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Complete List of Authors:	Mackinder, Alana; Carleton University, Earth Sciences Cousens, Brian; Carleton University, Ottawa-Carleton Geoscience Centre, Department of Earth Sciences Ernst, Richard; Carleton University, Ottawa-Carleton Geoscience Centre, Department of Earth Sciences; Tomsk State University, Faculty of Geology and Geography Chamberlain, Kevin; Dept of Geology and Geophysics; Tomsk State University, Faculty of Geology and Geography
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Geochemical, isotopic and U-Pb-zircon study of the central and southern portions of the 780 Ma Gunbarrel Large Igneous Province in western Laurentia

Alana Mackinder^{a,1}, Brian L. Cousens^{a,2}, Richard E. Ernst^{a,b,3}, Kevin R. Chamberlain^{c,b,4}

^aDepartment of Earth Sciences, Carleton University, 1125 Colonel By Drive, Ottawa, ON, Canada, K1S 5B6

^bFaculty of Geology and Geography, Tomsk State University, 36 Lenin Ave, Tomsk 634050, Russia

^c Department of Geology and Geophysics, University of Wyoming, 1000 E. University Ave., Laramie, Wyoming 82071-3006, USA

²Corresponding author: email: brian.cousens@carleton.ca

¹email: alana.mackinder@gmail.com

³email: Richard.Ernst@ErnstGeosciences.com

⁴emial: kchamber@uwyo.edu

Abstract

Spanning 2500 km along the western margin of North America are 780 Ma dykes, sills, and minor volcanic packages of the Gunbarrel Large Igneous Province. This study focuses on southern (northwestern USA) and central (northern British Columbia) Gunbarrel intrusions and metavolcanic rocks of the Irene and Huckleberry formation (Washington state). Southern Gunbarrel U-Pb ages range from 780 to 769 Ma, and new U-Pb zircon dates for the Turah and Rogers Pass sills are 778.6 ± 0.7 and 778.7 ± 0.9 Ma, respectively. Southern Gunbarrel intrusions are medium to coarse grained diabbases that are moderately evolved basaltic, continental tholeiites. Intrusions display negative Nb-Ta and positive Pb anomalies in normalized multi-element plots, and $\epsilon_{\text{Nd}}^{780}$ vary from +3.6 to +1.5. The Irene and Huckleberry volcanic rocks are E-MORB in composition with higher $\epsilon_{\text{Nd}}^{780}$ (+5 to +6), and likely represent partial melts of a mantle plume responsible for the Gunbarrel event. Assuming an Irene and Huckleberry parental magma, mixing models indicate that the southern Gunbarrel magmas were crustally contaminated, but local host rocks are not appropriate crustal contaminants. The modeling points to average upper crust as the crustal contaminant, with an $\epsilon_{\text{Nd}}^{780} \sim -2$. This crustal contaminant likely resides on the craton impinged upon by the mantle plume. The remarkable geochemical homogeneity of Gunbarrel intrusions from the Yukon to Wyoming is best explained if primary, plume-derived E-MORB magmas were contaminated in large magma reservoirs near the plume centre and were then injected laterally into the crust 100's to 1000's of km from the reservoir.

Keywords: Neoproterozoic, Gunbarrel LIP, Large Igneous Province, geochemistry, isotopic composition, mantle sources

1. Introduction

Spanning over 2500 km along the western margin of North America from the Yukon and Northwest Territories, Canada, to Montana, Wyoming, and Idaho, USA, are diabase dykes, sills and basaltic volcanic rocks that have been dated through multiple studies at 780 Ma (average 780.3 ± 1.4 Ma; Harlan et al. 2003, and references therein) and collectively comprise the

Gunbarrel Large Igneous Province (LIP) (Figure 1; Buchan et al., 2010; Dudás and Lustwerk, 1997; Harlan et al., 2003; Park et al., 1995; Sandeman et al., 2014). There have been multiple geochronological and paleomagnetic studies (Table 1) that have identified units (dykes, sills and volcanic flows) as belonging to the Gunbarrel LIP (Burtis et al., 2007; Devlin et al., 1988; Dudás and Lustwerk, 1997; Harlan et al., 1997, Harlan et al., 2003; Harlan et al., 2008; LeCheminant and Heaman, 1994; Park et al., 1995; Wooden et al., 1978). Only recently, Sandeman et al. (2014) completed a detailed geochemical and isotopic study of Gunbarrel intrusions and lava flows from northern Canada (the northern Gunbarrel LIP) and for the Christmas Lake dyke from Wyoming in the southern part of the LIP.

This study provides geochronological, geochemical and Nd isotopic data for the remaining poorly-studied, southern (northwest USA) and central (British Columbia, Canada) constituents of this LIP. We present new U-Pb zircon ages for Gunbarrel sills within the study area for the Rogers Pass and Turah sills. We evaluate the geochemical characteristics of the southern and central Gunbarrel rocks, test for relations between Gunbarrel rocks exposed in the Belt Purcell, Tobacco Root Mountains, Beartooth Mountains, Teton Range, and northern British Columbia, evaluate regional differences in the magmatic source and subsequent evolution of Gunbarrel magmas, establish mantle source and crustal contaminant compositions for the southern Gunbarrel rocks, and compare our results to those of the northern constituents of the Gunbarrel LIP (Sandeman et al., 2014). We also geochemically and isotopically characterize the Irene and Huckleberry volcanic rocks of northwest Washington, USA, that have been linked to the Gunbarrel event (e.g. Harlan et al., 2003; Buchan and Ernst, 2004) based on a Sm-Nd whole rock age of 762 ± 44 Ma (Devlin et al. 1988).

Originally it was proposed that the large (up to 50 m wide) Gunbarrel intrusions were the

result of lithospheric extension associated with the rifting of the western Laurentia margin during the Neoproterozoic breakup of the supercontinent Rodinia (LeCheminant and Heaman, 1994). Later, Park et al. (1995) noted the regionally radiating pattern of the NW-NNE intrusions (Figure 1) which he extrapolated back to an intersection point off Vancouver Island, BC and inferred a mantle plume origin for the rifting and generation of Gunbarrel magmas (see also Ernst and Buchan 1997; Harlan et al. 2003; Buchan et al., 2010; Ernst and Bleeker, 2010; Sandeman et al., 2014). If the plume model is correct, then the plume actually impinged on another craton adjacent to Laurentia at ca. 780 Ma and then emplaced the radial Gunbarrel dyke swarm into adjacent Laurentia. Gunbarrel intrusions have been linked to dyke events of approximately the same age in the South China craton (Li et al. 2003) and Gawler Craton in Australia (Zhao et al. 1994), both of which are commonly proposed to occupy a position on the west side of Laurentia prior to the breakup of Rodinia. Do dyke swarms or mafic igneous complexes in either of these cratons resemble Gunbarrel intrusions, and thus represent Gunbarrel units emplaced closer to the plume centre?

2. Geographic Distribution of Gunbarrel Igneous Rocks

Gunbarrel intrusions are exposed over 2500 km from northwestern Canada to northwestern USA and intrude an assortment of country rocks summarized herein from north to south (Figure 1). In the Mackenzie Mountains of the Yukon and N.W.T., Canada, the Gunbarrel intrusions are termed the Tzesotene sills and minor dykes that intrude the Mackenzie Mountains Supergroup sedimentary sequence (Dudás and Lustwerk, 1997; Buchan and Ernst, 2013; Sandeman et al, 2014). Capping the Mackenzie Mountains Supergroup are the Little Dal Basalts, proposed to be remnant continental flood basalts that were fed by the Gunbarrel dykes. Further

east in the Slave Craton (Figure 1), the ca. 779 Ma Hottah sills (sheets) and dykes intrude Archean to Paleoproterozoic basement and continental arc rocks of the Wopmay Orogen (Harlan et al., 2003; Buchan and Ernst, 2004, 2013; Buchan et al., 2010; Sandeman et al., 2014).

