig. 37). There is one outlier in this group which is 12-MT-21 which has an initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratio of 0.51254, $\epsilon\text{Nd}(t)$ of +17.81 and T_{DM} age of 382 Ma. It is

believed that this outlier has been more altered and was not included in the average ratio calculations.

Figure 37: Initial ϵ_{Nd} and $^{87}Sr/^{86}Sr$ values for selected Gunbarrel intrusions and Irene and Huckleberry metavolcanic rocks plotted with major geochemical reservoirs from White (2013 and references therein). Errors within $\pm 2\sigma$ fit within symbols. TRM – Tobacco Root Mountains, I&H – Irene and Huckleberry.

Chapter 7: Discussion

7.1 Petrography, major and trace geochemistry and isotopic fingerprint of the Gunbarrel LIP

7.1.1 Petrography

All Gunbarrel intrusions, whether sills or dykes, share similar petrographic characteristics and mineral assemblages that range from medium to coarser grain diabase with fine grained chill margins. Dykes are sub-vertical and while the sills are harder to trace, primary mineral phases are present in all samples along with variable alteration minerals, indicating fluctuating but low-grade metamorphic and deformation conditions. Well exposed, sharp contacts between dykes and country rocks were often observed with chill margins of 5-15 cm. No crustal xenoliths are observed in hand sample or thin section, indicating either little bulk crustal assimilation of country rock during emplacement or any crustal material was completely melted and mixed prior to emplacement.

Magnetite-ilmenite intergrowth observed in many thin sections suggest slow cooling of the magma with temperature ranges calculated between 574-778°C (Hanmmond and Taylor, 1982). Due to their often large size (10 - >60m wide/thick) it is reasonable to think that dyke/sill size, as well as emplacement depth, would provide sufficient insulation for a slow cooling. This slow cooling may have caused some deuteric alteration of the intrusions, which is why, despite the minimal metamorphic conditions thought to exist, some samples have plagioclase crystals almost completely replaced by sericite and white mica. The sericitization was also likely due to later stage

hydrothermal fluid interaction indicated by the presence of calcite veins in multiple outcrops.

Plagioclase from all the localities tend to have slightly different An contents from core to rim. For the Christmas Lake dyke, An content increases slightly from core to rim from An₄₉₋₅₃ to An₅₀₋₅₅. In the Mount Moran dyke An contents decrease from core to rim from An₅₂₋₆₀ to An₂₇₋₅₀. In the TRM both phenomena occur with An₁₄₋₆₀ for core samples and An₁₄₋₅₁ for rim samples. One highly altered plagioclase was almost pure albite with an An_{1.5} content. All plagioclases from the Irene and Huckleberry metavolcanic rocks showed uniformly low An contents of An_{0.5-2} in both rim and core analyses indicating albitization due to metamorphism and hydrothermal fluids. 12-MT-27 did, however, have a plagioclase with an An₄₄ content for the rim and An₃₈ content for the core. The increase/decrease in An content from core to rim in the Gunbarrel intrusions is usually small and zonation is not overly apparent in thin section or BSE images. This indicates the plagioclase were in semi-equilibrium state with the melt. Sandeman et al. (2014) documented plagioclases in chill margins from the Mackenzie Mountains and Wopmay Orogen having normal and reverse zonation with both steady and sharp changes in An content from rim to core. Sandeman et al. (2014) attributed sharp changes to indicate episodes of recharge from less fractionated but thermochemically similar magmas during residency in a magma chamber, while steady changes in An content indicate progressive oscillatory growth of plagioclase in semi-equilibrium with the melt.

The clinopyroxenes from all localities are mostly augite with rims of pigeonite, and some clinopyroxenes have slight alteration rims of amphibole (hornblende). The Wolf Creek Sill has a larger array of pyroxene compositions with some being augite, pigeonite

and clinoferrosilite. The I&H metavolcanic rocks have magnesium rich augite clinopyroxene compositions.

The mineralogical observations made from the southern United States and BC samples (this study) compare well with recorded observations made by Ootes et al. (2007) and Sandeman et al. (2008) between the Hottah Sheets and Tsezotene dykes and sills of northern Canada. This suggests that the magmas feeding all Gunbarrel intrusions were similar in composition and underwent similar crystallization histories.

7.1.2 Major, minor, and trace element geochemistry and isotopes

Despite distances of 2500 km between individual intrusions, the geochemistries of the units in the Gunbarrel LIP are remarkably similar. Varying degrees of alteration make using some mobile major elements unreliable, but other immobile elements are more robust and trustworthy. The TAS diagram (Fig. 21) indicates that Gunbarrel samples are tholeiitic basalts to basaltic andesites, however upon using immobile element ratios on a Pearce (1996) diagram (Fig. 22a), all samples plot as basalts. In most discriminatory diagram all Gunbarrel samples plot in a tight group. On the Cabanis and Lecolle (1989) diagram (Fig. 22b) all samples plot as continental tholeiites and on a Pearce (2008) diagram (Fig. 24) all samples plot in a tight group above the oceanic basalt array around E-MORB. This indicates there has likely been some enriched lithospheric component added to an asthenospheric magma source which likely produced the E-MORB signature seen on many geochemical diagrams. It is likely that this lithospheric component would also drive down ϵNd values, since it would be older and older material has lower Nd isotopic ratios than MORB (depleted, normal, enriched) sources (Faure and Mensing,

2005). ϵNd evolution for depleted MORB mantle (DMM) at 780 Ma using the curve from DePaolo, (1981) shows an ϵNd value of $\sim +6.3$, which is higher than Gunbarrel rocks. The lack of negative correlation seen between $\epsilon\text{Nd}(t)$ and SiO_2 (Fig. 38a) and a negative correlation between $\epsilon\text{Nd}(t)$ and Th/Yb (Fig. 38b) suggest that the lithospheric component driving down the ϵNd values it is not from the upper continental crust as a negative correlation would be expected but there is an older enriched component in Gunbarrel magmas. The older T_{DM} model ages for Gunbarrel intrusions (1409-1572 Ma) also suggests incorporating and mixing an older component into Gunbarrel magmas. The Nb-Ta depletion seen in primitive mantle normalized multi-element plots (Fig. 27) is a common signature of subduction settings, however, the depletion is subtle and therefore it is unlikely to represent arc magmatism due to subduction. It is believed that this Nb-Ta trough was also produced by this lithospheric component.

To try and determine the different components that make up Gunbarrel magmas, mixing models calculated with an offline spreadsheet created by Dr. Brian Cousens, were constructed assuming starting melts of normal mid-ocean ridge basalt (N-MORB) and enriched mid-ocean ridge basalts (E-MORB) incorporated either a 5% partial melt of middle continental crust, or sub-continental lithospheric mantle using mantle xenoliths from the Big Pine Volcanic Field, California as reference material. Curves were plotted for Nb/La vs. La/Sm as contamination proxies (Fig. 39a, b). Nb/La and La/Sm values were also plotted for lower crust to demonstrate it is an unlikely mixing component since it shares similar trace element ratios with many upper limit Gunbarrel intrusions (Fig. 39a). This would suggest 100% melting of lower crust to generate Gunbarrel magmas

which is highly unlikely as magmas with dacitic composition would be expected, thus the more enriched middle crust was used as a more appropriate mixing component.

None of the mixing curves in Figure 39a match the mixing curve for Gunbarrel intrusions or the Irene and Huckleberry metavolcanic rocks, however, it is noted that the Irene and Huckleberry metavolcanic rocks plot closer to the E-MORB end member while Gunbarrel intrusions plot in the middle of the four end members. This shows that the Gunbarrel intrusions and I&H metavolcanic magmas are comprised of different components. The lack of curve fitting shows the system may be more complex than a two component mixing model. It is noted that when extrapolated, the Gunbarrel intrusions' trend appears to fall between the mixing line between N-MORB and E-MORB. It is interpreted that this may represent the initial plume component. Figure 39b shows the different mixing ratios between N-MORB and E-MORB as the starting plume component mixing with 5% partial melts of middle crust or sub-continental lithospheric mantle (represented by xenoliths from the Big Pine Volcanic Field). By doing this the mixing curves for both middle crust and sub-continental lithospheric mantle become a closer match to the Gunbarrel samples, but again there is no definitive match. This brings up the limitation of mixing models, as the end member components may not be fully representative of what is melting and mixing for the actual Gunbarrel LIP. Also, the mixing curves from Figure 39b suggest large proportions of mixing (40-60%) of both middle crust or sub-continental lithospheric mantle, which should produce noticeable geochemical signatures such as andesitic magmas and the negative correlation between SiO_2 and $\epsilon\text{Nd}_{(t)}$ values mentioned before. Since there is no evidence of this, it may be that the enriched end-member is not fully represented by middle crust or the sub-continental

lithosphere from the BPVF. However, these mixing models do demonstrate that Gunbarrel magmas are composed of at least two components, an asthenospheric mantle “plume” component (N-MORB + E-MORB) and an enriched lithospheric component (middle crust, sub-continental lithospheric mantle?). It is unclear however, if the plume was a mixture of N-MORB and E-MORB and upon its ascent incorporated the lithospheric component and mixed in a residency magma chamber for some time before emplacement, or if the plume had all three components to start with and melted to generate Gunbarrel magmas. Since Gunbarrel samples appear to plot along mixing trends as seen in Figures 35 and 39, it indicates hot, turbulent magmas that would have been able to mix the different components sufficiently to homogenize the magmas (Jowitt and Ernst, 2013; Yuan et al., 2012).

Figure 38: Initial ϵ_{Nd} plotted against SiO_2 (A) and (Th/Yb) values (B) for selected Gunbarrel intrusions to examine crustal contamination and components.

Figure 39: Gunbarrel intrusions and Irene and Huckleberry (I&H) metavolcanic rocks plotted with Nb/La vs. La/Sm mixing models showing A) mixing of normal mid-ocean ridge basalt (N-MORB) and enriched mid-ocean ridge basalt (E-MORB) magmas with each other and 5% partial melts of either middle crust (MC) or lithospheric mantle from the Big Pine Volcanic Field (BPVF). B) MC and BPVF mixing with different “plume” compositions comprised of incorporating different ratios of N-MORB and E-MORB. Values for average N-MORB and E-MORB from Sun and McDonough (1989), BPVF from mantle xenoliths from Ormerod (1988), lower crust (LC) and MC from Rudnick (2004).

All Gunbarrel samples from northern Canada to the United States plot similarly in all plots (particularly those with trace and REE elements) to clearly show the magmas have been homogenized. Any variations are mostly seen in the more mobile major elements, such as the total alkali versus silica (TAS) plot. In a chondrite normalized REE plot, samples have moderate LREE enrichments and a moderate slope from the LREE to MREE which shallows slightly from the MREE to HREE with small negative Eu anomalies. In a primitive mantle normalized multi element plots, all samples show the same LREE enrichment, small Nb-Ta troughs, moderate K and Pb peaks, moderate Sr-P troughs and a moderate slope from the MREE to HREEs with a small negative Eu anomaly and small positive Ti anomaly. The negative Eu anomaly and to a lesser extent, negative Sr anomaly suggest that plagioclase was a fractionating phase controlling magma evolution (Rollinson, 1996). Likewise, due to the positive correlation between Mg#, CaO, Sc, Ni and FeO and TiO₂ content displayed in binary diagrams (Fig. 25), clinopyroxene, and potentially olivine, and Fe-Ti oxides were likely fractionating phases in controlling magma evolution. Gunbarrel samples had (Tb/Yb)_{PM} ratios calculated using PM values from McDonough and Sun (1995) and were found to be ~1.5. This represents the slope from the MREE to HREE. The slope is used to infer approximate melting depth in the mantle as the different mineral stability fields will result in different slopes (Rollinson, 1993). For instance, garnet incorporates the HREEs into its chemical structure and thus melting in the garnet field will produce HREE depleted melts resulting in a steep slope from the MREE to HREE. Spinel does not incorporate the HREEs into its chemical structure as readily as garnet and thus will produce a shallower slope from the MREE to HREE (Rollinson, 1993). (Tb/Yb)_{PM} ratios <2 indicate melting in the spinel

field, above 75 km depth whereas (Tb/Yb)PM ratios >2 indicate melting in the garnet stability field of the mantle (Rollinson, 1993). Thus Gunbarrel magmas represent melts from within the spinel stability field at <75 km depth.

Much like their geochemistry, the Gunbarrel intrusions tend to exhibit a tight grouping in some of their isotopes. For Pb isotopes most of the samples plot in a tight group with $^{207}\text{Pb}/^{206}\text{Pb}$ ratios between 15.53-15.60, and $^{206}\text{Pb}/^{204}\text{Pb}$ ratios between 17.34-18.32. Three samples, from Muncho Lake dyke, Christmas Lake dyke, and the Turah sill had elevated values. Gunbarrel samples show more spread in Sr isotopes, with samples having initial $^{87}\text{Sr}/^{86}\text{Sr}$ values between 0.7056-0.7080. Two samples, from Christmas Lake dyke and a Tobacco Root Mountain dyke both have elevated ratios of 0.7112. Pb and Sr are both mobile elements, and thus their isotopic systems can be disturbed by metamorphism and hydrothermal fluid alteration which may have affected these dykes slightly more than other intrusions. This interpretation is supported by the Nd isotopes, which are more immobile and resistant to metamorphism/alteration and are a key determining factor as to whether the Gunbarrel intrusions are fed from a similar source. When looking at the Nd isotopes, all Gunbarrel samples plot within a tight range of initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios between 0.51172-0.51182 and ϵNd values between +1.7 and +3.6 and show similar T_{DM} model ages between 1409 Ma – 1572 Ma. These T_{DM} ages which are older than the 780 Ma emplacement age of Gunbarrel magmas support the mixture of an older component.

The size, distribution and radiating pattern of intrusions, coupled with the overall similarity all Gunbarrel samples share in petrography, major and trace geochemistry and isotopic data, support the idea that Gunbarrel magmas were generated by a mantle plume

and likely fed from a single magma chamber. Magmas were likely injected laterally into the crust from the plume head center off the coast of present day Vancouver Island.

7.2 Relationship to the Irene and Huckleberry metavolcanic rocks

The metavolcanic rocks of northeast Washington State were proposed to be related to the nearby Gunbarrel intrusions as possible remnant flood basalts of the LIP (Harlan et al., 2003). Throughout this study, many problems have arisen with this interpretation that the Irene and Huckleberry (I&H) metavolcanic rocks are related to the Gunbarrel LIP. Field and petrographic observation clearly show that the I&H metavolcanic rocks have undergone low degrees of metamorphism and hydrothermal fluid interaction. All samples appear to have undergone greenschist facies metamorphic conditions based on a common mineral assemblage found in most samples of chlorite + albite + epidote + actinolite + quartz. Chlorites range from Fe-rich antigorites, based on anomalous blue interference colours, or pycnochlorite based on anomalous brown interference colours (Saggerson and Turner, 1982). Based on microprobe analysis, some of the greenstone members, such as 12-MT-18 have chlorite-amphibole (antigorite/pycnchlorite-actinolite) intergrowths which make up the fine grained matrix. All plagioclase appear to be pure to almost pure albite in composition. Primary mineral chemistry and mineral assemblage is sometimes difficult to ascertain due to the metamorphism and fluid alteration. Comparing the I&H metavolcanic rocks with the only other known volcanic rocks associated with the Gunbarrel LIP also raises questions. The Little Dal Basalts are red, green and grey brecciated flows with amygdaloidal tops with

maximum thicknesses of 92 m and indicators of subaerial and subaqueous eruptions (Dudás and Lustwerk, 1997). The I&H metavolcanic rocks are grey and green, with mostly amygdaloidal porphyritic flows and minor tuffs which suggest subaerial flows that have an estimated maximum cumulative thickness of 915 m (Devlin et al., 1985). The Little Dal Basalts have also been correlated with the Tzesotene dykes and sills in the Mackenzie Mountains, and thus the Gunbarrel LIP, through major and trace element geochemistry (Ootes et al., 2008). The LDBs have also experienced low degrees of metamorphism and alteration and show variations in some major element and mobile trace element geochemistry to Gunbarrel intrusions as seen on TAS diagrams (Fig. 21) and depleted CaO and elevated Al_2O_3 versus Mg# (Fig. 25). However, the LDBs plot with Gunbarrel intrusions on many incompatible and immobile element plots and share the same patterns REE and extended multi-element plots (Fig. 26, 27). Therefore, if the I&H metavolcanic rocks belong to the Gunbarrel LIP they should display similar geochemical and isotopic patterns as the Little Dal Basalts and the rest of the Gunbarrel LIP units through immobile and incompatible elements, even under greenschist facies metamorphic conditions. Although the I&H metavolcanic rocks are tholeiitic basalts, they do not have as high iron content as Gunbarrel intrusions (6.04 – 14.38 wt%, mean=12.38). The lower magnetic susceptibility suggests less magnetite crystallization or replacement of magnetite with less magnetic minerals during metamorphism. I&H metavolcanic rocks are slightly less fractionated with slightly higher Mg#'s of 0.4-0.53 than the Gunbarrel intrusions. Whereas the Gunbarrel intrusions and Little Dal Basalts plot well within the continental tholeiite field on a Cabanis and Lecolle (1989) diagram (Fig. 22b), the I&H metavolcanic rocks plot along the boundary between E-MORB and