In northern British Columbia, Canada, the ca. 777 Ma Muncho Lake dykes intrude unmetamorphosed, predominantly fine-grained siliciclastic and carbonate strata of the Muskwa assemblage, situated in the Canadian Rockies (Figure 1; Ross et al., 2001).

In the north-western USA the Gunbarrel LIP is exposed in several geological settings. The Turah, Wolf Creek, and Rogers Pass sills intrude sedimentary sequences of the Belt-Purcell basin in northern Idaho and Montana (Figure 1; Supplementary File a, panel B; Burtis et al., 2007; Harlan et al., 1997). The Tobacco Root Mountains of south-central Montana host sub-parallel, NW-trending dykes that intrude Precambrian basement-cored uplifts of the Wyoming craton (Figure 1; Supplementary File a, panel C; Wooden et al., 1978; Harlan et al., 1997; Harlan et al., 2008; Rogers et al., 2016). Further south in the Beartooth Mountains of Montana and Wyoming, Gunbarrel intrusions cut Archean crystalline basement and include the Christmas Lake dyke which can be traced for approximately 16 km (Figure 1; Supplementary File a, panel D; Harlan et al., 1997). In northwestern Wyoming, Gunbarrel dykes, including the Mount Moran dyke, intrude deformed gneisses, amphibolites and discordant plutons of the Archean crystalline basement that make up the Teton Range (Harlan et al., 1997; Reed and Zartman, 1973).

Exposed in northwestern Washington, USA, and south-central British Columbia, Canada, the Irene and Huckleberry (I&H) volcanic rocks (Figure 1; Supplementary File a, panel A) have been correlated with the Gunbarrel LIP based on a Sm-Nd isochron age of 762 ± 44 Ma (Devlin et al., 1988). The I&H volcanic rocks are part of the Huckleberry Formation, that is composed of a lower conglomerate member and an upper greenstone member.

148

149 **3. Sampling and Methods**

150 Field work was carried out during the summers of 2012 and 2013 in Montana, Idaho,
151 Wyoming, and Washington, USA, to collect samples from Gunbarrel intrusions and I&H
152 volcanic rocks. Sample locations are shown in Figure 1 and in Supplementary File a. Where
153 possible hand samples were collected from the center and margins of each intrusion. At poorly
154 exposed outcrops, samples were collected from scree slopes. Sample locations are listed in Table
155 2. A total of 26 samples of Gunbarrel intrusions were utilized in this study, 16 collected through
156 field work and 10 obtained from other sources, although not all samples include a complete
157 geochemical analysis (major, trace elements, isotopes).

158 Hand samples were cut into 1 cm thick slabs with a diamond saw. Weathered surfaces
159 were removed and the slabs were polished using 120 grit then 300 grit carborundum powder to
160 remove metal contamination introduced from the rock saws. Slabs were crushed in a Chipmunk
161 rock crusher and powdered in a Rocklabs ringmill at Carleton University using either an agate or
162 steel head. Comparisons of powder splits crushed in the steel versus agate head show that the
163 steel head only contributes Cr (variable, up to 50 ppm) to the powder; Cr data are not reported in
164 Supplementary File b. Standard and polished thin sections were made for each sample for
165 petrographic analysis and electron microprobe analysis. Powdered material from each sample
166 and a blind internal standard (sample 10-LT-05) were sent to the Ontario Geological Survey
167 (Sudbury, Ontario) for major element oxide and trace element geochemical analysis by fused-
168 disc XRF and acid-dissolution ICP-MS methods, respectively. For major element oxide analysis,
169 the sample powder was fused with a Li-borate flux to produce a glass bead and analyzed using
170 an x-ray fluorescence spectrometer. The loss on ignition (LOI) was determined at 1000°C under

oxygen atmosphere until a constant weight is maintained. Trace element abundances were determined through open beaker acid-dissolution and then analysed using inductively coupled plasma mass spectrometry (ICP-MS).

Four samples of I&H volcanic rocks and a sample of the Turah sill were re-analyzed for trace elements at ALS Laboratories (North Vancouver, BC) where samples were sintered with a lithium borate flux prior to acid digestion and analysis by ICP-MS. Re-analysis of these four samples was necessary because the heavy rare earth elements and Zr determined by acid-digestion ICP-MS were notably lower in concentration compared to other study samples and other published Gunbarrel analyses. Reanalysis produced values that corresponded with other samples from this study and with the I&H units from Devlin et al. (1988). Therefore, the ALS ICP-MS data from the reanalysed samples are used in this study, whereas the OGS data are used for all other samples. Data precisions were determined from replicate analyses of samples and the internal standard and are listed in Supplementary File b.

Thirteen Gunbarrel and eleven I&H volcanic samples were analysed for Sm-Nd isotopes at the Isotope Geochemistry and Geochronology Research Center (IGGRC) at Carleton University, Ottawa, Canada, using cation chromatography techniques of Cousens (2000). Samples were analysed using the Thermo Fisher Triton T1 thermal ionization mass spectrometer. A mixed ^{148}Nd - ^{149}Sm spike was added to each sample to calculate Nd and Sm concentrations. The bulk rare earth elements (REE) were separated using Dowex AG50-X8 cation resin, and this residue was re-dissolved in 0.26N HCl and loaded into an Eichrom chromatographic column containing a 2 cm-high bed of Teflon powder coated with HDEHP (di(2-ethylhexyl) orthophosphoric acid, Richard et al., 1976). Nd is eluted using 0.26N HCl, followed by Sm in 0.5N HCl. Total procedural blanks for Nd are < 150 picograms and are insignificant. Nd isotope ratios are

normalized to $^{146}\text{Nd}/^{144}\text{Nd} = 0.72190$. Thirty runs of an internal Nd metal standard yield $^{143}\text{Nd}/^{144}\text{Nd} = 0.511823 \pm 12$ ($n = 40$, Sept. 2008-July 2013), equivalent to a value for the La Jolla standard of 0.511852 based on comparative runs of the two metal standards. Eleven analyses of USGS standard BCR-2 average $^{143}\text{Nd}/^{144}\text{Nd} = 0.512644 \pm 0.000012$. All quoted uncertainties are 2-sigma standard deviations of the mean. Sm and Nd concentrations, initial Nd isotopic ratios, epsilon values, and depleted mantle model ages were calculated using an offline Excel program written by G. Tilton and B. Cousens. All samples were corrected for post-crystallization decay using an age of 780 Ma.

Additional samples were obtained from S. Harlan and A. LeCheminant for Gunbarrel intrusions in the Tobacco Root Mountains, Teton Ranges (USA) and Muncho Lake (British Columbia). T. Kilian provided two samples of Gunbarrel dykes from the Beartooth Mountains, and E. Burtis supplied geochemical analyses for the Rogers Pass sill (sample BURRPE-04) and the zircon separate RPKRC02-2 that was dated as part of this study.