continental tholeiites. On a Pearce (2008) plot (Fig. 24), the Gunbarrel intrusions and Little Dal Basalts plot above the oceanic basalt array around E-MORB while the I&H metavolcanic rocks plot in a group within the oceanic basalt array at E-MORB. This, along with the lack of a Nb-Ta trough in primitive mantle normalized multi-element plots, suggests the I&H magmas were derived from an E-MORB signature source but did not incorporate a lithospheric component as the Gunbarrel intrusions did. On chondrite and primitive mantle normalized multi-element plots (Figs. 28-29), the four I&H metavolcanic samples that were reanalyzed show 2 parallel but similar patterns. Two samples, 12-MT-22 and 12-MT-24 show slightly more elevated values for all trace and incompatible REEs than 12-MT-19 and 12-MT-25. On a primitive mantle normalized multi-element plot, these four samples have varying degrees of Rb-Ba enrichments, but then similar values for the remainder of the elements. The four metavolcanic samples have relatively flat patterns from Th-Pr, with moderate to large K depletions, likely due to metamorphism, in contrast to the Gunbarrel intrusions K enrichment (Fig. 27, 29). The I&H metavolcanic rocks do have a similar moderate Sr depletion as Gunbarrel intrusions, with the exception of 12-MT-25 which has a small Sr peak (Fig. 27, 29). The I&H metavolcanic rocks then have moderate slopes from the MREE-HREE, however, 12-MT-22 and 12-MT-24 have slightly shallower slopes than 12-MT-19 and 12-MT-25 (Fig. 29). This suggests that there may have been multiple pulses for the flows in which at least 2 different depths of melting were tapped. However, since these samples were not collected in a stratigraphic order, it is unclear if deep magmas were erupted first followed by shallower magmas or vice versa. Due to the low grade metamorphism experienced by the I&H metavolcanic rocks, their Pb and Sr isotopes were not readily analyzed and used

since the data would be expected to be disturbed. Devlin et al. (1985) reported scatter among Rb-Sr isotopic data and suggested that the system did not remain closed during metamorphism. Sm-Nd isotopes are much more resistant to mobilization under metamorphic conditions and all I&H metavolcanic samples were run for Nd- isotopes. I&H metavolcanic rocks have higher ϵ_{Nd} values at +2.9 to +6.4 which are much closer to isotopic ratios expected for depleted MORB mantle (DMM) of +6.3 (DePaolo, 1981). The metavolcanic samples also have T_{DM} model ages of 996 Ma to 1210 Ma, which are younger than the Gunbarrel intrusions. This supports the theory that I&H metavolcanic rocks have not experienced as much interaction with older crustal material as Gunbarrel magmas, and represent more primitive melts from an E-MORB source.

Given the differences seen in major and trace element geochemistry and Sm-Nd isotopes, it is unlikely that the I&H metavolcanic rocks were fed from any of the Gunbarrel intrusions but they may share a similar mantle source. It may be possible that the I&H magmas were generated by decompression melting caused by the rifting and break-up of Rodinia and thus are associated with the LIP as a by-product.

7.3 Ni-Cu-PGE potential of the Gunbarrel LIP

Over the past few years the links between mafic and ultra-mafic LIPs and magmatic Ni-Cu-PGE deposits has been well established (Song, 2011; Jowitt and Ernst, 2013; Ernst, 2014). Generally there are two groups of Ni-Cu-PGE deposits, the first is where Ni or Ni-Cu are dominant and PGEs are a by-product, and the second are sulphide poor, PGE rich deposits where Ni and/or Cu is a small, but important by-product (Maier,

2005; Song et al., 2011; Ernst and Jowitt, 2013). The most critical factors thought to be responsible in the formation of Ni-Cu-PGE magmatic deposits include 1) a large volume of fertile mafic-ultramafic magmas, 2) fractional crystallization and crustal contamination with the addition of sulphur to reach sulphur saturation and sulphide immiscibility, 3) timing of sulphide concentration in the intrusion, since it is important that S-saturation is not obtained before the magmas reach near surface levels (Song et al., 2011, Maier, 2005, Ernst and Jowitt, 2013). It is still difficult to determine which LIPs may have mineralization and which LIPs are barren, but some geochemical links have been found among economic LIPs (Ernst and Jowitt, 2013; Jowitt and Ernst, 2013).

In a Ni vs. MgO plot (Fig. 30a) all four LIP suites follow the within plate basalt array. On a (Nb/Th)PM vs. (Th/Yb)PM plot, with PM denoting elements were normalized to primitive mantle of McDonough and Sun (1995), Gunbarrel samples fall close to the mixing line in a tight group in between N-MORB and UCC which appear to follow and form a short mixing line (Fig 35). These data indicates that 1) the LIPs that form mixing arrays are likely hot and turbulent systems that were able to mix and homogenize the different components well and 2) the amount of crustal material and contamination appears to be variable between LIPs with known Ni-Cu-PGE deposits. In Figures 31 and 32, Th/Yb is a proxy for crustal contamination since Th is concentrated in the crust during partial melting, and placing chalcophile elements such as Pd and Cu over Yb indicates whether there is chalcophile element enriched or depleted magmas present relative to primitive mantle. In both (Cu/Yb)PM vs (Th/Yb)PM, and (Pd/Yb)PM vs. (Th/Yb)PM plots we see variable degrees of depletion in all 4 LIPs as they appear to experience crustal contamination. The Chukotat, Matachewan and Gunbarrel also show a

few samples that appear to have weakly chalcophile enriched magmas. The presence of both chalcophile element depleted and enriched magmas, as well as varying chalcophile depleted magmas, suggests that at least some of the magmas were fertile and upon a sulphur input by a lithospheric component (crust?), the chalcophile elements were stripped out of the magmas (Jowitt and Ernst, 2013). If all samples displayed similar depletion, either the LIP is barren or the chalcophile elements were stripped out as sulphides deep within the crust and not near surface. If all samples are chalcophile enriched magmas, it may be because S-saturation and sulphide immiscibility did not occur (Jowitt and Ernst, 2013). While the Gunbarrel magmas do not show large degrees of a crustal component based on the narrow spread along the (Th/Yb)PM axis and subtle Nb-Ta depletion in multi-element plots (Fig. 27), there does appear to be a mixing component stripping out chalcophile elements from the Gunbarrel magmas and potentially concentrating them in sulphide bodies. As mentioned in section 7.2, the lack of negative correlation between ϵNd and SiO_2 values (Fig. 38) indicate it is unlikely to mixing of an upper crustal component. Another method to test whether there has been S-saturation caused by contamination from an enriched source is plotting the chalcophile elements against each other such as Pd vs. Cu/Pd. Pd has a higher partitioning coefficient than Cu and will be stripped from S-saturated magmas faster than Cu (Keays and Lightfoot, 2007). Because of this, during contamination and S-saturation, Pd will decrease drastically and Cu/Pd will increase (Jowitt and Ernst, 2013). In Figure 33, a number of samples group around the line near primitive mantle, but the Gunbarrel samples and some of the Chukotat and Matachewan samples show large decreases in Pd and increases in the Cu/Pd ratio indicating S-saturation likely due to addition of crustal

sulphides and subsequent sulphide immiscibility. This is also seen in Figure 34, plotting Pd vs. Cu. There is a large decrease in Pd and very little Cu depletion in Gunbarrel samples showing that some samples fall in the S-saturated zone similar to the crustally contaminated Nadezhdinsky basalts of the Siberian Traps (Yuan et al., 2012).

The geochemical similarities the Gunbarrel LIP shares with known economic LIPs indicate that Gunbarrel magmas may be prospective for Ni-Cu-PGE deposits. These include 1) tholeiitic continental flood basalts signatures, 2) hot magmas that were likely able to melt sufficient amounts of fertile mantle material to create S-undersaturated magmas, 3) the presence of variable chalcophile depleted magmas 4) contamination from a crustal, or sulphur rich lithospheric component that likely cause S-Saturation and sulphide immiscibility (Jowitt and Ernst, 2013).

However, as noted by Ernst and Jowitt (2013), many mineralization “sweet spots” tend to be found within a few hundred (~500) kilometres of the plume head centers. In the case of the Gunbarrel LIP, with a plume center estimated to be off the coast of Vancouver Island, Canada, that would place any likely mineralization in the highly deformed and metamorphosed foreland uplifts of the Rocky Mountains, which drives down the potential for finding Ni-Cu-PGE deposits on the Laurentian block. This is why supercontinent reconstructions play an important role in the mining industry. If the adjacent continental block to Laurentia at the time of the Rodinia has equivalent Gunbarrel magmas, Ni-Cu-PGE deposits may be located on that block, so accurate reconstruction models may help locate new deposits.

7.4 Links with South China magmatism and Rodinia reconstructions

7.4.1 Introduction

It is now believed that due to their size and continental emplacements, LIPs have initiated and facilitated the break-up of supercontinents throughout time (Li et al., 2008; Ernst, 2014). The timing of the Gunbarrel LIP places it within the timespan of the rifting and break-up of the Neoproterozoic supercontinent Rodinia (Park et al., 1995; Li et al., 2008). It is thought that Rodinia was amalgamated around 1 Ga years ago and underwent a protracted break-up between 825 Ma – 740 Ma (Li et al., 2008, and authors therein). However, it is still unclear what the original Rodinia looked like. It is widely agreed that Laurentia was a central block because it is flanked by passive Neoproterozoic margins (Hoffman, 1991; Li et al., 2008) but there are multiple models using different criteria to try and explain what was adjacent to western Laurentia during that time (Li et al., 2008, and authors therein). There are four main models to address this question, using various tools. The first is the SWEAT model, in which Australia and east Antarctica lie adjacent to western Laurentia based on similar Neoproterozoic stratigraphy and basement rocks on their margins (Li et al., 2008 and authors therein). However, geochemical and isotopic variation exists among these cratonic margins (Borg and DePaolo, 1994; Li et al., 2008). The second is the “Missing Link” model, proposed by Li et al. (1995), that places the South China craton in between western Laurentia and Australia based on a) similar Neoproterozoic stratigraphy among Laurentia, South China and Australia and b) coeval magmatism among the three blocks. Other reconstruction models suggest that Australia-

Southwest-US (AUSWUS model) or Queensland Australia-Mexico (AUSMEX model) may have also been adjacent to western Laurentia (Li et al., 2008).

This chapter will look to compare the geochemical and isotopic fingerprint established for the Gunbarrel LIP previously in this work to coeval bimodal magmatism in the South China block to determine if any lithogeochemical similarities can be found to the “Missing Link” model. If the Gunbarrel and South China samples were created by the same mantle plume, and possibly even the fed from a similar magma chamber, then trace element and isotopic signatures should remain the same and provide an answer.

7.4.2 South China magmatism

Neoproterozoic, bimodal magmatism is widespread in the Yangtze craton of the South China block that includes predominantly granitic rocks and volumetrically less significant mafic dykes, gabbros and basalts with magmatic episodes at ~830-820 Ma and ~780-760 Ma (Li et al., 2003; Lin et al., 2007; Zheng et al., 2008). The Yangtze craton is bound by the failed Neoproterozoic Kangding rift in the west, Nanhua Rift to the south and Mesoproterozoic Jiangnan Orogen to the southeast (Lin et al., 2003; Zheng et al., 2007; Li et al., 2008). There is ongoing debate as to what the main cause for the South China magmatism is, whether it is mantle plume related or active rifting and island arc in origin (Zhou et al., 2002; Li et al., 2003).

Geochemical and Nd isotopic data from ~780 Ma mafic and granitic rocks were taken from three different studies from South China to compare with data from the Gunbarrel LIP. Data are from: four mafic dykes ranging in thickness from 20 cm – 100

cm from the Kangdian Rift from Li et al. (2003); two volcanic rocks and six granite samples from the eastern Jiangnan Orogen from Zheng et al. (2008); and five mafic dykes 1-10s of meter thick which intrude the 795 Ma Wasigou granite (Group I) and 10 mafic dykes 1-10 meters thick which intrude the 810 Ma Shimian granite (Group II), both found in the Kangding Rift from Lin et al. (2007).

7.4.3 Geochemical and isotopic comparison with the Gunbarrel LIP.

Most of the South China mafic dykes from all localities have large LOI values ranging from 1.47 – 7.87 wt % with the Jiangnan orogen granites having the lowest LOIs from 0.26 – 1.25 wt % and one sample with 4.25 wt %. In an AFM diagram, most of the mafic dykes and the volcanic rocks plot in the calc-alkaline field, with the Kangding dykes trending towards the alkalis and a few of the Shimian dykes plotting in the tholeiitic field towards MgO (Fig. 41a). However, none of the groups are high-Fe tholeiites like the Gunbarrel samples. In a Zr/Ti vs. Nb/Y plot by Pearce (1996), most of the mafic dykes plot as basalts with two Kangding Rift and the Group I samples plotting more within the basalt+basaltic andesite field (Fig. 40). In a La/10-Y/15-Nb/8 plot, the Group II dykes plot as volcanic arc tholeiites, with one volcanic sample and the Group I dykes plotting in the calc-alkaline field and the Kangding dykes plot in between (Fig. 41b). Two samples from the Group I dykes, one volcanic sample and one sample from the Kangding dykes, plot along with the Gunbarrel as continental tholeiites (Fig. 41b). In a chondrite normalized REE plot, the Kangding samples have parallel slopes in the LREE but lower REE abundances compared to the Gunbarrel samples. Three of the Kangding

dykes also have small positive Eu anomalies, with one sample having a large negative Eu anomaly, and all Kangding samples have a flat, slightly concave up pattern from the MREE-HREE (Fig. 42). The Group I mafic dykes from Lin et al. (2007) show a similar slope and enrichment in the LREE as the Gunbarrel samples. Some Group I samples have a small negative Eu anomaly while others display no noticeable positive or negative Eu anomalies and all Group I samples have moderate slopes in the MREE that flatten out by the end of the HREE. There is much more spread in REE concentrations in the Group I mafic dykes compared to the Gunbarrel LIP (Fig. 42). Group II mafic dykes from Lin et al. (2007) show minor LREE enrichments and flat REE patterns (Fig. 42). The two volcanic rock samples from Jiangnan Orogen have large LREE enrichments and a steep slope from La to Sm and small to moderate negative Eu anomalies. The dacite sample has a steep slope from Gd to Er while the tuff sample has a relatively flat slope and the two samples converge on Tm and flatten out (Fig. 43). The granite samples from the Jiangnan Orogen also have large LREE enrichments and steep slopes from La to Sm and all have large negative Eu anomalies (Fig. 43). The granites then have flat, slightly concave upwards patterns from the MREE to HREE (Fig. 43). In primitive mantle normalized multi element plots, the Kangding dykes from Li et al. (2003) have large LREE enrichments, moderate to large Nb-Ta troughs, large K peaks, flat MREE slopes and a moderate slope from Zr to Y with samples becoming more enriched in Yb and Lu (Fig. 44). For the Group I mafic dykes, they share some similarities with the Gunbarrel LIP. The Group I dykes display a trough from Rb to K, moderate depletions in Sr and P and a moderate slope from the MREE to HREE with some samples having small negative Zr and Eu anomalies (Fig. 44).

Figure 40: Nb/Y vs. Zr/Ti classification diagram after Pearce (1996) (after Winchester and Floyd, 1977) for Gunbarrel and South China samples. Alk. – alkalic, bas. – basalt, trach. – trachyte, andes. – andesite. for South China and Gunbarrel magmatism.

Figure 41: Classification diagrams for South China samples and Gunbarrel LIP. A) AFM diagram from Irvine and Baragar, (1971). Alk – alalkies ($\text{Na}_2\text{O} + \text{K}_2\text{O}$), Gun – Gunbarrel LIP. B) Nb/8-La/10-Y/15 diagram after Cabanis and Lecolle (1989). VAT – volcanic arc tholeiite, Cont. – continental basalt, EMORB – enriched mid-ocean ridge basalt, NMORB – normal mid-ocean ridge basalt, Gun – Gunbarrel LIP.

Figure 42: Chondrite normalized rare earth element (REE) plot for South China mafic magmatism and Gunbarrel LIP. Normalization values from Sun and McDonough (1989).

Figure 43: Chondrite normalized rare earth element (REE) plot for South China volcanic and granitic magmatism and Gunbarrel LIP. Normalization values from Sun and McDonough (1989).

Figure 44: Primitive Mantle normalized rare earth element (REE) plot for South China mafic magmatism and Gunbarrel LIP. Normalization values from Sun and McDonough (1989).

Figure 45: Primitive Mantle normalized rare earth element (REE) plot for South China volcanic and granitic magmatism and Gunbarrel LIP. Normalization values from Sun and McDonough (1989).

The Group II mafic dykes have patterns very different from the Gunbarrel LIP with large LREE enrichments, large negative troughs from Th to Ta, except for two samples which have a large U peak. All samples have large K peaks, likely due to alteration, and relatively flat signature from La to Lu (Fig. 44). The Jiangnan volcanic rocks and granites share similar patterns with the Gunbarrel LIP, although often at more enriched or depleted values. The samples have large LREE enrichments and large Nb-Ta troughs, large K peaks and large Sr-P troughs. The samples have shallower slopes from the MREE to HREE with large, negative Eu and Ti depletions (Fig. 45).

Since the South China studies do not include Pb or Sr isotopic data, $\epsilon\text{Nd}(t)$ ($t=780$ Ma or 760 Ma for Kangding dykes from Li et al. (2003)) values for some South China and Gunbarrel samples were plotted against incompatible element ratios to determine if any correlations and similarities could be determined for the two continents. In a La/Sm vs $\epsilon\text{Nd}(t)$ plot, distinct grouping can be seen between the samples from South China. The Group II mafic dykes from Lin et al. (2007) have the highest ϵNd values at +5.42-8.62 and low La/Sm ratios of 0.5 – 2.7 plotting to the upper left corner of the other samples. The Jiangnan granites and volcanic rocks of Zheng et al. (2008) have the lowest ϵNd values at +0.72 to -1.87 and some of the highest La/Sm ratios. The Group I mafic dykes of Lin et al. (2007) and the Kangding dykes of Li et al. (2003) have comparable ϵNd values (+0.9 to +4.56) to Gunbarrel samples but the Group I mafic dyke from Lin et al. (2007) have larger La/Sm ratios whereas the Kangding dykes of Li et al. (2003) have comparable La/Sm ratios to the Gunbarrel samples (Fig. 46).

Figure 46: La/Sm vs. $\epsilon Nd(t)$ plot for select South China and Gunbarrel samples.

Figure 47: Nb/Yb vs. Th/Yb after Pearce (2008) for South China and Gunbarrel LIP magmatism. NMORB- normal mid-ocean ridge basalts, EMORB – enriched mid-ocean ridge basalts, OIB – ocean island basalts.

Group II mafic dyke samples from Lin et al. (2007) do not share similar geochemistry with Gunbarrel magmas on many discriminatory diagrams. They plot as volcanic arc tholeiites and have relatively flat REE patterns on a chondrite normalized REE plot. They also plot just above N-MORB on a Pearce (2008) diagram suggesting only minor amounts of crustal component (Fig. 47). Finally, the epsilon Nd(t) values are much higher than Gunbarrel samples at +5.42 to +8.62, suggesting these magmas were derived from a depleted asthenospheric mantle source (Lin et al. 2007). These magmas do not appear to be linked with Gunbarrel magmas, however, Lin et al. (2007) believes that they were formed from a LIP event. Group I samples from Lin et al. (2007) plot between tholeiitic and calc-alkaline basalts and in a La/10-Y/15-Nb/8 diagram most samples plot in the calc-alkaline field while two samples plot in the continental field, albeit below Gunbarrel values. In a chondrite normalized REE plot, the Group I samples have a steeper slope than Gunbarrel samples from the LREE to HREE, indicating their magmas were generated at greater depths than Gunbarrel magmas. Group I samples do show a Nb-Ta depletion in a primitive mantle normalized multi-element plot, and also plot above the basalt array around E-MORB on a Pearce (2008) plot near Gunbarrel samples. The Kangding dykes of Li et al. (2003) are calc-alkaline basalts to basaltic andesites. They have also experienced crustal contamination as seen in Figure 47. However, they are in between N-MORB and E-MORB, suggesting insufficient magma mixing to homogenize samples and while one sample plots in the continental flood basalt field in Figure 41b, the other three plot as calc-alkaline and in between volcanic arc tholeiites and calc-alkaline. The Group I dykes and Kangding dykes do have similar ϵ_{Nd} values as Gunbarrel rocks. While the Group I samples and Kangding samples share some

similarities as the Gunbarrel magmas, since the Gunbarrel LIP has such a tight geochemical signature, Group I dyke and Kangding dykes samples do not appear to be fed from the same magma source. While the South China samples do not share a common source with the Gunbarrel LIP, they may share a similar one, as seen in the enriched MORB affinities, similar Nd isotopic ratios and Nb-Ta depletions suggesting an arc environment or inclusions of an arc-like component melt, such as a metasomatized lithospheric mantle above an ancient subduction slab. The granitic rocks and volcanic rocks, while they share similarities to each other, do not share many similarities with the Gunbarrel rocks. The granites and volcanic rocks plot as calc-alkaline, and in chondrite normalized and primitive mantle normalized multi-elements plots their patterns do not match the Gunbarrel LIP. The granites and volcanic rocks appear to be formed from shallower melting, likely in the plagioclase stability field of the mantle, of an enriched source. ϵNd values are also consistently lower than Gunbarrel values. Therefore, it is unlikely that the granitic rocks or volcanic rocks are related to Gunbarrel rocks. Li et al. (2003) and Lin et al. (2007) believe that this bimodal magmatism was the product of a mantle plume underneath South China. It may be that the same mantle plume which generated Gunbarrel magmas on the Laurentian side simultaneously generated melting underneath South China which produced the varying mafic and granitic magmatism seen on the South China block, but unrelated to the Gunbarrel LIP.

7.5 Future work

One of the most used tools for determining links between LIPs is precise U-Pb geochronology. Many of the areas studied in this thesis contain multiple generations of intrusions with some, like in the Tobacco Root Mountains, being sub-parallel to parallel to each other. This makes sampling difficult to only obtain specific units as older maps often describe all intrusions as “Proterozoic dykes”. High precision dating can be used to clearly identify age groups within each area, and in other continental blocks. If other examples of 780 Ma magmatism are identified in western North America, they can be tested against the Gunbarrel LIP. This is also true for magmatism on other continental blocks such as South China and Australia. This would help in strengthening reconstruction models for Rodinia.

Since it was determined in this study that the Irene and Huckleberry metavolcanic rocks are unlikely to belong to the Gunbarrel LIP based on geochemistry and isotopic data, it must be considered if they belong to another igneous event as continental flood basalts or are merely products of localized volcanism due to rifting of Rodinia. The younger T_{DM} ages may indicate a younger event. In northern Canada the 725 Ma Franklin LIP may have extended south similar to the Gunbarrel and fed the I&H metavolcanic rocks.

Finally, LIPs have been known to house world class economic deposits, and while preliminary results from this study show that the Gunbarrel LIP has some potential, further study is warranted. However, it is unlikely that a layered intrusions would be present on the Laurentian block as the plume head center is located off North America. Some of the sills for the Hottah Sheets are quite thick, and performing stratigraphy on individual sills may show small reefs.

Chapter 8: Summary and Conclusions

The intrusions and Little Dal Basalts that make up the Gunbarrel LIP of western North America are a homogeneous suite of rocks that share similar petrographical, geochemical and isotopic signatures despite the vast distances between units. This indicates that the Gunbarrel magmas were generated by a single source and possibly fed from a single magma chamber. Gunbarrel rocks are high Fe-Ti tholeiitic basalts with continental geochemical signatures and some arc like affinities. Gunbarrel magmas were formed from melting at depths of <75 km from an asthenospheric (N-MORB + E-MORB, plume?) source which incorporated at least one additional, likely lithospheric component (metasomatized sub-continental lithospheric mantle or middle crust). Mixing likely occurred early in magma generation rather than during emplacement based on the homogeneity of magmas and lack of crustal xenolith evidence in the field. Gunbarrel magmas were hot and turbulent and able to effectively mix all components into a homogeneous source with an E-MORB signature which fed the large intrusions that then cooled slowly upon emplacement as indicated by ilmenite-titano-magnetite geothermobarometry. While there is a small amount of scatter/spread in Pb and Sr isotopes, Nd isotopic ratios are very similar. Any minor geochemical, petrographical or isotopic differences seen across units are likely due to individual intrusions undergoing selective metamorphic and alteration conditions. Altogether, this study has provided a robust petrographical, geochemical and isotopic “fingerprint” for the Gunbarrel LIP that can be compared to other units within North America or on other continental blocks to determine if there are any linkages.

The Irene and Huckleberry metavolcanic rocks of Washington, State were correlated to the Gunbarrel LIP based on an imprecise Sm-Nd isochron age of 762 +/- 44 Ma. Upon investigation it has been concluded that the Irene and Huckleberry metavolcanic rocks were not fed from nearby Gunbarrel intrusions and are not related to the Gunbarrel LIP. Geochemically they also show affinities for continental tholeiitic basalts formed from moderate depth of melting of an enriched mantle source but they do not show incorporation of a lithospheric components and arc-like signatures as Gunbarrel samples do. Also, the Irene and Huckleberry metavolcanic rocks have substantially different Nd isotopic ratios, with their ϵ_{Nd} values being higher than Gunbarrel intrusions. While the Irene and Huckleberry metavolcanic rocks were not from the same source as the Gunbarrel LIP, they may still be related to the extensional event that created the Gunbarrel LIP, or they are part of a coeval LIP on the continental block that was adjacent to Laurentia at the time of Rodinia.

The Gunbarrel LIP shares many geochemical characteristics with LIPs with known Ni-Cu-PGE deposits, including high and low levels of Pt and Pd, variable chalcophile depleted magmas, and sulphide removal likely due to S-saturation. These make the Gunbarrel LIP, and possibly individual sills, potential targets for Ni-Cu-PGE exploration. However, many deposits are found within limited proximity to the plume head center of a LIP. The plume head center for the Gunbarrel LIP is estimated to lie off of Vancouver Island, Canada, leaving only a small area of land within the likely proximity of the plume head center. Much of the land area is also located within the highly deformed and metamorphosed Rocky Mountain foreland uplifts which mean the probability of finding a large ore body on the North American block decreases

substantially. This is why Rodinia reconstructions provide possibilities of locating potential ore bodies on blocks that were adjacent to North America during the emplacement of the Gunbarrel LIP.

The timing of the Gunbarrel LIP coincides with the breakup of Rodinia, and while there are multiple theories on what was adjacent to Laurentia during Rodinia times, this study examined the “Missing Link” model which places the South China Block as nearest neighbours to Laurentia. The South China Block has bi-modal episodic magmatism at 825 Ma, 780 Ma and 760 Ma. 780 Ma mafic dykes, granites and minor volcanic rocks were compared to the robust geochemical and isotopic “fingerprint” of the Gunbarrel LIP (this study). While some mafic dykes from the Kangding rift shared some similarities, most notably similar Nd isotopic ratios, the South China samples did not match the Gunbarrel LIP on many geochemical patterns. Again, like the Irene and Huckleberry metavolcanic rocks it is clear the South China rocks and Gunbarrel rocks were not fed from the same source and magma chamber, but it is difficult to say if they are not related at all. An anomalously hot mantle plume (thought to be underneath South China) would likely cause mantle melting at various depths and locations around the plume. The intrusions in South China are also on a much smaller scale, being only meters thick, compared to Gunbarrel intrusions which are 10’s of meters thick. It is also clear that the South China dyke swarms are not related to each other. The fact that there is 825 Ma magmatism in Australia and South China, and 780 Ma magmatism in South China and Laurentia still make South China a good fit in between Laurentia and Australia. The next step would be to test the Gunbarrel “fingerprint” with other possible candidates to see if a petrogenetic link can be found, such as in Australia.

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Appendix A: Conference Abstracts

***Fingerprinting the 780 Ma Gunbarrel LIP; a petrographical, geochemical and isotopic study of dykes, sills and volcanic rocks from western North America.**

¹A. Mackinder, ¹R. Ernst and ¹B. Cousens

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Along the western margin of North America lie dykes, sills and volcanic rocks that have been dated by U-Pb, Ar-Ar and Sm-Nd methods at 780 Ma and have been correlated to be part of the Gunbarrel Large Igneous Province (LIP). These units span for more than 2500 km from the Yukon and Northwest Territories, Canada, to Montana, Wyoming and Washington, United States. The intrusions of the Gunbarrel are medium to coarse grained diabase dykes and sills that are 10's of meters in thickness/width. Despite the distances between units the intrusions share remarkably similar geochemical signatures. They plot as tholeiitic basalts to basaltic andesites with moderate to large negative Nb-Ta anomalies and Pb peaks and a moderate MREE-HREE slope on primitive mantle normalized multi-element plots with Mg#'s between 0.27-0.46. These data suggests that Gunbarrel magmas derived from low degrees of partial melting in the spinel field at moderate depths in the mantle and experienced lithospheric interaction and magma mixing.

The Irene and Huckleberry metavolcanic rocks of Washington State have been correlated with the Gunbarrel LIP based on Sm-Nd age dates. They have been metamorphosed into the greenschist facies and often display different geochemical signatures than the rest of the intrusions on a variety of discrimination diagrams and Nd isotopic ratios. This indicates they were not fed from the Gunbarrel intrusions and were likely not part of the same event.

Gunbarrel intrusions consist of both chalcophile-element depleted and undepleted magmas based on a (Cu/Yb)PM vs. (Th/Yb)PM plot and show trends towards crustal contamination which suggests possible occurrence of S-saturation and possible sulphide immiscibility with the potential to produce Ni-Cu-PGE deposit somewhere in the plumbing system.

LIPs have also been linked with the breakup of supercontinents throughout time, and the timing of the Gunbarrel coincides with the breakup of the Proterozoic supercontinent Rodinia. Both South China and central Australia have intraplate magmatism of similar age that is also likely part of the Gunbarrel LIP, although the exact Rodinia reconstruction of these two blocks against western Laurentia remains debated. Our geochemical and isotopic data will be compared with published data from ca. 780 Ma units in South China to assess any petrogenetic linkages between these two continents.

*Abstract for 2014 Advances in Earth Sciences Research Conference (AESRC) 2014, Ottawa, Ontario.

Appendix B: Sample locations and coordinates

Sample	Geographic Area	Name	Sample Location	Latitude (°N)	Longitude (°W)
<i>Intrusions</i>					
12-MT-01	TRM (MT)	TRM Dyke	skree slope	45.3673	111.9177
12-MT-02	TRM	TRM Dyke	near dyke center	45.3665	111.9179
12-MT-03	TRM	TRM Dyke	dyke margin	45.3665	111.9179
12-MT-09	TRM	TRM Dyke	dyke center	45.4206	112.1116
12-MT-10	TRM	TRM Dyke	dyke margin	45.4206	112.1116
12-MT16	TRM	TRM Dyke	dyke center	45.3961	111.8781
13-AM-01	Beartooth Mtns (MT-WY)	X-Mas Lake Dyke	dyke center	44.9752	109.4339
13-AM-02	Beartooth Mtns	X-Mas Lake Dyke	dyke margin	44.9752	109.4339
13-AM-03	Beartooth Mtns	X-Mas Lake Dyke	near dyke center	44.9693	109.4360
13-AM-11	Northern MT	Wolf Creek Sill	near sill center?	47.0200	112.2099
13-AM-13	TRM	TRM Dyke	dyke center	45.4258	112.1327
13-AM-14	TRM	TRM Dyke	near dyke margin	45.4222	112.1086
13-AM-15	TRM	TRM Dyke	near dyke center	45.4230	112.1054
13-AM-26	Belt Basin (ID)	Turah Sill	near sill margin	46.8754	113.8561
TR-45*	TRM	TRM Dyke	unknown	45.3500	111.8280
TR-62*	TRM	TRM Dyke	unknown	45.3689	111.9274
91LAAT2-1**	Muskwa Ranges (BC)	Mucho Lake Dyke	near dyke margin	58.7830	125.6660
91LAAT2-2**	Muskwa Ranges	Mucho Lake Dyke	dyke center	58.7830	125.6660
91LAAT2-3**	Muskwa Ranges	Mucho Lake Dyke	dyke center	58.7830	125.6660
94LAAT1-2A**	Teton Range (WY)	Mount Moran Dyke	talus block	43.8334	110.7734
94LAAT003-1A**	Teton Range (WY)	Mount Moran Dyke	margin	43.8334	110.7734
<i>Volcanic rocks</i>					
12-MT-17	NE Washington State	I&H	near center of outcrop	48.3174	117.8414
12-MT-18	NE Washington State	I&H	large flow outcrop	48.3195	117.8171
12-MT-19	NE Washington State	I&H	skree	48.3347	117.8272
12-MT-20	NE Washington State	I&H	near center of outcrop	48.8714	117.1460
12-MT-21	NE Washington State	I&H	off of outcrop	48.8748	117.1465
12-MT-22	NE Washington State	I&H	center of outcrop	48.8808	117.1498
12-MT-23	NE Washington State	I&H	center of outcrop	48.8713	117.1448
12-MT-24	NE Washington State	I&H	near center of outcrop	48.9455	117.0955
12-MT-25	NE Washington State	I&H	near center of outcrop	48.9453	117.0917
12-MT-26	NE Washington State	I&H	large flow outcrop	48.7679	117.2923
12-MT-27	NE Washington State	I&H	small outcrop	48.3347	117.8272
13-AM-25	NE Washington State	I&H	small rounded outcrop	48.3161	117.8399

Coordinate system NAD27. TRM – Tobacco Root Mountains, Mtns- Mountains, X-MAS – Christmas, I&H – Irene and Huckleberry metavolcanic rocks, *samples obtained from Dr. Steven Harlan, **samples obtained from Dr. Anthony LeCheminant.