Zircon separates of the Rogers Pass and Turah sills were analyzed for U-Pb geochronology at the University of Wyoming. Zircon grains were separated and concentrated by standard crushing, density and magnetic methods. Zircons in each sample were anhedral, striated, thin flakes, morphologies typical of magmatic zircon growth in mafic rocks (e.g. Krogh et al., 1982; Doughty and Chamberlain, 1996). Selected zircons were annealed at 850 °C for 50 hours, then dissolved in two steps using a chemical abrasion, thermal ionization mass spectrometric (CA-TIMS) U-Pb dating method modified from Mattinson (2005), Krogh (1973), and Parrish et al. (1987). The first step was dissolution in hydrofluoric acid (HF) and nitric acid (HNO_3) at 180 °C for 12 hours. Individual grains were then spiked with a mixed ^{205}Pb - ^{233}U - ^{235}U tracer (ET535), dissolved in HF and HNO_3 at 240 °C for 30 hours, and converted to chlorides by the addition of

HCl. The dissolved samples were loaded onto rhenium filaments with phosphoric acid and silica gel (Pb) or graphite (U) without any further chemical processing. Pb and UO₂ isotopic compositions were determined in single Daly-photomultiplier mode on a Micromass Sector 54 mass spectrometer. Data were reduced and ages calculated using PbMacDat and ISOPLOT/EX after Ludwig (1988, 1991, 1998). Mass discrimination of 0.20 ± 0.10 ‰/amu for Pb was determined by replicate analyses of NIST SRM 981. Total common Pb varied from 1.5 to 0.6 picograms and was all assigned to blank. Pb blank was measured as 18.649 ± 0.40 , 15.540 ± 0.48 , and 38.808 ± 1.7 for $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, respectively. U blanks were consistently less than 0.2 pg. Concordia coordinates, intercepts, and uncertainties were calculated using MacPBDAT and ISOPLOT programs (based on Ludwig 1988, 1991); initial Pb isotopic compositions were estimated by Stacey and Kramers (1975) model. The decay constants used by MacPBDAT are those recommended by the I.U.G.S. Subcommittee on Geochronology (Steiger and Jäger, 1977): 0.155125×10^{-9} /yr for ^{238}U , 0.98485×10^{-9} /yr for ^{235}U and present-day $^{238}\text{U}/^{235}\text{U} = 137.88$. Sample locations are shown in Supplementary File a, panel B, and geographic coordinates and analytical data are reported in Table 3.

4. Results

4.1 Mineralogy

In general, all southern Gunbarrel intrusions are medium- to coarse-grained diabase with fine-grained chilled margins (where observed). Dykes are sub-vertical, 5-50 m in width, weather a rusty red colour and are highly fractured in outcrop (Figure 2a). The mineral assemblages and detailed petrographic observations for the Gunbarrel rocks of this study are listed in Supplementary Files c and d. The following is a generalized mineralogical summary.

Petrographically, the Gunbarrel intrusions from all localities in this study have a common mineral assemblage that includes plagioclase (40-70%) + clinopyroxene (12-40%) + Fe-oxides (2-12%) with minor amounts of interstitial quartz intergrown with alkali feldspar (granophyre) + altered biotite + amphibole + chlorite with an ophitic to subophitic texture (Figure 2b). Accessory minerals commonly include apatite, zircon, baddeleyite, rutile and rare, small disseminated pyrite and chalcopyrite grains. Plagioclase often occurs as elongate laths or euhedral prisms (0.5-7 mm in size) that are lightly to highly sericitized. Less altered examples of plagioclase display albite twinning with some zonation (Figure 2b). Microprobe analyses of plagioclase show that cores have a labradorite composition, with a few samples having an andesine composition. Plagioclase rims are andesine to oligoclase in composition. Clinopyroxene is present as anhedral to euhedral crystals (0.2-4 mm) with minor alteration rims (Figure 2b). Microprobe investigation of the clinopyroxenes revealed fine exsolution lamellae of orthopyroxene that were too fine to accurately analyse. Spot analysis on individual grains shows the majority of clinopyroxene crystals are augite with pigeonite rims. Pyroxene crystals in the Wolf Creek sill have pigeonite cores with clinoferrosilite rims. The Fe-Ti oxides display various morphologies including euhedral to anhedral prisms, globular and skeletal grains <0.1-2 mm in size. Many of these oxide crystals include titanomagnetite-ilmenite exsolution. Biotite occurs as small (<0.5 mm) tabular flakes with varying degrees of alteration to chlorite. Interstitial quartz grains are commonly pitted and have small inclusions of apatite, and/or rutile.

Although there is rare localized alteration in the form of quartz and calcite veins, Gunbarrel intrusions have undergone little metamorphism and deformation. Plagioclase grains are variably sericitized, and pyroxene grains are altered to amphibole along grain margins (Supplementary Files c, d). Biotite is commonly altered to chlorite. As we demonstrate in the

following sections, major element oxides such as Al_2O_3 , CaO , Fe_2O_3 , and K_2O vary smoothly with $\text{Mg\#}$ in all of the southern Gunbarrel rocks, as do trace element concentrations including potentially mobile elements such as Rb and Sr. We also observe very uniform Primitive Mantle-normalized incompatible element patterns in southern Gunbarrel rocks, without variable positive or negative spikes for more mobile elements such as Rb, K, Sr or Ba. However, Pb concentrations are more variable than most other trace elements. We conclude that the observed weathering and alteration in southern Gunbarrel intrusions has not had a deleterious effect on the observed geochemistry of the intrusions.

The I&H volcanic rocks of northwestern Washington State are not as uniform petrographically as the Gunbarrel intrusions. In the field three rock types were encountered, 1) a greenstone, 2) a grey phyllite, and 3) a brecciated tuff. All I&H volcanic rocks have been metamorphosed to greenschist facies and have been affected by fluids that produced large and numerous calcite, epidote and quartz veins (Figure 2c). The majority of I&H samples are fine grained, dark green and schistose greenstones and are locally porphyritic and/or amygdaloidal locally (Figure 2d). Rarely, samples are medium grained and preserve relic, interstitial or subophitic igneous textures. The groundmass is fine grained and is composed of intergrown chlorite, actinolite, plagioclase (albite), quartz, and Fe-Ti oxides and trace amounts of disseminated sulphides. Phenocrysts include plagioclase laths and needles (0.3-1.5 mm), euhedral to anhedral augite (0.2-0.8 mm), euhedral to anhedral amphibole (actinolite to anthophyllite in composition) prisms (0.3-3 mm) and subhedral epidote grains (0.3-0.6 mm). Vesicles are infilled with one or more minerals including quartz, calcite, epidote, chlorite or Fe-Ti oxides.

The phyllites are light grey in colour, with a slight sheen to the surface and weather brown. This rock type is composed of fine-grain plagioclase, carbonate, Fe-Ti oxides, chlorite, quartz, epidote, with minor amounts of amphibole, biotite and trace amounts of apatite.

The brecciated tuff rocks are light green in colour and contain semi-rounded to angular lithic fragments that are up to several centimeters in size. Lithic fragments contain spheroids (0.5 mm) of either calcite, chlorite, clays, or a fine grained unknown mineral or mixture of minerals that is set in a glassy to fine-grain matrix. The matrix also hosts microphenocrysts (0.1-0.5 mm) of euhedral clinopyroxene and plagioclase laths that form a trachytic texture, indicating that the tuff is igneous in origin. Other lithic fragments include sheets of chlorite (up to 1 mm) and small euhedral epidote grains. A third type of clast is composed of large (up to 3 mm) euhedral plagioclase laths that are altered to sericite. Plagioclase and clinopyroxene phenocrysts have minimal alteration, and can make up 25% of the rock, with the remainder composed of fine-grain chlorite, amphibole, and clays.