Appendix C: Petrography summaries

Sample	Location	Name	Plag	Pyx	Opq	Bt	Amph	Qtz	Alk. Feld	Chlr	Ep	Trace
12-MT-01	TRM	TRM dyke	50	25	10	3	8	2	1	1	-	Ap, Zr, py, chalco
12-MT-02	TRM	TRM dyke	45	30	10	3	5	4	3	1	-	Ap, Zr, py, chalco
12-MT-03	TRM	TRM dyke	50	25	8	2	6	4	3	2	-	Ap, Zr, Ttn
12-MT-09	TRM	TRM dyke	48	25	7	2	8	4	3	2	-	Ap, Ttn, Zr
12-MT-10	TRM	TRM dyke	50	27	12	1	5	2	1	2	-	Ap
12-MT-16	TRM	TRM dyke	70	20	3	1	3	2	-	-	-	Ap, Ttn,
91LAA T2-1	North B.C	Mucho Lake dyke	55	30	10	1	3	2	1	-	-	Ap, chalco, Badd, Zr
91LAA T2-2	North B.C	Mucho Lake dyke	55	25	5	1	8	4	2	-	-	Ap, chalco, Badd, Zr
91LAA T2-3	North B.C	Mucho Lake dyke	50	35	8	1	4	2	1	1	-	Ap, Zr, chlaco
94LAA T1-2A	Teton Range	Mount Moran dyke	55	30	4	1	4	3	2	1	-	Zr, badd
94LAA T003-1A	Teton Range	Mount Moran dyke	60	25	10	1	2	2	1	1	-	Ap, Zr, , rut
TR-45	TRM	TRM dyke	45	40	5	1	3	2	1	1	-	Ap, Zr
TR-62	TRM	TRM dyke	70	12	2	2	4	8	2	1	-	Ap, Zr
13-AM-01	Beartooth Mtn	X-Mas Lake dyke	60	27	6	1	3	2	1	1	-	Ap, chalco, Zr,
13-AM-02	Beartooth Mtn	X-Mas Lake dyke	50	30	7	1	4	3	2	2	-	Ap, rutile, py, chalco, Zr
13-AM-03	Beartooth Mtn	X-Mas Lake dyke	60	27	5	1	4	2	1	-	-	Ap, chlr,
13-AM-11	North Montana	Wolf Creek Sill	60	30	4	1	2	1	1	-	-	Ap, chalco, py, opx
13-AM-13	TRM	TRM dyke	50	25	4	3	8	8	2	1	-	Ap, Zr, py, chalco
13-AM-14	TRM	TRM dyke	55	25	7	3	4	3	1	-	-	Ap, rutile
13-AM-15	TRM	TRM dyke	45	30	10	1	6	5	2	2	-	Ap, Zr, chlaco
12-AM-26A	Belt Supergroup	Turah Sill	40	3	5	-	20	2	-	28	2	Ap, Ttn
13-AM-26B	Belt Supergroup	Turah Sill	65	15	3	-	10	5	-	3	-	Ap, py, Zr

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Sample	Location	Name	Plag	Pyx	Opq	Bt	Amph	Qtz	Alk. Feld	Chlr	Ep	Trace
MT-17	North WA	I&H	20	10	2	-	4	1	-	5	4	Py, chalco
MT-18	North WA	I&H	10	-	1	-	15	2	1	15	10	Ap, py, chalco, Zr
MT-19	North WA	I&H	10	2	2	-	3	4	-	8	8	Py, chlaco
MT-20	North WA	I&H	25	-	10	5	4	10	-	15	5	-
MT-21	North WA	I&H	35	-	1	-	15	5	-	30	2	Ap, py, chalco
MT-22	North WA	I&H	40	-	10	-	20	5	-	20	-	Ap, clays
MT-23	North WA	I&H	30	-	2	-	-	3	-	50	2	Chalco, Ttn
MT-24	North WA	I&H	10	-	20	-	10	10	-	40	-	Ap, Ttn, py
MT-25	North WA	I&H	10	2	5	1	20	-	10	40	10	Calcite, chalco, Ttn
MT-26	North WA	I&H	20	5	10	-	15	10	-	25	-	Alk. Feld
MT-27	North WA	I&H	15	-	18	35	20	10	-	2	-	Xenotime,
13-AM-25A	North WA	I&H	25	10	2		5	1	1	10	3	Py, Ttn
13-AM-25B	North WA	I&H	20	6	1	-	3	5	-	15	3	Py, chalco

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Appendix C: Petrography summaries

Sample	Location	Comments
12-MT-01	TRM	medium grained, sub-ophitic texture, plagioclase laths (1-2.5 mm) are highly altered to sericite and sub-hedral cpx (0.2-1.5 mm) have alteration rims of amphibole. Hornblende and biotite grains starting to alter to chlorite. Oxides are blocky to skeletal and quartz is found interstitially and intergrown with alkali feldspar in granophyre
12-MT-02	TRM	medium grained, sub-ophitic texture, very similar to 12-MT-01
12-MT-03	TRM	medium grained, ophitic texture, minor to moderate sericitization of euhedral blocky to elongate plagioclase and euhedral to anhedral cpx. There is ~2% granophyre.
12-MT-09	TRM	medium grained, ophitic texture, plagioclase laths (0.5-3 mm) have been highly sericitized, cpx is euhedral to sub-hedral prisms (0.5-1.5 mm) with alteration rims of amphibole. There is 3% granophyre.
12-MT-10	TRM	finer grained, ophitic texture, some hematite staining on grains. Plagioclase laths (0.3 - 1 mm) are highly altered and cpx sub-hedral prism/laths (0.5 mm) have alteration rims of amphibole. There is ~2% granophyre.
12-MT-16	TRM	medium grained, sub-ophitic texture, plagioclase are highly altered to sericite, oxides are globular and skeletal. Cpx are altering to amphibole.
91LAA T2-1	North B.C	finer grained, ophitic texture, minor alteration of plagioclase laths. Cpx are stubby to elongate prisms with some brown amphibole rims. Oxides are stubby to skeletal and some quartz is intergrown with alkali feldspar in granophyre, while other quartz is interstitial.
91LAA T2-2	North B.C	medium grained, ophitic texture, minor sausseritization of randomly oriented plagioclase laths (mm's), cpx partly altered to hornblende and sometimes have alteration rims of amphibole (hornblende-actinolite), quartz is mainly intergrown with alkali feldspar in granophyre but also a few interstitial grains
91LAA T2-3	North B.C	medium grained, ophitic texture very similar to 91LAAT2-2
94LAA T1-2A	Teton Range	medium grained, slightly porphyritic with a few larger 4-6 mm cpx phenocrysts, plagioclase are highly altered to sericite, cpx are stubby, sub-hedral crystals moderately altered to brown amphibole.
94LAA T003-1A	Teton Range	medium grained, ophitic texture, plagioclase are lightly to moderately altered to sericite, and cpx altering to amphibole. Oxides are stubby and globular and there is ~1% granophyre.
TR-45	TRM	coarser grained than other samples, sub-ophitic texture. Minor alteration of plagioclase laths by sericite, cpx are subhedral to anhedral prisms, quartz is intergrown with alkali feldspar in granophyre as well as found as interstitial quartz.
TR-62	TRM	coarser grained than other samples, sub-ophitic texture, plagioclases are highly altered by sericite and cpx are moderately replaced by brown amphibole (hornblende). Quartz is found interstitially and intergrown with alkali feldspar in granophyre.
13-AM-01	Beartooth Mtn	medium grained, ophitic texture. Moderate sericite alteration of plagioclase laths, quartz intergrown with alkali feldspar in granophyre with some interstitial grains. Cpx are subhedral and altering to hornblende, oxides are anhedral blocky to skeletal

Sample	Location	Comments
13-AM-02	Beartooth Mtn	medium grained ophitic texture, plagioclase are euhedral prisms to laths (0.3-2.5 mm) and are moderately altered by sericite. Cpx are euhedral to subhedral prisms to elongate laths (0.2-2.3 mm) with some rims altered to hornblende. Quartz and alkali feldspar are intergrown in granophyre with some interstitial quartz with rutile and apatite inclusions
13-AM-03	Beartooth Mtn	coarser grained than other samples, ophitic texture, plagioclase are laths that are lightly altered by sericite, cpx are anhedral and blocky with rims of hornblende, bt are small grains which are being altered to chlorite, amphibole is hornblende, quartz and alkali feldspar are intergrown in granophyre
13-AM-11	North Montana	medium grained, sub-ophitic texture. Plagioclase are randomly oriented laths with minor to moderate amounts of sericite alteration, cpx are pristine and show little alteration. Oxides are stubby blocks to anhedral masses and quartz is found as interstitial grains and intergrown with alkali feldspar in granophyre.
13-AM-13	TRM	medium grained, sub-ophitic texture and plagioclases are highly sericitized. Oxides are anhedral and there is ~2% granophyre.
13-AM-14	TRM	medium grained, sub-ophitic texture. Plagioclases have highly altered and pristine crystals. Oxides are blocky to skeletal and there is ~2% granophyre
13-AM-15	TRM	Finer grained, sub-ophitic to ophitic in texture. Plagioclases are highly altered to sericite and cpx is lightly altered to amphibole, oxides are blocky to skeletal and there is ~3% granophyre.
12-AM-26A	Belt Supergroup	medium grained, ophitic texture. Near the fault scarp and highly altered. Slickelines of actinolite and chlorite on surface. Large veins of calcite are present
13-AM-26B	Belt Supergroup	medium grained, ophitic texture. Plagioclases and clinopyroxenes are highly altered to sericite and amphibole/orthopyroxene respectively. Large chlorite sheets are also present.
12-MT-17	North WA	brecciated tuff. Large clasts of porphyritic basalt with phenocrysts of plagioclase and cpx in an opaque to semi-opaque glassy matrix. There are spheroids (0.5 -1.5 mm) in filled with either calcite, clays, chlorite, titanite or an unknown mineral/mixture of minerals. Other clasts are composed of fine grained chlorite
12-MT-18	North WA	dark green, porphyritic and moderately foliated. Groundmass (40%) is composed of chlorite, sericite, quartz and clays. Small veins of calcite are also present. Phenocrysts are plagioclase, amphibole and epidote.
12-MT-19	North WA	dark green, porphyritic with plagioclase, epidote and pyroxene pseudomorphs now amphibole phenocrysts. There are large flake of chlorite with anomalous blue interference colours. Groundmass (63%) is fine grained and appears to be composed of chlorite, sericite and clays.
12-MT-20	North WA	light grey, fine grained, uniform, moderately foliated. Lots of carbonate in the rock (25%). Oxides are elongated and broken up.
12-MT-21	North WA	light green in thin section, fine grained and foliated. Chlorite and amphibole are intergrown and appear to make up 45% of the thin section. Calcite in fill small veins (10%)
12-MT-22	North WA	fine grained, and foliated. Calcite veins and some individual grains in groundmass. Chlorite, amphibole, plagioclase, oxides, quartz and clays make up the groundmass.

Sample	Location	Comments
12-MT-23	North WA	porphyritic, amygdaloidal with quartz and epidote infilling vesicles. Plagioclase in matrix completely replaced by sericite and large white mica grains. Large (0.8-1.5 mm) phenocrysts of amphibole (actinolite) are present.
12-MT-24	North WA	fine grained, amygdaloidal, massive. Calcite veins and calcite and quartz are infilling vesicles (10%), fine grained plagioclase and quartz in matrix (20%), chlorite and amphibole are intergrown in matrix
12-MT-25	North WA	porphyritic, amygdaloidal, foliated. Euhedral epidote along with quartz and sometimes oxides are infilling vesicles, actinolite phenocrysts (5%), fine grained quartz and plagioclase make up part of the matrix (15%) but are difficult to distinguish. Fine grained intergrown chlorite and amphibole make up the rest of the matrix.
12-MT-26	North WA	porphyritic but more medium grained, amygdaloidal, foliated. Calcite in matrix and vesicles (15%), actinolite sub-hedral to euhedral prisms phenocrysts (0.3-3 mm). Cpx phenocrysts are being replaced by amphibole. Groundmass is composed of chlorite, plagioclase, quartz, amphibole, oxides and clays.
12-MT-27	North WA	more of a biotite schist, fine-medium grained, foliated with oxides, plag and quartz, amphibole are acicular anthophyllite in vesicles? clasts?
13-AM-25A	North WA	brecciated tuff, 2 large clasts of porphyritic basalt. Phenocrysts of plagioclase (<0.5 - 1.5 mm) and cpx (0.2 -0.5 mm) set in a glassy matrix. phenocrysts of plagioclase (10%) and cpx (10%) and larger chlorite grains (2%). Groundmass is composed of fine grained chlorite, plag, clays, and amphibole.
13-AM-25B	North WA	fine grained, porphyritic and amygdaloidal. Vesicles in filled with large chlorite sheets, epidote and oxides. There are phenocrysts of plagioclase (5%) (0.5-1 mm), cpx (0.5 mm) and epidote (0.4 mm). The groundmass is composed of chlorite, amphibole, plagioclase, sericite, quartz and minor oxides.

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Appendix D: Major and trace element geochemical data

Sample	12-MT-01	12-MT-02	12-MT-03	12-MT-09	12-MT-10	13-AM-01
<i>Major elements (wt%)</i>						
Al₂O₃	12.52	12.75	11.71	12.27	12.54	13.26
CaO	7.50	7.94	8.29	7.85	7.21	7.45
FeO	15.04	14.99	16.81	15.79	15.41	14.92
K₂O	1.41	1.32	1.08	1.23	1.59	1.50
LOI	0.67	0.53	0.05	1.52	0.87	0.95
MgO	3.84	4.25	4.88	4.38	3.85	3.19
MnO	0.21	0.21	0.24	0.25	0.22	0.22
Na₂O	2.72	2.64	2.41	2.49	2.54	2.77
P₂O₅	0.28	0.23	0.19	0.23	0.25	0.27
SiO₂	50.46	50.34	48.91	49.13	50.43	51.51
TiO₂	2.50	2.47	2.88	2.49	2.71	2.58
Total	98.83	99.34	99.32	99.39	99.33	100.29
Mg#	0.31	0.34	0.34	0.33	0.31	0.28

Sample	13-AM-02	13-AM-03	13-AM-11	13-AM-13	13-AM-14	13-AM-15
<i>Major elements (wt%)</i>						
Al₂O₃	12.26	12.28	13.16	11.65	12.25	12.40
CaO	8.11	8.36	9.53	7.40	8.15	8.05
FeO	15.65	15.65	14.07	16.10	15.76	15.49
K₂O	1.26	1.19	0.83	1.40	1.16	1.09
LOI	0.74	0.44	0.64	0.84	0.90	1.09
MgO	4.38	4.40	5.78	3.95	4.48	4.11
MnO	0.22	0.22	0.23	0.24	0.22	0.22
Na₂O	2.42	2.32	2.29	2.56	2.43	2.59
P₂O₅	0.24	0.25	0.19	0.30	0.22	0.25
SiO₂	50.66	50.75	49.88	51.38	50.42	50.71
TiO₂	2.58	2.58	2.20	2.56	2.60	2.62
Total	100.26	100.17	100.38	100.17	100.33	100.33
Mg#	0.33	0.33	0.42	0.41	0.30	0.32

Sample	13-AM-26B	TR-45	TR-62	91LAAT2-2	91LAAT2-1	91LAAT2-3
<i>Major elements (wt%)</i>						
Al ₂ O ₃	12.53	12.45	14.52	12.10	12.03	10.79
CaO	9.78	7.71	7.10	8.17	7.82	8.70
FeO ^T	13.73	15.64	12.47	16.12	16.02	17.63
K ₂ O	0.78	1.21	1.69	1.38	1.20	1.11
LOI	1.58	1.15	0.77	0.75	0.85	0.50
MgO	5.68	4.20	2.64	4.73	4.28	5.68
MnO	0.25	0.23	0.18	0.24	0.22	0.26
Na ₂ O	2.54	2.58	3.06	1.99	2.19	1.79
P ₂ O ₅	0.23	0.23	0.32	0.29	0.31	0.24
SiO ₂	49.29	49.81	53.53	48.34	48.73	46.76
TiO ₂	2.24	2.65	1.92	3.05	3.19	3.46
Total	100.16	99.60	99.58	98.94	98.63	98.88
Mg#	0.42	0.32	0.27	0.34	0.32	0.36

Sample	94LAAT1-2A	94LAAT003-1A	12-MT-17	12-MT-18	12-MT-19	12-MT-20
<i>Major elements (wt%)</i>						
Al ₂ O ₃	12.77	12.89	12.85	12.84	12.97	11.47
CaO	9.15	7.42	8.72	9.59	7.08	15.74
FeO ^T	14.21	14.31	12.30	14.14	13.37	6.04
K ₂ O	0.82	1.57	0.78	1.02	0.46	1.16
LOI	0.77	0.56	2.15	2.89	2.94	14.58
MgO	5.20	3.69	5.01	5.20	5.78	2.61
MnO	0.22	0.21	0.19	0.22	0.18	0.18
Na ₂ O	2.36	2.65	3.70	2.92	3.94	3.13
P ₂ O ₅	0.21	0.28	0.25	0.38	0.31	0.10
SiO ₂	49.65	52.08	50.11	45.26	48.45	42.42
TiO ₂	1.97	2.14	2.21	3.11	2.59	1.16
Total	98.91	99.39	99.64	99.15	99.56	99.27
Mg#	0.39	0.31	0.42	0.40	0.44	0.44

Sample	12-MT-21	12-MT-22	12-MT-23	12-MT-24	12-MT-25	12-MT-26
<i>Major elements (wt%)</i>						
Al₂O₃	13.05	11.62	13.50	10.96	13.51	8.89
CaO	9.07	11.37	15.88	7.54	8.40	11.70
FeO^T	10.38	10.97	11.94	14.38	13.60	13.27
K₂O	0.11	0.06	0.11	0.36	0.10	0.05
LOI	8.84	9.96	3.15	7.90	3.59	10.33
MgO	5.41	4.23	5.09	5.51	6.80	5.68
MnO	0.16	0.24	0.19	0.21	0.21	0.27
Na₂O	3.27	3.60	1.06	2.39	3.10	0.42
P₂O₅	0.45	0.55	0.24	0.41	0.28	0.71
SiO₂	44.02	42.75	44.56	44.43	44.97	43.70
TiO₂	2.93	2.98	2.13	3.23	2.62	2.37
Total	98.85	99.55	99.18	98.92	98.70	98.87
Mg#	0.48	0.41	0.43	0.41	0.47	0.43

Sample	12-MT-27	12-MT-19R	12-MT-22R	12-MT-24R	12-MT-25R	10-LT-05	1σ OGS	1σ ALS
<i>Major elements (wt%)</i>								
Al₂O₃	11.98	12.65	11.60	10.80	13.60	18.05	0.13	0.37
CaO	5.16	7.01	11.30	7.36	8.74	9.53	0.01	0.04
FeO^T	12.39	13.38	11.13	14.41	13.92	9.45	0.05	0.12
K₂O	0.56	0.44	0.05	0.35	0.09	1.02	0.01	0.01
LOI	0.88	2.92	9.29	7.41	3.46	0.66	0.12	0.10
MgO	7.73	5.58	4.18	5.36	6.73	6.60	0.08	0.04
MnO	0.13	0.18	0.24	0.20	0.21	0.14	0.00	0.01
Na₂O	1.95	3.88	3.61	2.38	3.17	3.51	0.02	0.03
P₂O₅	0.50	0.29	0.53	0.40	0.28	0.38	0.00	0.01
SiO₂	53.54	48.90	43.80	44.60	46.60	48.37	0.38	0.51
TiO₂	2.98	2.56	3.00	3.23	2.62	1.43	0.01	0.03
Total	99.18	97.79	98.73	96.50	99.42	99.13	0.55	1.04
Mg#	0.53	0.43	0.40	0.40	0.46			

All Fe is reported as total FeO, 10-LT-05 is internal standard and values are for average run. Standard deviation (1σ) was calculated from 5 runs and 2 duplicates for OGS values and 5 runs for ALS values. 12-MT-19R to 12-MT-25R are reanalysed Irene and Huckleberry metavolcanic rocks from ALS.

$$\text{Mg\#} = [\text{atomic Mg}^{2+} / (\text{Mg}^{2+} + \text{Fe}^{2+})]$$

OGS- Ontario Geological Survey Geoclabs, Sudbury, ON; ALS- ALS Laboratories, North Vancouver, BC

Appendix D: Major and trace element geochemical data

Sample	12-MT-01	12-MT-02	12-MT-03	12-MT-09	12-MT-10	13-AM-01
<i>Trace elements (ppm)</i>						
Ba	226.5	203.1	177	208.7	305.1	269.3
Be	1.44	1.39	1.17	1.24	1.33	1.52
Bi	0.078	0.073	0.141	0.085	0.074	0.144
Cd	0.15	0.13	0.14	0.26	0.13	0.18
Ce	46.66	42.25	37.19	40.12	43.31	49.86
Co	49.5	51.2	58.4	50.6	44.9	44.5
Cr	89	95	71	52	55	<24
Cs	1.07	1.55	1.48	0.48	1.2	2
Cu	255	232	366	226	251	278
Dy	8.05	7.32	6.82	7.19	7.61	8.25
Er	4.42	4.09	3.75	3.93	4.1	4.53
Eu	2.22	2.02	1.88	2.06	2.02	2.29
Ga	23.26	22.99	22.44	22.26	22.48	24.25
Gd	8.41	7.46	6.83	7.14	7.61	8.46
Hf	4.88	4.54	4.17	4.38	4.61	5.98
Ho	1.58	1.46	1.34	1.41	1.47	1.6
La	20.19	18.56	15.94	17.29	18.54	21.24
Li	13.6	14.2	12.5	19.8	15.6	24.3
Lu	0.56	0.52	0.49	0.5	0.52	0.59
Mo	1.56	1.49	1.26	1.2	1.25	1.16
Nb	12.29	11.61	10.59	11.44	12.23	14.05
Nd	30.26	26.88	24.07	25.5	27.17	30.33
Ni	37	43	51	49	41	25
Pb	7.1	6.6	5.6	4.9	6.6	12.8
Pr	6.67	6.1	5.36	5.69	6.08	6.87
Rb	55.18	52.79	42.23	45.19	52.09	60.83
Sb	0.27	0.29	0.22	0.26	0.27	0.34
Sc	33.2	34.7	39.5	33.7	31.7	31.1
Sm	7.62	6.83	6.27	6.68	6.93	7.73
Sn	2.22	2.08	1.73	2.09	2.24	2.12
Sr	184	183	175	179	198	277
Ta	0.9	0.8	0.7	0.8	0.8	0.9
Tb	1.297	1.173	1.089	1.146	1.174	1.315
Th	4.66	4.58	3.91	3.93	4.65	5.18
Ti	>12000	>12000	>12000	>12000	>12000	>12000
Tl	0.22	0.22	0.18	0.14	0.2	0.23
Tm	0.612	0.561	0.526	0.545	0.575	0.636
U	1.23	1.2	1.03	1.05	1.18	1.39
V	468.54	496.28	>500	>500	>500	370.25
W	0.8	0.78	0.65	0.74	0.73	0.83
Y	42.22	38.53	35.96	37.47	39.16	44.28
Yb	3.82	3.534	3.339	3.398	3.611	4.051
Zn	132.06	128.23	134.11	165.25	109.26	140.5
Zr	176	165	149	160	165	227

Sample	13-AM-02	13-AM-03	13-AM-11	13-AM-13	13-AM-14	13-AM-15
<i>Trace elements (ppm)</i>						
Ba	221.5	214.4	153.9	273.2	209.6	198.7
Be	1.36	1.32	0.95	1.59	1.32	1.43
Bi	0.127	0.144	0.136	0.118	0.088	0.084
Cd	0.17	0.15	0.2	0.17	0.21	0.13
Ce	43.18	44	29.88	54.29	42.39	45.74
Co	54.1	51.7	47.6	48.9	53.5	50.9
Cr	28	27	105	<24	26	<24
Cs	1.93	2.35	1.46	2.66	1.79	1.12
Cu	249	248	285	235	270	259
Dy	7.38	7.45	6.78	8.82	6.98	7.59
Er	4.13	4.13	3.89	4.91	3.94	4.22
Eu	2.03	2.07	1.77	2.45	1.93	2.04
Ga	22.69	22.45	21.33	23.1	22.14	23.04
Gd	7.59	7.67	6.52	9.01	7.15	7.63
Hf	5.25	5.22	3.77	5.34	4.67	5.24
Ho	1.45	1.47	1.35	1.74	1.39	1.48
La	18.36	18.85	12.01	22.97	17.97	19.44
Li	18.3	15.1	23.1	21.5	17.1	15.5
Lu	0.53	0.53	0.52	0.62	0.51	0.55
Mo	1.17	1.24	0.77	1.41	0.97	1.16
Nb	12.15	12	9.06	14.96	11.31	12.52
Nd	26.44	27.09	20.19	33.24	25.69	27.49
Ni	47	47	69	39	48	42
Pb	6.5	7	10.7	8.3	7.7	5.8
Pr	5.97	6.01	4.23	7.41	5.76	6.25
Rb	51.72	45.84	32.62	60.46	44.23	42.84
Sb	0.28	0.24	0.47	0.25	0.22	0.26
Sc	36.3	34.7	41	33.9	35.9	34.3
Sm	6.88	6.9	5.6	8.23	6.52	7.05
Sn	1.97	1.9	1.63	2.49	1.73	2.08
Sr	210	183	169	184	176	189
Ta	0.8	0.8	0.6	1	0.8	0.9
Tb	1.19	1.2	1.062	1.416	1.132	1.198
Th	4.47	4.55	2.16	5.44	4.26	4.71
Ti	>12000	>12000	>12000	>12000	>12000	>12000
Tl	0.2	0.2	0.15	0.24	0.17	0.16
Tm	0.572	0.576	0.545	0.681	0.546	0.582
U	1.26	1.25	0.56	1.42	1.1	1.26
V	499.72	>500	422.54	433.66	>500	492.6
W	0.7	0.72	<0.5	0.86	0.69	0.74
Y	39.78	39.6	37.09	47.83	37.9	40.97
Yb	3.632	3.636	3.515	4.244	3.462	3.725
Zn	139.09	135.73	143.83	171.91	155.33	146.28
Zr	201	197	138	200	172	200

Sample	13-AM-26B	TR-45	TR-62	91LAAT2-2	91LAAT2-1	91LAAT2-3
<i>Trace elements (ppm)</i>						
Ba	169.6	203	277	194.8	198.9	156.2
Be	0.94	1.29	1.85	1.34	1.54	1.09
Bi	0.078	0.11	0.12	0.102	0.128	0.14
Cd	0.12	0.13	0.17	0.2	0.17	0.16
Ce	29.86	42.94	60.86	44.45	49.57	37.71
Co	42.7	50.30	35.20	48.4	47	55.1
Cr	117	64.00	40.00	84	58	92
Cs	0.96	1.37	2.87	2.29	2.05	2.22
Cu	319	257	168	159	162	233
Dy	6.85	7.34	8.63	9.48	10.47	8.44
Er	3.91	3.99	4.68	5.6	6.07	4.99
Eu	1.69	2.02	2.52	2.17	2.39	1.89
Ga	20.46	22.65	24.94	22.02	22.76	20.47
Gd	6.74	7.40	9.13	8.89	9.7	7.81
Hf	2.65	4.68	5.29	5.73	6.2	4.88
Ho	1.37	1.42	1.67	1.91	2.07	1.72
La	12.12	18.20	26.69	18.53	20.62	15.58
Li	23.5	21.40	16.40	13.2	15.7	11.3
Lu	0.47	0.51	0.58	0.75	0.82	0.67
Mo	0.79	1.12	1.49	1.15	1.08	1.13
Nb	8.89	12.12	14.80	13.39	14.74	11.2
Nd	20.17	26.20	35.26	28.32	32.23	24.24
Ni	67	44.00	24.00	50	41	65
Pb	6	6.30	8.30	4.3	5.8	4.6
Pr	4.29	5.82	7.82	6.26	6.96	5.29
Rb	25.18	50.02	70.62	42.36	37.66	33.72
Sb	2.1	0.28	0.27	0.15	0.28	0.2
Sc	41.8	34.20	23.90	38.8	37.3	43.3
Sm	5.62	6.68	8.45	7.64	8.43	6.56
Sn	1.61	2.05	2.55	2.41	2.73	1.85
Sr	150	185	214	145	131	122
Ta	0.6	0.80	1.00	0.9	1	0.8
Tb	1.089	1.17	1.38	1.452	1.579	1.274
Th	2.08	4.29	6.87	3.98	4.37	3.25
Ti	>12000	>12000	11501	>12000	>12000	>12000
Tl	0.1	0.16	0.26	0.16	0.15	0.15
Tm	0.534	0.57	0.64	0.793	0.862	0.708
U	0.48	1.09	1.72	1.06	1.09	0.88
V	437.22	>500	279.26	>500	>500	>500
W	<0.5	0.79	0.93	0.52	0.61	<0.5
Y	37.11	39.07	45.49	52.22	56.59	45.75
Yb	3.325	3.57	3.98	5.07	5.533	4.519
Zn	93.33	121.43	140.34	140.15	155.69	146.41
Zr	86	171	201	212	229	179

Sample	94LAAT1-2A	94LAAT003-1A	12-MT-17	12-MT-18	12-MT-19	12-MT-20
<i>Trace elements (ppm)</i>						
Ba	139.1	280.1	274	204	121	367
Be	0.93	1.62	1.04	1.38	1.04	1.89
Bi	0.063	0.08	0.11	0.02	0.01	0.25
Cd	0.12	0.15	0.10	0.10	0.07	0.15
Ce	35.05	53.15	32.03	52.77	33.58	107.20
Co	46.8	43.5	37.80	50.30	48.40	16.80
Cr	99	72	142.00	91.00	133.00	40.00
Cs	2.83	2.45	1.13	3.41	6.73	0.90
Cu	255	205	207	214	197	14
Dy	6.89	8.36	5.38	7.13	6.14*	10.12
Er	4.13	4.59	2.70	3.12	2.94*	5.10
Eu	1.71	2.32	1.85	2.43	1.79	2.07
Ga	19.89	23.69	18.35	22.78	15.93	19.50
Gd	6.5	8.62	5.88	8.11	6.64	10.06
Hf	4.06	5.35	2.72	2.39	2.78*	1.95
Ho	1.41	1.62	1.00	1.25	1.14*	1.88
La	15.04	22.57	13.08	21.93	12.68	49.90
Li	24	17.4	12.10	17.20	14.40	20.10
Lu	0.56	0.58	0.29	0.23	0.24*	0.47
Mo	1.13	1.59	0.89	1.06	1.01	0.30
Nb	12.21	13.5	14.10	26.05	15.78	40.88
Nd	21.28	31.21	21.34	33.62	23.54	52.05
Ni	62	38	57.00	67.00	71.00	19.00
Pb	2.9	8.8	1.60	3.40	1.90	5.90
Pr	4.75	7.14	4.69	7.55	5.02	13.36
Rb	39.9	59.58	12.79	34.43	10.02	22.29
Sb	0.17	0.31	0.79	0.18	2.44	0.22
Sc	38.5	28.7	30.60	32.60	35.50	14.70
Sm	5.58	7.98	5.48	8.07	6.09	10.74
Sn	1.58	2.36	1.65	2.38	1.77*	5.73
Sr	152	195	83	290	157	155
Ta	0.8	0.9	0.90	1.70	1.00	2.70
Tb	1.059	1.318	0.88	1.18	1.02*	1.60
Th	3.02	5.5	1.06	1.83	1.11*	12.01
Ti	11862.72	>12000	>12000	>12000	>12000	7151.9
Tl	0.19	0.24	0.05	0.14	0.05	0.06
Tm	0.582	0.633	0.35	0.38	0.361*	0.65
U	0.81	1.46	0.30	0.61	0.4*	2.60
V	407.07	449.34	331.95	394.03	392.83*	130.45
W	<0.5	0.86	<0.5	<0.5	<0.5	0.58
Y	38.07	43.93	26.75	32.77	29.44*	50.93
Yb	3.764	4.016	2.15	1.99	2.046*	3.73
Zn	112.44	137.82	95.26	127.76	110.80	80.96
Zr	153	200	77	63	85*	63

Sample	12-MT-21	12-MT-22	12-MT-23	12-MT-24	12-MT-25	12-MT-26
<i>Trace elements (ppm)</i>						
Ba	41	18.1*	22	96.7*	22	12
Be	1.01	1.14	1.42	1.13	1.02	0.69
Bi	0.14	0.08	0.07	0.19	0.01	0.23
Cd	0.05	0.13	0.16	0.11	0.11	0.06
Ce	61.43	65.55*	29.83	45.44*	32.51	47.22
Co	36.70	39.40	34.00	38.90	49.60	36.80
Cr	90.00	59*	209.00	102*	229.00	51.00
Cs	0.06	0.03*	0.06	1.66	0.11*	0.64
Cu	37	75	263	266	282	28
Dy	7.62	10.29*	6.12	7.96*	7.05	5.80
Er	3.84	5.53*	3.55	4.32*	3.91	2.43
Eu	2.49	2.58*	1.74	2.13*	2.03	2.51
Ga	19.16	17.8*	26.14	19.36	20.23*	19.96
Gd	8.30	10.19*	5.76	7.89*	6.79	7.13
Hf	0.65	0.74*	1.98	0.46*	1.35*	0.47
Ho	1.41	1.98*	1.22	1.54*	1.37	1.00
La	26.51	28.79*	12.52	18.86*	13.36	19.37
Li	15.60	17.20	5.80	19.20	11.90	29.70
Lu	0.30	0.49*	0.39	0.4*	0.37*	0.18
Mo	0.26	0.48	1.57	0.44	0.45	0.68
Nb	25.87	31.97*	14.40	22.73*	15.69	17.94
Nd	36.61	40.13*	19.64	29.82*	22.15	30.48
Ni	44.00	28.00	84.00	48.00	72.00	25.00
Pb	1.00	2.50	3.20	1.20	1.30	2.40
Pr	8.34	8.97*	4.23	6.46	4.71	6.68
Rb	1.36	0.58	1.67	13.82	1.93	0.66
Sb	0.25	0.26	1.44	0.11	0.20	0.09
Sc	32.90	35.10	40.50	39.20	44.30	22.10
Sm	8.25	9.66*	5.09	7.57*	5.92	7.29
Sn	1.74	2.84	1.61	2.12	1.34*	1.37
Sr	188	213*	800	115	416	95
Ta	1.60	2.10	0.90	1.50	1.00	1.20
Tb	1.25	1.609*	0.94	1.258*	1.10	1.01
Th	1.70	2.45*	1.22	1.74*	1.15*	1.81
Ti	>12000	>12000	>12000	>12000	>12000	>12000
Tl	<0.005	<0.005	0.01	0.07	0.01	0.05
Tm	0.50	0.728*	0.47	0.567*	0.521*	0.29
U	0.22	0.33*	0.36	0.11*	0.33*	0.34
V	380.47	346.74*	404.16	413.18*	389.57*	211.43
W	<0.5	0.60	0.52	<0.5	<0.5	<0.5
Y	37.53	53.71*	33.81	39.97*	37.15*	26.07
Yb	2.77	4.207*	2.92	3.319*	3.032*	1.52
Zn	101.77	103.69	70.98	131.69	117.89	119.76
Zr	16	16*	52	10*	31*	16