As we demonstrate in the following sections, I&H rocks exhibit large variation in major and trace element compositions that likely reflect the effects of alteration and metamorphism. CaO varies from ~5 to 19 wt%, K₂O from ~1.4 to 0.1 wt%, P₂O₅ from 0.80 to 0.12, and Sr from 85 to 833 ppm over a small range in Mg# (0.55 to 0.43). More immobile elements such as Th and the heavy REE show less variability, but even a commonly immobile element such as Nb varies from 14 to 48 ppm. Ratios of commonly immobile elements, such as Th/La, Th/Nb, La/Nb, and La/Sm, show more limited variation than absolute concentrations, indicating that these ratios may still include some original geochemical information about the I&H rock suite.

Multiple thin sections were probed using the EMPA and individual mineral analyses were collected for plagioclase, pyroxene, amphibole and Fe-Ti oxide minerals. Data for mineral chemistry analyses are presented in Supplementary File e.

The main pyroxene in all samples is augite (Figure 4A). Upon investigation with BSE images, it was found that most pyroxenes in Gunbarrel intrusions are composed of ultra-fine orthopyroxene-clinopyroxene lamellae, however, when analysed using the EPMA compositions were uniformly clinopyroxene (Figure 3A). All I&H metavolcanic pyroxene cores and rims are high Mg and, in some cases, high Ca augites. All Christmas Lake pyroxenes are augites. In the Tobacco Root Mountains and Mount Moran samples, all pyroxene cores are augite in composition but most of the rims have lost Ca and have 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.

For plagioclase, the Tobacco Root Mountain samples have a large spread in compositions from labradorite to almost pure albite, in one case all in one sample (Figure 3B). Samples from the Christmas Lake dyke and Mount Moran have more uniform analyses that plot in the labradorite field, with a rim of a Mount Moran plagioclase plotting as andesine. All I&H metavolcanic plagioclases are almost pure albite in composition, with the exception of 12-MT-27 that includes a plagioclase of andesine composition.

4.2 CA-TIMS Zircon Geochronology, Rogers Pass and Turah sills

Previous attempts to date zircons from these sills produced U-Pb data with 9 to 78% discordance (Burtis et al., 2007). Chemical abrasion of the zircon separates in this study removed effects of Pb loss and produced concordant data from all 8 analyses (Figure 4). Three of the four single grain zircon analyses from RPKRC02-2 (Rogers Pass sill, sample BURRPE-04) overlap at ca. 778 Ma (Table 3), with the fourth analysis being concordant with a slightly younger $^{206}\text{Pb}/^{238}\text{U}$ date of 776 Ma, possibly due to Pb loss. The Concordia Age (Ludwig 1998) of the three overlapping fractions is 778.6 ± 1.2 Ma (Fig. 2). The weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date is

778.7 $\pm$ 0.9 Ma (Figure 4) and is interpreted as the best estimate of the intrusive age of this sill. All four single grain analyses from MT TU-1 (Turah sill) lie on Concordia and yield a Concordia Age of 778.3 $\pm$ 1.3 Ma and weighted mean $^{206}\text{Pb}/^{238}\text{U}$ date of 778.6 $\pm$ 0.7 Ma (Table 3; Figure 4). The weighted mean average is interpreted as the best estimate for the intrusive age of this sill, overlapping with the Rogers Pass sill, at 778.63 $\pm$ Ma. The agreement between these two dates strongly supports an interpretation that they are from the same magmatic event. Zircons from the Holland Lake sill, located northwest of the Rogers Pass sill (MTHL-12, Burtis et al., 2007, their Figure 2), were not reanalyzed in this study since previous data were only a few percent discordant and yielded an upper intercept date (777.5 $\pm$ 2.5 Ma) that overlaps within error of these two new dates. Based on the previous and new U-Pb data, intrusion of the Rogers Pass, Turah and Holland Lake sills are interpreted to reflect a common magmatic event at ca. 778.6 Ma.

4.3 Major, minor and trace element geochemistry

With one exception, central and southern Gunbarrel intrusions are basalt to basaltic andesites in composition (Figure 5A) and are tholeiitic (Figure 5B). Gunbarrel intrusions from this study have Mg#s between 0.30-0.46 and high FeO^{T} of 12-18 wt% with high TiO_2 of 1.9-3.5 wt% (Figure 5C) making them high Fe-Ti tholeiites. K_2O and P_2O_5 contents generally increase with decreasing Mg# (not shown). Southern and central Gunbarrel rocks have a positive trend between $\text{CaO}/\text{Al}_2\text{O}_3$ vs Mg# (Figure 5D) as CaO decreases while Al_2O_3 increases with decreasing Mg# (not shown), indicating that clinopyroxene is a major fractionating phase in these Gunbarrel magmas.

Gunbarrel intrusions of this study have negative correlations between incompatible elements Ba, Yb, and Th (as well as Rb, Ce, Zr and Pb, not shown) versus Mg# (Figure 6). Vanadium and Sc concentrations decrease sharply at Mg# below 0.4. Yb and Zr (not shown) are notably lower in the TRM, one Mount Moran and the Christmas Lake intrusions compared to those of the Muncho Lake samples; Yb also appears slightly higher in the Turah, Wolf Creek and Rogers Pass sills. Ba and Th increase in abundance with decreasing Mg#, as do Nb, Zr and Sr abundances (not shown).

In incompatible element diagrams normalized to Primitive Mantle (N ; Sun and McDonough, 1989), southern and central Gunbarrel intrusions have similar patterns with a small negative Eu anomaly ($Eu_N/((Sm_N + Gd_N)/2)$, in the range of 0.72-0.99, mean = 0.79) indicative of plagioclase fractionation, and a moderate slope from the light to heavy rare earth elements ($La/Yb_N = 2.5$ to 3.9 ; Figure 7). The sills of the Belt Purcell basin (Rogers Pass, Wolf Creek, Turah) and the Mount Moran dyke have lower light REE abundances than the Tobacco Root Mountains, Christmas Lake dyke, and the Muncho Lake Gunbarrel intrusions, but all overlap in heavy REE with the exception of the Muncho Lake locality (Figure 7). The La/Sm_N ratios range from 1.4 in the Wolf Creek and Turah sills to 1.8 in the Mt. Moran dyke and Tobacco Root Mountains exposures. Gunbarrel intrusions of this study have a small range of Gd/Yb_N ratios from 1.6 to 2.1, with the exception of the Mount Moran dyke, Muncho Lake dyke, Turah sill and Wolf Creek sill that range from 1.45 to 1.53. All southern and central Gunbarrel samples have subparallel normalized incompatible element patterns, with positive Th-U, K and Pb anomalies and negative Nb-Ta, Sr and P anomalies relative to the adjacent REE (Figure 8A,B,C).

In a Nb/Y vs. Zr/Ti diagram (Pearce, 1996) southern and central Gunbarrel intrusions are subalkaline basalts as shown in Figure 5A (Figure 9A). These Gunbarrel intrusions can be

classified as continental basalts in a Y/15 - Nb/8 - La/10 tectonic setting diagram (Figure 9B; Cabanis and Lecolle, 1989). In a Th/Yb vs. Ta/Yb diagram (Gorton and Schandl, 2000) the Gunbarrel intrusions plot in a tight cluster parallel to and above the E-MORB part of the mantle array (Figure 9C). Samples that plot above the MORB-OIB array are interpreted to include a crustal component (Gorton and Schandl, 2000).