Sample	12-MT-27	12-MT-19R	12-MT-22R	12-MT-24R	12-MT-25R	10-LT-05	1 σ OGS	1 σ ALS
<i>Trace elements (ppm)</i>								
Ba	185	125.5	19.4	103.5	21.6	536.47	9.47	11.52
Be	1.36					1.18	0.06	
Bi	0.13					0.02	0.01	
Cd	0.09					0.17	0.01	
Ce	53.76	34.6	70.8	49.2	31.8	47.35	0.66	2.104
Co	37.70					41.63	0.92	
Cr	89.00	140	70	110	220	180.60	6.07	14.83
Cs	2.77	6.67	0.07	1.67	0.12	0.23	0.01	0.045
Cu	28					43.00	0.89	
Dy	6.71	6.51	11.45	9.48	6.84	3.72	0.03	0.094
Er	3.18	3.28	6.47	5.17	3.84	1.94	0.02	0.04
Eu	2.48	1.9	3.07	2.46	2.02	1.58	0.02	0.09
Ga	19.78	16	19.6	20	18.7	19.03	0.42	0.39
Gd	7.77	6.78	11.45	9.14	6.54	4.43	0.04	0.383
Hf	0.20	4.7	8.4	6.3	4.2	3.41	0.07	0.055
Ho	1.21	1.29	2.34	1.92	1.38	0.70	0.01	0.03
La	23.34	13.1	30.6	20.5	13.1	21.94	0.32	0.95
Li	31.90					7.58	0.42	
Lu	0.31	0.44	0.93	0.78	0.53	0.24	0.00	0.019
Mo	1.12					1.49	0.04	
Nb	27.75	15.9	34.9	24.1	15	10.67	0.21	0.358
Nd	32.99	23.8	42.7	31.6	21.2	25.26	0.45	0.91
Ni	35.00					117.50	1.05	
Pb	2.60					4.87	0.08	
Pr	7.40	5.15	9.64	6.79	4.53	6.13	0.09	0.335
Rb	12.15	10.3	0.6	14.5	1.8	12.80	0.25	0.16
Sb	0.15					0.09	0.01	
Sc	33.20					20.28	0.50	
Sm	7.63	6.33	10.7	8.4	6.11	5.00	0.04	0.382
Sn	1.76	2	3	2	2	1.53	0.08	0.447
Sr	247	164	236	120	436	896.00	7.32	25.2
Ta	1.70	1	2.2	1.5	1	0.60	0.00	0.05
Tb	1.13	1.09	1.92	1.53	1.14	0.63	0.01	0.04
Th	1.92	1.37	3.44	2.54	1.22	1.94	0.04	1.25
Ti	>12000					8652.98	175.02	
Tl	0.06					0.05	0.00	
Tm	0.41	0.47	0.93	0.76	0.53	0.27	0.00	0.2
U	0.11	0.45	0.98	0.75	0.43	0.57	0.01	0.07
V	403.77	460	439	494	423	158.29	2.66	12.74
W	<0.5					0.34	0.01	
Y	31.76	31.5	60.4	50	34.8	19.36	0.18	0.71
Yb	2.40	2.77	5.86	5.13	3.51	1.65	0.02	0.138
Zn	100.67					90.84	2.99	
Zr	8	177	322	237	149	152.83	3.06	5

10-LT-05 is internal standard and values are for average run. Standard deviation (1 σ) was calculated from 5 runs and 2 duplicates for OGS values and 5 runs for ALS values. 12-MT-19R to 12-MT-25R are reanalysed Irene and Huckleberry metavolcanic rocks from ALS.

*on elements from samples 12-MT-19, 12-MT-22, 12-MT-24, 12-MT-25 indicate values that are <90% confidence from reanalysed samples.

Appendix E: Mineral chemistry data

Feldspars

Sample	12-MT-02 1	12-MT-02- 2	12-MT-02- 3	12-MT-02- 4	12-MT-09- 1	12-MT-09- 2	13-AM-1- 1	13-AM-1- 2
<i>Oxides (wt%)</i>								
SiO ₂	57.37	60.54	64.78	65.48	56.27	54.34	56.60	56.64
Al ₂ O ₃	26.01	24.67	21.77	21.42	28.06	29.25	26.19	26.76
FeO	0.47	0.38	0.09	0.09	0.61	0.62	0.63	0.72
CaO	9.10	6.83	3.06	2.88	10.53	12.10	10.33	10.26
Na ₂ O	5.99	7.30	9.28	9.91	5.23	4.41	5.47	5.39
K ₂ O	0.50	0.51	1.14	0.34	0.42	0.33	0.39	0.42
Total	99.46	100.23	100.11	100.13	101.12	101.05	99.61	100.18
<i>Formula (8 oxygen)</i>								
Si	2.59	2.69	2.86	2.88	2.51	2.44	2.56	2.55
Al	1.39	1.29	1.13	1.11	1.48	1.55	1.40	1.42
Fe	0.02	0.01	0.00	0.00	0.02	0.02	0.02	0.03
Ca	0.44	0.33	0.14	0.14	0.50	0.58	0.50	0.49
Na	0.53	0.63	0.79	0.85	0.45	0.38	0.48	0.47
K	0.03	0.03	0.06	0.02	0.02	0.02	0.02	0.02
Σ cations	4.99	4.99	5.00	5.00	4.99	4.99	4.99	4.99
<i>End Members</i>								
Ab	52.78	63.97	79.16	84.51	46.19	39.00	47.82	47.55
An	44.30	33.10	14.42	13.57	51.38	59.11	49.93	50.04
Or	2.92	2.93	6.43	1.93	2.43	1.90	2.25	2.41

Sample	13-AM-1- 3	13-AM-1- 4	13-AM-13- 1	13-AM-13- 2	13-AM-13- 3	13-AM-13- 4	13-AM-13- 5
<i>Oxides (wt%)</i>							
SiO ₂	55.54	55.12	67.22	60.20	62.44	56.06	59.08
Al ₂ O ₃	26.89	26.53	18.83	24.49	23.17	27.19	25.39
FeO	0.79	1.35	0.55	0.38	0.20	0.57	0.42
CaO	10.88	11.26	0.32	6.16	4.75	10.23	7.85
Na ₂ O	5.00	4.87	11.30	7.46	8.37	5.47	6.75
K ₂ O	0.35	0.33	0.09	0.94	0.90	0.41	0.44
Total	99.45	99.46	98.31	99.63	99.82	99.93	99.92
<i>Formula (8 oxygen)</i>							
Si	2.52	2.52	3.00	2.70	2.78	2.53	2.65
Al	1.44	1.43	0.99	1.29	1.21	1.45	1.34
Fe	0.03	0.05	0.02	0.01	0.01	0.02	0.02
Ca	0.53	0.55	0.02	0.30	0.23	0.49	0.38
Na	0.44	0.43	0.98	0.65	0.72	0.48	0.59
K	0.02	0.02	0.00	0.05	0.05	0.02	0.03
Σ cations	4.99	5.00	5.00	5.01	5.00	5.00	4.99
<i>End Members</i>							
Ab	44.46	43.08	97.97	64.96	72.26	48.01	59.33
An	53.51	55.03	1.54	29.63	22.65	49.60	38.12
Or	2.02	1.89	0.49	5.41	5.09	2.39	2.55

Ab- albite; An- anorthite; Or- orthoclase

Feldspars

Sample	94LAAT3-1A-1	94LAAT3-1A-2	94LAAT3-1A-3	94LAAT3-1A-4	94LAAT3-1A-5	12-MT17-1	12-MT-20-1
<i>Oxides (wt%)</i>							
SiO ₂	54.19	53.82	56.94	55.22	61.20	69.83	70.28
Al ₂ O ₃	28.77	29.36	27.34	28.42	25.07	19.79	20.05
FeO	0.66	0.67	0.64	0.68	0.44	0.14	0.32
CaO	12.01	12.43	9.94	10.86	6.10	0.12	0.31
Na ₂ O	4.51	4.41	5.70	5.27	7.88	12.11	12.02
K ₂ O	0.29	0.28	0.41	0.36	0.50	0.09	0.08
Total	100.43	100.97	100.97	100.80	101.19	102.08	103.06
<i>Formula (8 oxygen)</i>							
Si	2.45	2.42	2.54	2.48	2.70	2.99	2.99
Al	1.53	1.56	1.44	1.50	1.30	1.00	1.00
Fe	0.02	0.03	0.02	0.03	0.02	0.00	0.01
Ca	0.58	0.60	0.48	0.52	0.29	0.01	0.01
Na	0.39	0.38	0.49	0.46	0.67	1.01	0.99
K	0.02	0.02	0.02	0.02	0.03	0.00	0.00
Σ cations	4.99	5.00	5.00	5.01	5.00	5.01	5.01
<i>End Members</i>							
Ab	39.78	38.46	49.70	45.77	68.03	98.98	98.19
An	58.55	59.95	47.92	52.17	29.12	0.54	1.38
Or	1.66	1.59	2.38	2.06	2.85	0.47	0.43

Sample	13-AM-25B-1	13-AM-25B-2	12-MT27-1	12-MT27-2
<i>Oxides (wt%)</i>				
SiO ₂	68.90	69.45	58.00	59.01
Al ₂ O ₃	19.75	19.74	27.57	25.96
FeO	0.05	0.06	0.43	1.52
CaO	0.46	0.20	9.29	7.79
Na ₂ O	11.54	11.72	6.56	6.95
K ₂ O	0.07	0.04	0.05	0.10
Total	100.76	101.22	101.91	101.33
<i>Formula (8 oxygen)</i>				
Si	2.99	3.00	2.56	2.62
Al	1.01	1.00	1.43	1.36
Fe	0.00	0.00	0.02	0.06
Ca	0.02	0.01	0.44	0.37
Na	0.97	0.98	0.56	0.60
K	0.00	0.00	0.00	0.01
Σ cations	4.99	4.99	5.01	5.00
<i>End Members</i>				
Ab	97.47	98.83	55.95	61.41
An	2.13	0.95	43.77	38.03
Or	0.40	0.22	0.28	0.55

Ab- albite; An- anorthite; Or- orthoclase

Pyroxenes

Sample	12-MT-02-1	12-MT-02-2	12-MT-02-3	12-MT-02-4	12-MT-02-5	12-MT-09-1	12-MT09-2	12-MT09-3
<i>Oxide (wt%)</i>								
SiO ₂	51.03	51.49	48.71	49.85	50.38	52.14	50.85	51.79
TiO ₂	0.72	0.47	0.39	0.71	0.64	0.41	0.80	0.33
Al ₂ O ₃	1.98	1.20	0.77	1.57	1.84	1.10	1.96	1.77
Cr ₂ O ₃	0.02	0.00	0.01	0.00	0.00			
FeO	15.11	24.77	32.03	19.51	17.87	11.44	16.77	17.82
MnO	0.32	0.51	0.76	0.44	0.37	0.26	0.41	0.34
MgO	14.04	16.64	10.00	11.38	11.28	12.07	12.65	11.61
CaO	16.05	4.82	6.07	15.06	16.00	20.99	16.17	13.91
Na ₂ O	0.24	0.07	0.03	0.21	0.23	0.27	0.25	0.43
K ₂ O	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.05
TOTAL	99.51	99.99	98.80	98.74	98.61	98.69	99.90	98.17
<i>Formula (6 oxygen)</i>								
Si	1.94	1.96	1.96	1.94	1.95	1.98	1.94	2.00
Ti	0.02	0.01	0.01	0.02	0.02	0.01	0.02	0.01
Al	0.09	0.05	0.04	0.07	0.08	0.05	0.09	0.08
Fe3+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe2+	0.48	0.79	1.08	0.64	0.58	0.36	0.53	0.58
Mn	0.01	0.02	0.03	0.01	0.01	0.01	0.01	0.01
Mg	0.79	0.95	0.60	0.66	0.65	0.69	0.72	0.67
Ca	0.65	0.20	0.26	0.63	0.66	0.86	0.66	0.58
Na	0.02	0.01	0.00	0.02	0.02	0.02	0.02	0.03
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	4.00	3.98	3.98	3.99	3.98	3.98	3.99	3.96
<i>End members</i>								
Wo	34.14	10.20	13.50	32.80	35.06	44.94	34.58	31.63
En	41.53	48.94	30.93	34.49	34.37	35.95	37.63	36.74
Fs	24.33	40.86	55.57	32.71	30.57	19.11	27.79	31.63

Wo- wollastonite; En- enstatite, Fs- forsterite

Pyroxenes

Sample	12-MT09-4	12-MT09-5	12-MT09-6	12-MT09-7	12-MT09-8	13-AM-1-1	13-AM-1-2	13-AM-1-3
<i>Oxide (wt%)</i>								
SiO ₂	51.80	50.92	50.96	51.33	50.48	50.72	48.88	50.93
TiO ₂	0.24	0.72	0.84	0.46	0.50	0.78	0.78	0.65
Al ₂ O ₃	1.17	2.05	2.86	1.35	1.06	2.39	2.05	1.79
Cr ₂ O ₃	0.04	0.02	0.04	0.00	0.00	0.00	0.00	0.00
FeO	23.64	13.84	13.53	23.02	26.54	14.08	18.66	16.66
MnO	0.34	0.33	0.28	0.47	0.54	0.35	0.37	0.37
MgO	8.84	14.23	14.49	17.33	15.13	12.76	13.48	15.06
CaO	10.97	16.99	16.60	5.45	5.32	18.25	13.81	13.91
Na ₂ O	0.24	0.21	0.25	0.08	0.05	0.24	0.23	0.22
K ₂ O	0.11	0.00	0.00	0.00	0.02	0.02	0.01	0.01
TOTAL	97.52	99.31	99.85	99.49	99.63	99.59	98.26	99.60
<i>Formula (6 oxygen)</i>								
Si	2.05	1.93	1.91	1.95	1.95	1.93	1.91	1.93
Ti	0.01	0.02	0.02	0.01	0.01	0.02	0.02	0.02
Al	0.05	0.09	0.13	0.06	0.05	0.11	0.09	0.08
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.78	0.44	0.42	0.73	0.86	0.45	0.61	0.53
Mn	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01
Mg	0.52	0.80	0.81	0.98	0.87	0.72	0.78	0.85
Ca	0.46	0.69	0.67	0.22	0.22	0.74	0.58	0.57
Na	0.02	0.02	0.02	0.01	0.00	0.02	0.02	0.02
K	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	3.92	4.00	4.00	3.99	3.99	4.00	4.02	4.01
<i>End members</i>								
Wo	26.28	36.13	35.30	11.47	11.37	39.07	30.66	29.67
En	29.49	42.10	42.90	50.72	44.96	38.01	41.63	44.70
Fs	44.23	21.77	21.81	37.81	43.67	22.92	27.71	25.63