The I&H volcanic rocks have Mg#’s between 0.42-0.53 and SiO₂ contents between 43-53 wt %. FeO^T is lower than southern Gunbarrel intrusions, ranging from 6-14 wt%, and TiO₂ concentrations ranges from 1.16-3.23 wt%. Using immobile elements, like the Zr/Ti vs. Nb/Y diagram, the I&H rocks are subalkaline basalts but are shifted to the right of the Gunbarrel intrusions, closer to the alkaline field (Figure 9A). In a Y/15 - Nb/8 - La/10 diagram, the volcanic rocks plot in a group along the boundary between “E-MORB” and “Continental” basalt fields (Figure 9B). In a Th/Yb vs. Nb/Yb plot, the I&H volcanic rocks cluster around E-MORB within the MORB-OIB array, unlike the Gunbarrel intrusions that all plot above the array (Figure 9C). In a primitive mantle normalized incompatible trace element plot, the I&H volcanic rocks display patterns distinct from Gunbarrel intrusions (Figure 8D). Ignoring the more mobile elements such as K, Pb, and Sr, the I&H rocks have hump-shaped patterns with maxima at Nb and Ta. The I&H samples exhibit a small negative Eu anomaly ranging from 0.77-0.89, and a moderate slope from the MREE to HREE. Compared to the southern Gunbarrel intrusions, I&H volcanic rocks have low and highly variable K concentrations (possibly the result of metamorphism) and lack negative Nb-Ta anomalies (La/Nb = 0.84 – 1.22).

4.4. Isotope geochemistry

Gunbarrel intrusions from the study area have a small range of present day $^{143}\text{Nd}/^{144}\text{Nd}$ ratios between 0.51251-0.51269 (mean=0.51257), but initial $^{143}\text{Nd}/^{144}\text{Nd}$ ratios at 780 Ma are more limited between 0.51172-0.51182 (mean =0.51175), corresponding to ϵNd^{780} values of +1.70 to + 3.60 (Table 4). The intrusions with the highest ϵNd^{780} are the Turah and Wolf Creek sills ($\sim +3.5$). Three analyses of the Christmas Lake dyke yield results that fall just outside analytical uncertainty (± 0.3 epsilon units) at +1.5, +1.9, and +2.9. The Muncho Lake and Mt. Moran dykes have slightly higher ϵNd^{780} than the Tobacco Root Mountains dykes, but all these rocks overlap within analytical uncertainty. The southern Gunbarrel intrusions have calculated T_{DM} ages between 1400 Ma and 1600 Ma (Figure 10; DM model modified from Michard et al., 1985). Sandeman et al. (2014) reported ϵNd^{780} values of +1.4 to +1.7 for the northern suite of the Gunbarrel LIP.

Milton et al. (2017) report ϵHf^{780} values for zircons from a Little Dal basalt that range from +9.3 to +9.7 (± 0.02 to 0.04). These values fall slightly below the depleted mantle model evolution line for Hf isotopes at 775 Ma (ca. +12).

With two exceptions, the I&H rocks have higher ϵNd^{780} values compared to central and southern Gunbarrel intrusions (Figure 10). ϵNd^{780} are +2.9 to +6.4, with one outlier at +17.8 (not plotted). Model ages are all younger than those of the Gunbarrel intrusions of this study, ranging from ~ 1.0 to 1.2 Ga. The Sm-Nd isotopic system is commonly considered to be robust

during greenschist facies metamorphism, and the agreement of most I&H rocks at ϵNd^{780} between +5.1 and +6.4 suggests that these ϵNd^{780} are close to original magmatic values.

5.0 Discussion

Southern and central Gunbarrel intrusions from this study are continental tholeiites that show minimal variation in major and trace element composition. These Gunbarrel magmas are all evolved based on their $\text{Mg\#}$'s between 0.45 and 0.30. Northern Gunbarrel rocks also have low $\text{Mg\#}$'s (0.51 to 0.21) (Sandeman et al., 2014). Thus there are no Gunbarrel intrusions with near-“primary” magma compositions – all have either undergone fractional crystallization and/or assimilation of crustal rocks prior to being emplaced.

5.1 Fractional Crystallization History

In southern and central Gunbarrel intrusions, $\text{CaO}/\text{Al}_2\text{O}_3$ and Sc decrease with decreasing $\text{Mg\#}$. Combined with the negative Eu anomaly in most Gunbarrel intrusions, their geochemistry is consistent with a fractionating assemblage of clinopyroxene and plagioclase. Mass balance calculations (Carr, 2012) indicate that the least evolved southern Gunbarrel magmas (e.g., sample 13-AM-01) could be produced from ~40% crystallization of a less evolved magma (e.g., sample 13-AM-11) of a mineral assemblage of 45% clinopyroxene, 40% plagioclase, 8% olivine, and 7% Fe-Ti oxides, yielding a sum of the squares of residuals of 0.35. The negative P anomaly (Figures 7, 8) seen in southern Gunbarrel rocks is probably not due to apatite as a crystallizing phase, because P_2O_5 concentrations increase from ~0.2 to ~0.32% as $\text{Mg\#}$'s decrease in the sample set. If apatite was a crystallizing phase there should be a positive correlation between

P₂O₅ and Mg#. The negative P₂O₅ anomaly could be due to: (1) primary magmas being saturated in P₂O₅ earlier in their crystallization history, (2) primary magmas assimilating a P₂O₅-poor but REE-rich material, or (3) the presence of residual apatite after melting in the source of Gunbarrel magmas.

5.2 Constraints on Depth of Melting

The geochemistry of mantle-derived magmas includes indicators of the depth of partial melting, although these indicators can be overprinted by the addition of crustal melts as magmas ascend through the lithosphere. The aluminosilicate phase that is stable in the mantle varies as a function of depth, and the primary mineralogical change that effects the composition of magmas is the spinel to garnet transition in peridotite at ~ 75 km depth. Garnet has strong affinities for the heavy REE and other trace elements compared to spinel, and thus melting at depths > 75 km in the garnet stability field imparts strong heavy REE depletion in melts generated below that depth compared to melts generated in the spinel stability field (e.g., Stracke et al., 2003). Common average melting depth indicators include the ratio of middle to heavy REE (e.g., Gd/Yb_N) and the concentrations of trace elements that are preferentially retained in garnet compared to spinel (e.g., Sc).

Figure 11 shows REE, Mg#, and Sc data for basalts from Kilauea volcano, Hawaii [GEOROC, 2017 #5359], midocean ridge basalts (MORB) from the Explorer and northern Juan de Fuca ridges (Gill et al. 2016; Cousens et al. 2017), and central and southern Gunbarrel and I&H metavolcanics rocks from this study. Kilauea lavas are derived by melting of a mantle plume at the base of the Pacific plate, where the partial melting depth interval is ~300 to 75km (Putirka 1999). In contrast, MORB magmas are primarily melts of the upper mantle, beginning

at ~125km and ending at as little as 10 km depth (Putirka 1999). In both cases, the minimum melt depth is controlled by the thickness of the lithosphere above the region of melt generation. The fractionation of middle and heavy REE due to melting in the garnet versus spinel peridotite fields is clear, as Kilauea lavas have $Gd/Yb_N > 2$ whereas Explorer/Juan de Fuca MORB have $Gd/Yb_N < 1.6$. On average, Sc concentrations are lower in Kilauea basalts than in most Explorer/Juan de Fuca MORB due to the retention of Sc in residual garnet during melting. The Gd/Yb_N ratio can also vary as a function of the percentage of partial melting of a mantle source (increases with decreasing % melting) and as the result of assimilation of crustal rocks (e.g., granitoids) that commonly have high Gd/Yb_N .

Central and southern Gunbarrel magmas fall in between the MORB and Kilauea data arrays in Gd/Yb_N and Sc concentrations. In particular, Gd/Yb_N ratios suggest that the Gunbarrel magmas may be aggregate melts derived from both the garnet and spinel stability fields in the mantle. If the thickness of the lithosphere is the controlling factor in the minimum depth of melting, then the more MORB-like Gd/Yb_N of Gunbarrel rocks suggest that there was a greater contribution from melting in the spinel stability field. I&H rocks commonly overlap with Gunbarrel rocks, indicating that the two suites of rocks share a common mantle melting history. We also note that Gd/Yb_N gently increase with decreasing Mg#, Sc content, and increasing La/Sm_N, all of which are consistent with fractionation of clinopyroxene (decreases Sc) combined with assimilation of a higher-Gd/Yb crustal component.

5.3 Constraints on Mantle vs. Crustal Components

In Figure 9C, the central and southern Gunbarrel samples plot in a tight group above E-MORB in the Within-Plate Volcanic Zone (WPVZ) array, indicating some enriched

component(s) with a high Th/Nb, either from subduction-modified mantle or the overlying crust, was added to Gunbarrel magmas during their evolution. Model ϵ_{Nd} values for depleted MORB mantle (DMM) at 780 Ma, using the model of Michard et al. (1985), predicts an ϵ_{Nd} value of $\sim +8$, which is higher than the ϵ_{Nd} measured in Gunbarrel rocks. Addition of an older, enriched component would lower ϵ_{Nd} values in Gunbarrel magmas relative to MORB since older rocks generally have lower Nd isotopic ratios than depleted upper mantle sources (Faure and Mensing, 2005).

The I&H metavolcanics rocks have E-MORB-like incompatible elements patterns (Figure 8D) and have higher $\epsilon_{\text{Nd}}^{780}$ values than southern Gunbarrel rocks, and thus we propose that they represent the mantle-derived, primary “E-MORB” component in southern Gunbarrel magmas. The I&H age determination is imprecise (762 $\pm$ 44 Ma, Table 1) compared to the tight range of Gunbarrel U-Pb zircon and baddeleyite dates, but the ages of the two overlap within analytical uncertainty. U-Pb zircon or baddeleyite dating of the I&H rocks is required to confirm or deny their link to the Gunbarrel event.

The source(s) of the crustal (lithospheric) component include at least three possibilities: a) crustal components were included in the mantle source, as is proposed for the Hawaiian plume (e.g., Huang et al., 2009), b) crustal components may have been added to magmas in crustal reservoirs prior to the injection of dykes, sills and emplacement of lava flows, or c) crustal components were added during the emplacement of the Gunbarrel intrusions.

Gunbarrel magmas are considered to have been derived by melting of a mantle plume, located beneath another continental lithospheric block that has subsequently moved away from

Laurentia (Figure 1A; LeCheminant and Heaman, 1994; Park et al., 1995; Buchan et al., 2010; Harlan et al. 2003). A survey of modern ocean island tholeiitic basalts, also considered to be derived from mantle plumes, demonstrates that most OIB are slightly enriched in Nb and Ta relative to Ba and La, are depleted in Pb relative to the REE, and have steep REE patterns ($\text{La/Yb}_N = 10\text{-}15$; Stracke et al., 2003). This is also true for ocean island tholeiites that are considered to be derived from plume sources with a recycled crustal component (e.g., Huang et al., 2005, 2009; Stracke et al., 2003). The negative Nb-Ta anomalies in Gunbarrel intrusions are not characteristic of any modern OIB. We conclude that the crustal component in Gunbarrel rocks is unlikely to have come from a plume source.

Figure 12 presents ratios of less mobile trace elements and ϵNd^{780} to investigate potential crustal contributions to Gunbarrel magmas. We also include the I&H metavolcanic rocks as unmodified, plume-derived magmas in our trace element and isotopic modeling. Mixing curves are presented between the average of the I&H rocks with partial melts of Wyoming craton lithospheric mantle (mantle xenoliths; Carlson and Irving, 1994), Wyoming craton upper crust (data from Frost, 1993), Average Upper Crust and Average Lower Crust (averages from Rudnick and Gao 2003). We have included the lithospheric mantle as a potential contaminant since ancient subduction events can add incompatible elements (in hydrous fluids, silicate melts) to the lithospheric mantle, and Wyoming craton mantle xenoliths include hydrous phases and have high Rb/Sr and low Sm/Nd (Carlson and Irving, 1994). In all of the panels in Figure 12, the Wolf Creek, Rogers Pass and Turah sills, and to a lesser extent the Mount Moran dyke, plot closest to the I&H rocks, indicating less crustal contamination (magma chamber replenishment?) in the Belt Purcell sills and Mt. Moran dyke. Mixing curves between an average Wyoming craton lithospheric mantle or average Wyoming craton upper crust do not pass through the southern

528 Gunbarrel array; calculated ϵNd^{780} (-12 to -25 for mantle, -12 to -38 for crust) are much too
529 negative for either to be a contaminant. For most trace element ratios, the Average Upper Crust
530 of Rudnick and Gao (2003) is a satisfactory mixing endmember (Figure 12A). Fitting of mixing
531 curves for Average Upper and Average Lower Crust to the Gunbarrel data set is only successful
532 if the ϵNd^{780} of the crust is approximately -2 (Figure 12B,C). La/Sm_N ratios are not modeled
533 well by mixing of average I&H with Average Upper Crust, but the direction of elongation of the
534 southern Gunbarrel data array is parallel to that mixing curve. Choosing the I&H rock with the
535 lowest La/Sm_N, rather than the average of I&H rocks, would shift the mixing curve closer to the
536 southern Gunbarrel data array (Figure 12C). Alternatively, the La/Sm_N data are shifted to the left
537 of the Average Upper Crust mixing curve in the direction of mixing with Average Lower Crust,
538 implicating a small degree of interaction between Gunbarrel magmas and the lower crust. Both
539 trace element ratios and ϵNd^{780} suggest that the proportion of the upper crustal component in the
540 southern Gunbarrel rocks is between 5 and 15%.

541 If local lithospheric mantle and crustal rocks do not make appropriate contaminants, then
542 the crustal component added to southern Gunbarrel plume-derived magmas must be sourced on
543 the crustal block under which the plume was located at 780 Ma. The approximate ϵNd^{780} of -2
544 for the contaminant is a major constraint for the identification of this crustal block. Two
545 hypotheses have been presented, one that places the South China craton adjacent to western
546 Laurentia, the other placing South Australia in that position (compare Li et al. 2003; Medig et al.
547 2014). However, available data for crustal rocks from both cratons indicate that ϵNd^{780} are
548 mostly too negative to represent potential crustal endmembers. Plutonic, volcanic, and

metasedimentary rocks from the Gawler craton in South Australia have ϵNd^{780} between -12 and -25 (Creaser 1995; Swain et al. 2005). Metasedimentary rocks from the central part of the South China craton have ϵNd^{780} between -14 and -20 (Qiu et al. 2018). However, another suite of metasedimentary rocks from the South China craton have ϵNd^{780} between -8 and +0.3 (Wang et al. 2010), which are closer to our proposed contaminant composition than the rocks described elsewhere in the South China and south Australia cratons. More data on crustal rocks from both cratons are necessary to firmly establish which craton is the best candidate as a Gunbarrel contaminant.