Wo- wollastonite; En- enstatite, Fs- forsterite

Pyroxenes

Sample	13-AM-1-4	13-AM-1-5	13-AM-1-6	13-AM-1-7	13-AM-1-8	13-AM-1-9	13-AM-1-10	13-AM-1-11
<i>Oxide (wt%)</i>								
SiO ₂	50.22	50.22	50.65	50.59	49.65	49.69	49.98	49.22
TiO ₂	0.91	0.75	0.73	0.71	0.80	0.65	0.91	0.59
Al ₂ O ₃	2.44	1.57	1.52	2.22	2.18	1.36	2.07	1.65
Cr ₂ O ₃	0.01	0.00	0.01	0.04	0.00	0.02	0.00	0.03
FeO	15.40	17.44	17.46	13.53	15.21	21.41	16.86	21.90
MnO	0.32	0.42	0.40	0.34	0.34	0.49	0.37	0.50
MgO	13.71	12.70	12.65	14.51	13.99	10.63	13.17	8.88
CaO	16.15	15.82	15.84	16.71	15.42	14.36	15.68	16.02
Na ₂ O	0.25	0.20	0.24	0.26	0.24	0.19	0.23	0.19
K ₂ O	0.00	0.01	0.01	0.00	0.00	0.00	0.01	0.01
TOTAL	99.43	99.13	99.53	98.90	97.84	98.80	99.29	99.00
<i>Formula (6 oxygen)</i>								
Si	1.91	1.94	1.94	1.92	1.92	1.95	1.92	1.94
Ti	0.03	0.02	0.02	0.02	0.02	0.02	0.03	0.02
Al	0.11	0.07	0.07	0.10	0.10	0.06	0.09	0.08
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.49	0.56	0.56	0.43	0.49	0.70	0.54	0.72
Mn	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02
Mg	0.78	0.73	0.72	0.82	0.81	0.62	0.75	0.52
Ca	0.66	0.65	0.65	0.68	0.64	0.60	0.64	0.68
Na	0.02	0.01	0.02	0.02	0.02	0.01	0.02	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	4.01	4.00	4.00	4.01	4.01	3.99	4.01	3.99
<i>End members</i>								
Wo	34.86	34.14	34.03	35.96	33.72	31.38	34.00	35.40
En	41.17	38.13	37.80	43.44	42.55	32.33	39.72	27.31
Fs	23.97	27.73	28.18	20.59	23.73	36.29	26.27	37.29

Wo- wollastonite; En- enstatite, Fs- forsterite

Pyroxenes

Sample	13-AM-1-12	13-AM-1-13	13-AM-11-1	13-AM-11-2	13-AM-11-3	13-AM-11-4	13-AM-11-5	13-AM-11-6
<i>Oxide (wt%)</i>								
SiO ₂	49.36	49.33	50.52	50.28	51.23	48.30	49.04	50.14
TiO ₂	0.66	0.15	0.76	0.91	0.74	0.16	0.43	0.42
Al ₂ O ₃	1.81	0.46	2.22	1.77	2.10	0.21	0.52	0.97
Cr ₂ O ₃	0.01	0.00	0.10	0.04	0.11	0.01	0.00	0.04
FeO	16.81	25.72	11.93	17.29	12.22	38.58	33.73	28.06
MnO	0.39	0.50	0.25	0.38	0.29	0.68	0.71	0.56
MgO	11.18	5.81	14.75	12.49	15.03	9.77	11.95	14.37
CaO	17.42	17.48	16.81	16.06	17.08	1.29	2.80	4.81
Na ₂ O	0.24	0.16	0.24	0.18	0.23	0.01	0.03	0.04
K ₂ O	0.02	0.01	0.00	0.01	0.02	0.00	0.00	0.01
TOTAL	97.89	99.61	97.56	99.41	99.05	99.01	99.20	99.42
<i>Formula (6 oxygen)</i>								
Si	1.93	1.98	1.93	1.93	1.93	1.98	1.96	1.96
Ti	0.02	0.00	0.02	0.03	0.02	0.00	0.01	0.01
Al	0.08	0.02	0.10	0.08	0.09	0.01	0.02	0.04
Fe3+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe2+	0.55	0.86	0.38	0.56	0.39	1.32	1.13	0.92
Mn	0.01	0.02	0.01	0.01	0.01	0.02	0.02	0.02
Mg	0.65	0.35	0.84	0.72	0.85	0.60	0.71	0.84
Ca	0.73	0.75	0.69	0.66	0.69	0.06	0.12	0.20
Na	0.02	0.01	0.02	0.01	0.02	0.00	0.00	0.00
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	4.00	4.00	3.99	4.00	4.00	3.99	3.99	3.99
<i>End members</i>								
Wo	38.46	38.70	36.04	34.47	36.15	2.90	6.17	10.35
En	34.33	17.89	44.01	37.32	44.28	30.46	36.62	43.02
Fs	27.21	43.41	19.95	28.21	19.58	66.64	57.21	46.62

Wo- wollastonite; En- enstatite, Fs- forsterite

Pyroxenes

Sample	13-AM-11-7	13-AM-11-8	13-AM-11-9	13-AM-13-1	13-AM-13-2	13-AM-13-3	94LAAT3-1A-1	94LAAT3-1A-2
<i>Oxide (wt%)</i>								
SiO ₂	51.20	49.03	48.35	49.46	49.10	49.99	50.69	48.77
TiO ₂	0.74	0.45	0.16	0.50	0.43	0.67	0.75	0.62
Al ₂ O ₃	1.90	0.73	0.26	0.92	0.88	1.52	1.62	1.43
Cr ₂ O ₃	0.09	0.00	0.00	0.00	0.00	0.00	0.02	0.00
FeO	14.30	32.01	39.26	28.07	30.23	19.33	18.36	23.95
MnO	0.34	0.64	0.76	0.57	0.72	0.43	0.43	0.53
MgO	15.13	11.95	9.26	13.14	12.04	10.97	11.85	7.60
CaO	15.53	4.48	1.43	5.78	5.57	16.01	15.93	16.52
Na ₂ O	0.19	0.02	0.01	0.04	0.09	0.23	0.23	0.23
K ₂ O	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
TOTAL	99.41	99.32	99.49	98.47	99.06	99.16	99.89	99.64
<i>Formula (6 oxygen)</i>								
Si	1.93	1.95	1.98	1.96	1.95	1.94	1.94	1.94
Ti	0.02	0.01	0.01	0.01	0.01	0.02	0.02	0.02
Al	0.08	0.03	0.01	0.04	0.04	0.07	0.07	0.07
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe ²⁺	0.45	1.07	1.34	0.93	1.01	0.63	0.59	0.80
Mn	0.01	0.02	0.03	0.02	0.02	0.01	0.01	0.02
Mg	0.85	0.71	0.56	0.78	0.71	0.64	0.68	0.45
Ca	0.63	0.19	0.06	0.25	0.24	0.67	0.65	0.70
Na	0.01	0.00	0.00	0.00	0.01	0.02	0.02	0.02
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	4.00	3.99	3.99	3.99	3.99	4.00	3.99	4.00
<i>End members</i>								
Wo	32.78	9.84	3.21	12.58	12.31	34.83	34.14	36.95
En	44.47	36.53	28.90	39.81	37.03	33.22	35.33	23.64
Fs	22.75	53.63	67.89	47.61	50.65	31.95	30.53	39.41

Wo- wollastonite; En- enstatite, Fs- forsterite

Pyroxenes

Sample	94LAAT3-1A-3	94LAAT3-1A-4	94LAAT3-1A-5	94LAAT3-1A-6	94LAAT3-1A-7	94LAAT3-1A-8	12-MT-17-1	12-MT-17-2
<i>Oxide (wt%)</i>								
SiO ₂	49.46	50.54	50.40	50.63	50.89	49.98	50.70	51.09
TiO ₂	0.50	0.71	0.85	0.52	0.77	0.77	1.09	0.98
Al ₂ O ₃	1.42	1.77	1.93	1.07	1.93	1.91	3.81	3.70
Cr ₂ O ₃	0.01			0.01	0.01	0.01	0.40	0.39
FeO	27.07	16.92	15.30	28.40	15.05	19.38	8.87	9.68
MnO	0.62	0.36	0.33	0.71	0.37	0.44	0.18	0.25
MgO	13.42	13.32	12.62	13.36	12.74	10.83	14.84	15.92
CaO	6.33	15.39	17.77	5.60	16.97	15.95	19.24	18.04
Na ₂ O	0.09	0.23	0.21	0.06	0.17	0.18	0.32	0.28
K ₂ O			0.01	0.01	0.01	0.00	0.01	0.00
TOTAL	98.91	99.24	99.48	100.36	98.91	99.45	99.49	100.39
<i>Formula (6 oxygen)</i>								
Si	1.94	1.94	1.93	1.96	1.95	1.94	1.89	1.89
Ti	0.01	0.02	0.02	0.02	0.02	0.02	0.03	0.03
Al	0.07	0.08	0.09	0.05	0.09	0.09	0.17	0.16
Fe3+	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
Fe2+	0.89	0.54	0.49	0.92	0.48	0.63	0.28	0.30
Mn	0.02	0.01	0.01	0.02	0.01	0.01	0.01	0.01
Mg	0.79	0.76	0.72	0.77	0.73	0.63	0.82	0.88
Ca	0.27	0.63	0.73	0.23	0.70	0.66	0.77	0.71
Na	0.01	0.02	0.02	0.00	0.01	0.01	0.02	0.02
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	3.99	4.00	4.00	3.98	3.98	3.99	4.00	4.00
<i>End members</i>								
Wo	13.85	33.05	38.12	12.08	36.55	34.56	41.14	38.25
En	40.88	39.80	37.68	40.10	38.16	32.65	44.15	46.98
Fs	45.27	27.15	24.20	47.83	25.30	32.79	14.71	14.77

Wo- wollastonite; En- enstatite, Fs- forsterite

Pyroxenes

Sample	13-AM-25A-1	13-AM-25A-2	13-AM-25A-3	13-AM-25A-4	13-AM-25B-1	13-AM-25B-2	13-AM-25B-3	13-AM-25B-4
<i>Oxide (wt%)</i>								
SiO ₂	50.63	52.63	53.57	50.40	51.22	50.46	50.33	52.88
TiO ₂	1.12	0.70	0.54	1.22	0.87	1.13	1.13	0.59
Al ₂ O ₃	3.85	2.20	1.57	4.06	3.17	3.86	3.39	1.70
Cr ₂ O ₃	0.40	0.32	0.24	0.47	0.35	0.55	0.34	0.28
FeO	10.05	9.44	10.62	9.32	9.36	9.02	9.20	9.48
MnO	0.26	0.21	0.30	0.22	0.20	0.21	0.20	0.27
MgO	15.89	16.84	18.22	14.94	15.66	15.08	15.19	17.42
CaO	16.97	17.15	15.02	19.18	18.49	19.15	19.18	17.08
Na ₂ O	0.27	0.22	0.19	0.32	0.30	0.30	0.26	0.20
K ₂ O			0.00	0.01	0.01	0.01		
TOTAL	99.44	99.72	100.31	100.15	99.63	99.77	99.22	99.92
<i>Formula (6 oxygen)</i>								
Si	1.88	1.94	1.96	1.87	1.90	1.88	1.88	1.95
Ti	0.03	0.02	0.01	0.03	0.02	0.03	0.03	0.02
Al	0.17	0.10	0.07	0.18	0.14	0.17	0.15	0.07
Fe ³⁺	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cr	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.01
Fe ²⁺	0.31	0.29	0.33	0.29	0.29	0.28	0.29	0.29
Mn	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Mg	0.88	0.93	0.99	0.83	0.87	0.84	0.85	0.96
Ca	0.68	0.68	0.59	0.76	0.74	0.76	0.77	0.67
Na	0.02	0.02	0.01	0.02	0.02	0.02	0.02	0.01
K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	4.00	3.99	3.98	4.00	4.00	4.00	4.01	3.99
<i>End members</i>								
Wo	36.20	35.77	30.87	41.22	39.22	41.08	41.08	35.06
En	47.18	48.86	52.10	44.66	46.21	45.01	45.28	49.75
Fs	16.62	15.37	17.04	14.12	14.58	13.91	13.63	15.19

Wo- wollastonite; En- enstatite, Fs- forsterite

Pyroxenes

Sample	13-AM-25B-5
<i>Oxide</i>	
<i>(wt%)</i>	
SiO ₂	49.74
TiO ₂	1.06
Al ₂ O ₃	3.78
Cr ₂ O ₃	0.40
FeO	8.97
MnO	0.19
MgO	14.89
CaO	19.23
Na ₂ O	0.28
K ₂ O	
TOTAL	98.56
<i>Formula (6 oxygen)</i>	
Si	1.88
Ti	0.03
Al	0.17
Fe ³⁺	0.00
Cr	0.01
Fe ²⁺	0.28
Mn	0.01
Mg	0.84
Ca	0.78
Na	0.02
K	0.00
Σ cations	4.01
<i>End members</i>	
Wo	41.81
En	45.05
Fs	13.14

Wo- wollastonite; En- enstatite, Fs- forsterite

Amphiboles

Sample	12-MT-02-1	12-MT-02-2	12-MT09-1	12-MT09-2	12-MT09-3	12-MT09-4	12-MT09-5	12-MT09-6
<i>Oxide (wt%)</i>								
SiO ₂	41.77	43.83	39.59	45.47	43.58	44.55	41.76	51.80
Al ₂ O ₃	7.26	6.46	12.54	7.85	6.75	6.13	7.66	1.17
TiO ₂	1.33	0.99	3.92	0.72	1.13	0.71	2.04	0.24
Cr ₂ O ₃	0.01	0.00	0.00	0.01	0.02		0.02	0.04
FeO	26.69	25.82	20.18	19.47	27.70	27.20	27.74	23.64
MnO	0.21	0.31	0.24	0.25	0.25	0.27	0.22	0.34
MgO	5.35	6.12	6.88	10.12	5.07	6.13	4.60	8.84
CaO	10.16	9.97	10.66	10.79	9.91	9.76	10.01	10.97
Na ₂ O	1.76	1.63	2.38	1.96	1.68	1.58	1.91	0.24
K ₂ O	1.16	0.93	0.97	1.07	0.87	0.63	1.08	0.11
F	0.33	0.41	0.55	1.06	0.32	0.28	0.60	0.05
Cl	0.69	0.67	0.49	0.35	0.60	0.43	0.78	0.08
TOTAL	96.71	97.14	98.40	99.12	97.90	97.67	98.42	97.52
O≠F,Cl	0.29	120.43	0.34	0.53	0.27	0.21	0.43	0.04
Σ -X	0.32	121.43	110.43	111.43	112.43	113.43	114.43	115.43
Si	6.76	6.98	6.11	6.90	6.93	7.04	6.69	7.87
Al	1.38	1.21	2.28	1.40	1.27	1.14	1.44	0.21
Ti	0.16	0.12	0.45	0.08	0.14	0.08	0.25	0.03
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	3.61	3.44	2.61	2.47	3.69	3.60	3.71	3.00
Mn	0.03	0.04	0.03	0.03	0.03	0.04	0.03	0.04
Mg	1.29	1.45	1.58	2.29	1.20	1.44	1.10	2.00
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	1.76	1.70	1.76	1.75	1.69	1.65	1.72	1.79
Na	0.55	0.50	0.71	0.58	0.52	0.48	0.59	0.07
K	0.24	0.19	0.19	0.21	0.18	0.13	0.22	0.02
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	15.79	15.64	15.74	15.71	15.64	15.61	15.75	15.04
F	0.17	0.21	0.27	0.51	0.16	0.14	0.30	0.02
Cl	0.19	0.18	0.13	0.09	0.16	0.11	0.21	0.02

O≠F,Cl – proportion of F and Cl bonded to oxygen in MgO that must be subtracted from the total oxide weight percent

Σ -X – Total minus O≠F,Cl to obtain “true” total of oxide weight percent

Amphiboles

Sample	12-MT09-7	12-MT09-8	94LAAT3-1A-2	13-AM-1-1	13-AM-1-2	13-AM-1-3	13-AM-1-4	13-AM-1-5
<i>Oxide (wt%)</i>								
SiO ₂	52.91	45.49	43.36	46.95	49.37	44.60	44.41	49.11
Al ₂ O ₃	2.28	6.20	6.84	3.95	2.17	5.05	5.35	2.12
TiO ₂	0.45	0.51	0.72	0.61	0.27	1.44	0.90	0.27
Cr ₂ O ₃	0.02		0.02	0.02	0.00	0.00	0.01	0.00
FeO	15.27	24.06	27.47	28.22	33.56	27.99	28.24	34.27
MnO	0.27	0.39	0.33	0.43	0.69	0.37	0.37	0.65
MgO	14.30	8.07	5.63	5.83	6.03	5.28	5.15	6.24
CaO	11.69	10.22	9.94	9.71	4.64	10.03	10.04	4.34
Na ₂ O	0.39	1.68	1.68	1.01	0.76	1.56	1.58	0.78
K ₂ O	0.04	0.82	0.89	0.37	0.08	0.79	0.79	0.07
F	0.05	0.70	0.59	0.22	0.19	0.77	0.58	0.17
Cl	0.11	0.47	0.56	0.08	0.07	0.36	0.47	0.09
TOTAL	97.78	98.60	98.03	97.40	97.85	98.23	97.86	98.09
O≠F,Cl	0.05	0.40	0.37	0.11	0.09	0.40	0.35	0.09
Σ -X	116.43	117.43	109.43	100.43	101.43	102.43	103.43	104.43
Si	7.71	7.05	6.91	7.39	7.76	7.09	7.09	7.72
Al	0.39	1.13	1.28	0.73	0.40	0.95	1.01	0.39
Ti	0.05	0.06	0.09	0.07	0.03	0.17	0.11	0.03
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	1.86	3.12	3.66	3.72	4.41	3.72	3.77	4.50
Mn	0.03	0.05	0.04	0.06	0.09	0.05	0.05	0.09
Mg	3.11	1.86	1.34	1.37	1.41	1.25	1.23	1.46
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	1.83	1.70	1.70	1.64	0.78	1.71	1.72	0.73
Na	0.11	0.50	0.52	0.31	0.23	0.48	0.49	0.24
K	0.01	0.16	0.18	0.07	0.02	0.16	0.16	0.01
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	15.10	15.65	15.72	15.36	15.13	15.59	15.62	15.18
F	0.02	0.34	0.30	0.11	0.09	0.39	0.29	0.08
Cl	0.03	0.12	0.15	0.02	0.02	0.10	0.13	0.02