5.4. Comparison with the northern Gunbarrel suite

The geochemical characteristics of the southern and central Gunbarrel rocks of this study are nearly indistinguishable from those of the northern Gunbarrel suite (Sandeman et al., 2014). All Gunbarrel rocks are subalkaline, continental tholeiitic basalts to basaltic andesites (Figure 9A,B) with similar ranges of trace element abundances (Figure 6). Northern Gunbarrel rocks extend to more differentiated compositions (lower Mg#, Figure 6) than central and southern Gunbarrel rocks. All Gunbarrel rocks plot above the “mantle array” (MORB-EMORB) in the Th/Yb versus Ta/Yb plot (Figure 9C) and include a crustal component. Figure 13A presents a comparison of central and southern Gunbarrel normalized incompatible element patterns with those of typical northern Gunbarrel intrusions and lavas (Sandeman et al., 2014). The parallelism of the patterns from the south and north Gunbarrel units is remarkable: all are enriched in Th and U relative to Ba and Nb, have negative Nb-Ta anomalies, are slightly enriched in K relative to La, have prominent positive Pb anomalies, and are depleted in Sr and P

relative to the adjacent REE. Northern Gunbarrel rocks have similar La/Sm_N ratios (Figure 12C) but have lower Gd/Yb ratios (1.11 to 1.64), yielding slightly flatter normalized patterns from the middle to heavy REE. ϵNd^{780} in the northern Gunbarrel suite ranges from +1.1 to +2.2, overlapping the range of ϵNd^{780} in the southern Gunbarrel suite within analytical uncertainty (± 0.5 epsilon units) with the exception of the Turah and Wolf Creek sills (+3.4 to +3.6).

Sandeman et al. (2014) conclude that Gunbarrel magmas originated as E-MORB melts from a mantle plume that subsequently were contaminated by interaction with the lower crust, likely when magmas ponded at the crust-mantle boundary. Although contamination with lower crust is possible, our modeling shows that upper crust makes a better contaminant based on geochemistry. Mixing calculations shown in Figure 12 of Sandeman et al. (2014) are also consistent with our proposal that upper crust is a viable crustal contaminant for Gunbarrel magmas.

Sandeman et al. (2014) also pointed out that Gunbarrel units intruded a variety of terranes across a vast distance, yet the isotopic compositions of Gunbarrel rocks cover only a small range over a length of >2500 km. This makes incorporation of a local crustal component in each intrusion unlikely, due to the wide variety of ages and geochemistry of crustal rocks in the Northwest Territories.

5.5 Location of the plume and magma reservoirs

We conclude that contamination of primary magmas, represented by the I&H metavolcanics rocks, could only have occurred in a single area, in the plume centre region (Figure 14), prior to emplacement of the Gunbarrel intrusions to explain the remarkable

homogeneity of geochemical and isotopic compositions throughout this LIP. The multi-component makeup of Gunbarrel magmas suggests that there was sufficient time, heat, and energy, likely in a magma reservoir, to effectively mix the different components to produce this homogeneity prior to lateral intrusion or eruption (also concluded by Sandeman et al., 2014).

Magnetic fabric and geochemical studies from other LIPs, including the 1270 Ma Mackenzie dyke swarm, show that magmas can be injected laterally for >2000 km through crustal rocks from a focal point above the centre of the plume without undergoing significant crustal interaction (Ernst and Baragar, 1992; Baragar et al. 1996; Ernst, 2014). A likely scenario for the Gunbarrel LIP is that a mantle plume located beneath a cratonic block that was on the western margin of Laurentia at 780 Ma generated localized melting at the plume center, and magmas accumulated and differentiated within a single or multiple homogenous magma chambers located in the same region (the focal region; see models of Baragar et al. 1996; Blanchard et al. 2017). Magmas were also contaminated by crustal components in the host cratonic block. Evolved magmas were then emplaced laterally from these chambers along radiating dyke and sill systems far into the interior of the Laurentian craton to the east and northeast, and feeding volcanic packages such as the Little Dal Basalts of the Mackenzie Mountains (Figure 14).

Paleogeographic reconstructions suggest that either the South China or south Australia blocks were located on the western flank of Laurentia prior to the breakup of Rodinia (Park et al., 1995) (Li et al. 2008). Both cratons host dyke swarms dated between 830 and 770 Ma, close to, but not identical to, the age range of Gunbarrel intrusions in North America (Li et al. 2008). Published trace element data for dyke swarms in the South China (Li et al. 2003) and south Australia (ca. 820 Ma Gairdner dykes and Amata suite, Zhao et al. 1994) blocks are presented in

Figure 13B. The normalized incompatible element patterns for both dyke swarms do not match those of the Gunbarrel intrusions (Figure 13A). Both dyke swarms lack the distinct Th and U enrichment relative to Ba in Gunbarrel rocks and have low La/Yb_N compared to Gunbarrel rocks. The Gairdner and Amata rocks are only slightly deficient in Nb relative to La ($\text{La/Nb} = 1.0$ to 1.1) and the South China dykes have large Nb anomalies ($\text{La/Nb} = 1.3$ to 6.3). The Gairdner and Amata rocks have ϵNd^{800} of $+2.4$ to $+4.3$, close to the range of southern Gunbarrel samples, but lack the evidence for crustal contamination that is present in Gunbarrel samples. If the Gairdner and Amata rocks were the Australian equivalents of the I&H metavolcanic rocks, our proposed plume melt, then they should have higher ϵNd^{800} ($+5$ to $+6$). Thus, we see no clear link between either the south Australia or South China dyke rocks with the Gunbarrel event in Laurentia.

5. Conclusions

The 780 Ma Gunbarrel LIP formed as the result of a mantle plume located west of the Laurentia margin. Dykes and sills of the southern (northwest USA) and central (northern British Columbia) Gunbarrel LIP exposed in the Belt Purcell Basin, the Tobacco Root and Beartooth Mountains, the Teton Range and the Muskwa assemblage (British Columbia) constitute a remarkably homogeneous suite of high-Fe continental tholeiites, primarily basalt in composition. The southern and central Gunbarrel magma underwent fractionation of clinopyroxene and plagioclase in deep crustal magma reservoirs prior to their emplacement. The southern Gunbarrel rocks have high Ba, Th, Pb and light REE concentrations, but are deficient in Nb relative to La compared to MORB and have low ϵNd^{780} compared to depleted upper mantle ($+1.7$ to $+3.6$) indicating that they have assimilated a crustal component. Primary magmas were

derived from the mantle plume and were likely E-MORB in composition, and mantle melting likely occurred at a range of depths that straddled the garnet-spinel peridotite transition. The Irene and Huckleberry volcanic rocks of Washington state, previously correlated with the Gunbarrel LIP based on a Sm-Nd isochron age of 762 ± 44 Ma, have E-MORB incompatible element characteristics and high ϵNd^{780} (+5 to +6) and we propose that they represent partial melts of the mantle plume. Local lithospheric mantle and crustal rocks of the Wyoming craton do not serve as appropriate crustal contaminants as their calculated ϵNd^{780} are too negative. Our trace element and isotopic modeling indicates that the crustal contaminant has an ϵNd^{780} of approximately -2, and is therefore much younger than the host rocks that most Gunbarrel rocks intrude. The crustal contaminant likely resides on the craton that was impinged upon by the mantle plume, but published data from two of the primary candidates (South China, south Australia) show that these crustal rocks are also commonly too negative at 780 Ma to be candidates for the crustal contaminant. Further comparison of crustal rock compositions and other ca. 780 Ma igneous events on other continental blocks is required to identify which block was impinged by the plume while it was connected to western Laurentia at 780 Ma.