O≠F,Cl – proportion of F and Cl bonded to oxygen in MgO that must be subtracted from the total oxide weight percent

Σ -X – Total minus O≠F,Cl to obtain “true” total of oxide weight percent

Amphiboles

Sample	13-AM-1-6	13-AM-1-7	13-AM-13-1	13-AM-13-2	13-AM-13-3	12-MT-17-1	12-MT-17-2	12-MT-18-1
<i>Oxide (wt%)</i>								
SiO ₂	42.56	41.69	42.56	50.90	48.05	53.44	54.47	51.47
Al ₂ O ₃	6.05	6.85	6.97	1.80	2.47	0.78	1.17	3.77
TiO ₂	0.38	0.55	2.03	0.16	0.40	1.54	0.12	0.07
Cr ₂ O ₃	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01
FeO	29.91	29.81	25.68	23.79	29.13	18.86	18.61	19.04
MnO	0.35	0.34	0.28	0.26	0.48	0.29	0.26	0.29
MgO	3.94	3.38	6.16	8.03	5.00	10.63	11.80	10.22
CaO	9.51	10.06	10.22	11.70	9.94	13.24	12.59	11.40
Na ₂ O	1.74	1.86	1.88	0.13	0.74	0.08	0.17	1.13
K ₂ O	0.76	0.95	1.03	0.07	0.25	0.02	0.08	0.26
F	0.87	0.46	0.60	0.00	0.12	0.02		
Cl	0.38	0.55	0.51	0.07	0.14	0.01	0.01	0.02
TOTAL	97.41	97.39	97.92	96.91	96.71	98.93	99.29	97.68
O≠F,Cl	0.45	0.32	0.37	0.02	0.08	0.01	0.00	0.00
Σ -X	105.43	106.43	117.43	118.43	119.43	118.43	119.43	107.43
Si	6.99	6.86	6.76	7.80	7.63	7.84	7.91	7.66
Al	1.17	1.33	1.30	0.33	0.46	0.13	0.20	0.66
Ti	0.05	0.07	0.24	0.02	0.05	0.17	0.01	0.01
Cr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Fe	4.11	4.10	3.41	3.05	3.87	2.31	2.26	2.37
Mn	0.05	0.05	0.04	0.03	0.06	0.04	0.03	0.04
Mg	0.97	0.83	1.46	1.84	1.18	2.32	2.56	2.27
Ni	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Ca	1.67	1.77	1.74	1.92	1.69	2.08	1.96	1.82
Na	0.56	0.59	0.58	0.04	0.23	0.02	0.05	0.33
K	0.16	0.20	0.21	0.01	0.05	0.00	0.01	0.05
Ba	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	15.73	15.81	15.74	15.04	15.23	14.93	15.00	15.19
F	0.45	0.24	0.30	0.00	0.06	0.01	0.00	0.00
Cl	0.11	0.15	0.14	0.02	0.04	0.00	0.00	0.00

O≠F,Cl – proportion of F and Cl bonded to oxygen in MgO that must be subtracted from the total oxide weight percent

Σ -X – Total minus O≠F,Cl to obtain “true” total of oxide weight percent

Amphiboles

Sample	12-MT-18- 2	12-MT-25- 1	12-MT-25- 2	12-MT-27- 1	12-MT-27- 2	12-MT-27- 3
<i>Oxide (wt%)</i>						
SiO ₂	52.87	54.61	54.72	54.71	56.18	54.97
Al ₂ O ₃	1.45	0.87	0.97	0.73	0.86	0.64
TiO ₂	0.10	0.01	0.03	0.03	0.08	0.02
Cr ₂ O ₃	0.01	0.26	0.03	0.00	0.03	0.01
FeO	19.21	15.95	16.50	23.33	11.97	22.93
MnO	0.31	0.30	0.34	0.23	0.03	0.28
MgO	11.22	13.53	13.16	17.91	16.32	17.84
CaO	12.17	12.72	12.47	0.71	12.72	0.72
Na ₂ O	0.41	0.14	0.08	0.07	0.13	0.05
K ₂ O	0.13	0.03	0.04	0.01	0.03	0.02
F	0.02	0.05	0.03	0.15	0.07	0.12
Cl			0.01			
TOTAL	97.90	98.46	98.38	97.88	98.43	97.60
O≠F,Cl	0.01	0.02	0.01	0.06	0.03	0.05
Σ -X	108.43	115.43	116.43	120.43	121.43	122.43
Si	7.84	7.92	7.95	7.96	7.97	8.00
Al	0.25	0.15	0.17	0.13	0.14	0.11
Ti	0.01	0.00	0.00	0.00	0.01	0.00
Cr	0.00	0.03	0.00	0.00	0.00	0.00
Fe	2.38	1.93	2.00	2.84	1.42	2.79
Mn	0.04	0.04	0.04	0.03	0.00	0.03
Mg	2.48	2.92	2.85	3.89	3.45	3.87
Ni	0.00	0.00	0.00	0.00	0.00	0.00
Zn	0.00	0.00	0.00	0.00	0.00	0.00
Ca	1.93	1.98	1.94	0.11	1.93	0.11
Na	0.12	0.04	0.02	0.02	0.04	0.02
K	0.02	0.01	0.01	0.00	0.01	0.00
Ba	0.00	0.00	0.00	0.00	0.00	0.00
Σ cations	15.09	15.01	14.98	14.98	14.97	14.95
F	0.01	0.02	0.01	0.07	0.03	0.05
Cl	0.00	0.00	0.00	0.00	0.00	0.00

O≠F,Cl – proportion of F and Cl bonded to oxygen in MgO that must be subtracted from the total oxide weight percent

Σ -X – Total minus O≠F,Cl to obtain “true” total of oxide weight percent

Fe-Oxides

Sample	12-MT-02-Mag1	12-MT-02-IL1	12-MT-09-Mag1	12-MT-09-Mag2	12-MT-09-IL1	12-MT-09-IL2	12-MT-09-IL3
<i>Oxide (wt%)</i>							
SiO ₂	0.04		0.06	0.06	0.00	0.00	0.00
Al ₂ O ₃	0.95	0.02	2.91	2.60	0.02	0.04	0.05
TiO ₂	14.32	50.75	9.68	10.10	51.15	51.68	51.15
FeO	76.60	46.63	79.42	79.03	46.16	46.88	46.40
Cr ₂ O ₃	0.11	0.05	0.14	0.12	0.00	0.05	0.04
CaO	0.03	0.02	0.02	0.03	0.01	0.04	0.08
MnO	0.33	1.00	0.41	0.44	1.89	1.85	2.01
V ₂ O ₃	0.92		1.15	1.18	0.00	0.00	0.00
NiO	0.02	0.02	0.01	0.03	0.00	0.02	0.00
ZnO	0.09	0.01	0.18	0.36	0.04	0.00	0.01
Total	93.41	98.53	93.98	93.98	99.28	100.56	99.74

Sample	12-MT-09-IL4	94LAAT3-1A-Mag1	94LAAT3-1A-IL1	94LAAT3-1A-Mag2	94LAAT3-1A-IL2	13-AM-1-Mag1	13-AM1-Mag2
<i>Oxide (wt%)</i>							
SiO ₂	0.00	0.01	0.00	0.10	0.00	0.02	0.07
Al ₂ O ₃	0.05	2.75	0.01	1.68	0.03	1.78	1.98
TiO ₂	51.54	13.78	51.22	16.01	51.37	19.78	19.13
FeO	46.65	75.14	46.87	75.68	47.16	69.93	70.44
Cr ₂ O ₃	0.06	0.14	0.03	0.09	0.00	0.11	0.18
CaO	0.06	0.13	0.01	0.09	0.00	0.05	0.06
MnO	1.96	0.24	0.97	0.51	0.71	0.75	0.71
V ₂ O ₃	0.00	1.22	0.00	0.85	0.00	0.69	0.68
NiO	0.00	0.02	0.01			0.02	0.02
ZnO	0.04	0.07	0.03	0.08	0.00	0.18	0.13
Total	100.35	93.65	99.41	95.14	99.62	93.31	93.40

Sample	13-AM-1-IL1	13-AM1-IL2
<i>Oxide (wt%)</i>		
SiO ₂	0.00	0.00
Al ₂ O ₃	0.06	0.02
TiO ₂	49.17	49.89
FeO	46.40	46.56
Cr ₂ O ₃	0.04	0.02
CaO	0.08	0.20
MnO	1.45	1.43
V ₂ O ₃	0.00	0.00
NiO	0.00	0.00
ZnO	0.00	0.00
Total	97.20	98.12

Appendix F: Isotopic data

Sample	²⁰⁶ Pb/ ²⁰⁴ Pb(raw)	²⁰⁶ Pb/ ²⁰⁴ Pb(i)	*2σ error (±)	²⁰⁷ Pb/ ²⁰⁴ Pb(raw)	²⁰⁷ Pb/ ²⁰⁴ Pb(i)	*2σ error (±)	²⁰⁸ Pb/ ²⁰⁴ Pb(raw)	²⁰⁸ Pb/ ²⁰⁴ Pb(i)	*2σ error (±)
TR-45	19.425	18.026	9.0E-04	15.632	15.602	8.0E-04	39.161	37.572	3.0E-03
TR-62	19.579	17.887	1.0E-03	15.611	15.562	1.0E-03	39.302	37.317	4.0E-03
91LAAT2-2	19.635	17.611	2.0E-03	15.619	15.548	2.0E-03	39.266	37.019	5.0E-03
94LAAT1-2a	20.686	18.325	4.0E-03	15.813	15.721	4.0E-03	40.079	37.452	1.0E-02
12-MT-01	16.887	17.687	2.0E-03	15.598	15.569	2.0E-03	38.865	37.356	9.0E-03
12-MT-09	19.518	17.761	2.0E-03	15.636	15.583	2.0E-03	39.565	37.643	6.0E-03
13-AM-01	20.035	19.151	7.0E-04	15.964	15.969	8.0E-04	40.482	39.602	3.0E-03
13-AM-03	19.515	18.065	3.0E-03	15.631	15.598	4.0E-03	39.332	37.820	1.2E-02
13-AM-11	17.710	17.342	1.0E-03	15.490	15.527	1.0E-03	37.211	36.910	4.0E-03
13-AM-13	19.136	17.763	1.0E-03	15.614	15.586	1.0E-03	38.935	37.425	4.0E-03
13-AM-14	18.806	17.654	5.0E-04	15.578	15.545	4.0E-04	38.650	37.369	1.4E-03
13-AM-15	19.517	17.738	2.0E-03	15.630	15.575	2.0E-03	39.447	37.501	7.0E-03
13-AM-26B	21.223	20.575	2.0E-03	15.788	15.807	2.0E-03	41.172	40.433	7.0E-03
12-MT-17	19.771	18.244	4.0E-03	15.595	15.557	1.0E-03	39.211	37.663	1.0E-03
12-MT-20	22.229	18.277	5.0E-03	15.768	15.572	4.0E-03	42.589	36.967	1.0E-02
12-MT-21	21.905	19.990	4.0E-03	15.752	15.689	3.0E-03	41.815	37.221	8.0E-03

*2σ error on individual sample runs. ²⁰⁶Pb/²⁰⁴Pb(raw) – raw data measured by ICP-MS, ²⁰⁶Pb/²⁰⁴Pb(i) – time corrected initial isotopic ratios (t=780 Ma).

Sample	Rb ppm	Sr ppm	$^{87}\text{Sr}/^{86}\text{Sr}_{(\text{m})}$	*2 σ error ($\pm$)	$^{87}\text{Rb}/^{86}\text{Sr}$	$^{87}\text{Sr}/^{86}\text{Sr}_{(\text{i})}$
TR-45	50	185	0.71527	2.4E-05	0.78290	0.70655
TR-62	71	214	0.71624	2.6E-05	0.95563	0.70559
91LAAT2-2	42	145	0.71574	1.6E-05	0.84674	0.70630
94LAAT12-A	40	152	0.71871	1.5E-05	0.76225	0.71022
12-MT-01	55	184	0.71759	1.2E-05	0.86887	0.70791
12-MT-09	45	179	0.71933	3.0E-05	0.73130	0.71117
13-AM-01	61	277	0.71831	2.0E-05	0.63606	0.71122
13-AM-03	46	183	0.715371	1.4E-06	0.72532	0.707293
13-AM-11	33	169	0.713338	5.0E-06	0.55879	0.707114
13-AM-13	60	184	0.717018	8.0E-06	0.95161	0.706419
13-AM-14	44	176	0.713784	8.0E-06	0.72757	0.705681
13-AM-15	43	189	0.715316	7.0E-06	0.65633	0.708006
13-AM-26B	27	58	0.72150	1.4E-05	1.37124	0.70623
12-MT-17	13	83	0.70789	6.0E-05	0.44622	0.70292
12-MT-20	22	155	0.71073	2.1E-05	0.41640	0.70609
12-MT-21	1	188	0.70463	2.6E-05	0.02000	0.70441

$^{87}\text{Sr}/^{86}\text{Sr}_{(\text{m})}$ – measured isotopic ratios from ICP-MS, $^{87}\text{Sr}/^{86}\text{Sr}_{(\text{i})}$ – time corrected initial ratios (t=780 Ma)

*2 σ error on individual sample runs

Sample	Note	$^{143}\text{Nd}/^{144}\text{Nd}(\text{m})$	$^{147}\text{Sm}/^{144}\text{Nd}$	$^{143}\text{Nd}/^{144}\text{Nd}(\text{i})$	*2 σ error ($\pm$)	$\epsilon\text{Nd}_{(t)}$	T_{DM} (Ma)
TR-45	Dyke	0.51253	0.15649	0.51173	1.0E-05	1.9	1542
TR-62	Dyke	0.51250	0.14933	0.51173	1.6E-05	2.0	1450
91LAAT2-2	Dyke	0.512602	0.16433	0.511761	8.0E-06	2.5	1572
94LAAT1-2A	Dyke	0.51259	0.16037	0.51177	1.0E-05	2.6	1496
12-MT-01	Dyke	0.512516	0.15541	0.511722	8.0E-06	1.7	1554
12-MT-09	Dyke	0.51252	0.15629	0.51172	1.6E-05	1.7	1568
13-AM-01	Dyke	0.51257	0.15557	0.5118	1.0E-04	2.9	1409
13-AM-03	Dyke	0.512528	0.15602	0.511730	9.0E-06	1.9	1541
13-AM-11	Sill	0.512691	0.17111	0.511816	6.0E-06	3.6	1503
13-AM-13	Dyke	0.512517	0.15596	0.511719	8.0E-06	1.7	1569
13-AM-14	Dyke	0.512543	0.15661	0.511742	8.0E-06	2.2	1516
13-AM-15	Dyke	0.51253	0.15645	0.51173	1.0E-05	1.9	1545
13-AM-26B	Sill	0.512674	0.16923	0.511808	8.0E-06	3.4	1499
12-MT-17	I&H	0.512732	0.15702	0.511929	9.0E-06	5.8	1024
12-MT-18	I&H	0.51268	0.14728	0.51193	1.4E-05	5.7	997
12-MT-19	I&H	0.51274	0.15933	0.51193	1.0E-05	5.7	1044
12-MT-20	I&H	0.512437	0.12869	0.511779	5.0E-06	2.9	1210
12-MT-21	I&H	0.512615	0.01398	0.512543	8.0E-06	17.8	382
12-MT-22	I&H	0.51268	0.14957	0.51192	1.8E-05	5.6	1022
12-MT-23	I&H	0.51278	0.16265	0.51195	1.2E-05	6.2	990
12-MT-24	I&H	0.51276	0.15890	0.51195	7.0E-05	6.2	977
12-MT-25	I&H	0.51279	0.16344	0.51196	1.4E-05	6.4	967
12-MT-26	I&H	0.51251	0.13769	0.51180	1.1E-05	3.4	1209
12-MT-27	I&H	0.51260	0.13911	0.51189	1.2E-05	5.1	1042

$^{143}\text{Nd}/^{144}\text{Nd}(\text{m})$ – measured isotopic ratios, $^{143}\text{Nd}/^{144}\text{Nd}(\text{i})$ – time corrected initial ratios ($t=780$ Ma) *2 σ error on individual sample runs

$\epsilon\text{Nd}(t) = ((^{143}\text{Nd}/^{144}\text{Nd}(\text{i})/\text{CHUR}(t))-1)*10000$; ($t=780$ Ma), CHUR – Chondrite Uniform Reservoir

TDM- depleted mantle model age, using values from DePaolo, (1981).

Standards	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$
#runs	56	56	56	79	115
average	16.8809	15.4272	36.4987	0.710246	0.511826
2 σ error ($\pm$)	0.009	0.012	0.04	0.000023	0.000014

Internal standards with number of runs used to calculate the standard deviations (2 σ) and average isotopic ratios of the different isotopic systems for the past 4 years