Geochemical data from the southern and central portions of the Gunbarrel LIP demonstrate remarkably similar geochemical and isotopic compositions to the Gunbarrel rocks in the northern suite of this LIP (Sandeman et al., 2014), with only slight systematic variations in certain trace elements ratios. Mixing of components from plume and crust occurred early in magma evolution in deep crustal magma chamber(s) rather than during magma emplacement, based on the general homogeneity of magmas throughout the LIP. We propose that dykes were injected laterally away from a large magma reservoir(s) located in the crust around the plume

centre, such that magmas all followed approximately the same magma evolution path (fractionation+assimilation+replenishment). The sills of the Belt Purcell Basin (Turah, Wolf Creek, Rogers Pass) are the least contaminated Gunbarrel rocks in the LIP, and may represent a magma chamber replenishment event.

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Figure Captions

Figure 1: A) Map of western North America showing general location of the 780 Ma Gunbarrel LIP including dykes (red), sills (green) and volcanic rocks (black). Modified from Buchan et al. (2010). MM- Mackenzie Mountains. Northern, Central and Southern sections of the LIP are labelled. Yellow circles indicate the number of samples from each dyke or sill swarm included in this study. Boxes indicate field areas and sample localities : A) northeastern Washington state,

USA, B) Wolf Creek, Rogers Pass and Turah sills in northwest Montana, C) Tobacco Root Mountains, and D) dykes in the Beartooth Mountains. Grey dashed field shows the extent of the Wyoming Craton. Detailed geological maps of these four localities and sample sites are shown in Supplementary File a.

Figure 2: A) Outcrop photo of a typical dyke in the Tobacco Root Mountains. Location of site 12-MT-01. B) Photomicrograph in XPL of 12-MT-02 displaying common mineral assemblage, lightly to highly altered plagioclase, clinopyroxene with alteration rims of amphibole and subophitic texture. Amph-amphibole, cpx - clinopyroxene, gphyr – granophyre, plag – plagioclase, Fe-Ti ox - Fe-Ti oxides, qtz- quartz. C) Irene and Huckleberry volcanic rocks, showing close up view of outcrop near sample 12-MT-18. Part of the outcrop showing cm scale epidote veins with carbonate blebs forming on the surface of the outcrop. D) Photomicrograph of Irene and Huckleberry greenstone unit, site 12-MT-19 in cross-polarized light. chl_r – chlorite, ep – epidote.

Figure 3. A. Pyroxene and B. plagioclase feldspar compositions determined by electron microprobe.

Figure 4: A, B: Examples of zircons recovered from Rogers Pass (A) and Turah (B) sills. Their anhedral, striated and tabular habits are typical of magmatic zircon growth in mafic rocks. C to F: Concordia plots (C, D) and weighted mean plots of ²⁰⁶Pb/²³⁸U dates (E, F) of chemical abrasion, single grain U-Pb TIMS data (CA-TIMS) from RPKRC02-2, Rogers Pass sill (C, E) and MTTU-1, Turah sill (D, F). The paler ellipse and error bar with slightly younger date from RPKRC02-2 was excluded from the Concordia Age and weighted mean calculations. The weighted mean dates are interpreted as the best estimates of the intrusive ages of these sills, which overlap tightly at 778.63 Ma.

Figure 5. Major element variation diagrams for southern and central Gunbarrel rocks and I&H metavolcanic rocks. Dashed fields enclose analyses from the northern (NWT) part of the Gunbarrel LIP (Sandeman et al., 2014). A. Total alkalis-silica diagram (divisions after Le Bas et al. 1986). B. FeO^t versus SiO₂ classification diagram (after Miyashiro 1974). C. TiO₂ (wt%)

versus atomic $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$, calculated assuming 90% of total Fe is Fe^{2+} . D. $\text{CaO}/\text{Al}_2\text{O}_3$ versus $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$.

Figure 6. Trace element concentrations (weight parts per million, ppm) versus $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$. Note Muncho Lake rocks have V contents exceeding the laboratory analytical range (> 500 ppm). Dashed fields enclose analyses of northern Gunbarrel rocks (Sandeman et al., 2014).

Figure 7. Primitive mantle-normalized (Sun and McDonough, 1989) rare earth patterns for examples of southern and central Gunbarrel dykes and sills. Note that the y-axis is not logarithmic to better show the subtle light REE differences between the intrusions.

Figure 8: Primitive mantle-normalized extended rare earth element plots for Gunbarrel intrusions of this study. A. Tobacco Root and Beartooth Mountains dykes, B. Mount Moran and Muncho Lake intrusions, C. sills from the Belt Purcell Basin and D. metavolcanics rocks of the I&H suite (only rocks analyzed at ALS Laboratories). Normalization values from Sun and McDonough (1989).

Figure 9: A. Nb/Y vs. Zr/Ti classification diagram after Pearce (1996) (modified 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) showing variation in basalt tectonic settings. VAT – volcanic arc tholeiite, E-MORB – enriched mid-ocean ridge basalt, N-MORB – normal mid-ocean ridge basalt, BA – back-arc basin, TRM – Tobacco Root Mountains, NWT – Northwest Territories. Only the four I&H rocks analyzed at ALS Labs are plotted. C. Classification diagram of Nb/Yb vs. Th/Yb after Gorton and Shandl (2000) for Gunbarrel intrusions and volcanic rocks. MORB – normal mid-ocean ridge basalt, E-MORB – enriched mid-ocean ridge basalt, WPVZ = Within-plate Volcanic Zone, ACM – Active Continental Margins. In all panels, NWT sills/dykes and Little Dal Basalts enclosed in dashed fields are northern Gunbarrel rocks (Sandeman et al., 2014).

Figure 10: ϵNd vs. time showing isotopic evolution lines and depleted mantle model ages for selected Gunbarrel and Irene and Huckleberry volcanic rocks. Initial ratios are indicated by symbols at 780 Ma. Depleted Mantle (DM) Curve from Michard et al. (1985).

Figure 11: Gd/Yb_N variations as a function of A. $\text{Mg}\#$ (atomic $\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$) and B. Sc concentration in mantle plume-derived magmas (Kilauea volcano, Hawaii, GEOROC 2017), N-MORB and E-MORB from the Explorer and northern Juan de Fuca Ridges (Gill et al. 2016; Cousens et al. 2017), southern Gunbarrel and I&H rocks. Arrows approximate the effects of increasing fractional crystallization, increasing crustal contamination, increasing average depth of melting, and decreasing % partial melting.

Figure 12: Models of the effects of continental lithospheric contamination of mantle plume-derived magmas. A. Ba/Nb versus Th/La , B. La/Nb versus ϵNd^{780} , and C. La/Sm_N versus ϵNd^{780} in southern and central Gunbarrel samples and I&H metavolcanics rocks. Four mixing curves are shown, all of which assume an average I&H composition as the mantle plume melt. Modeled contaminants are a 5% partial melt of Wyoming lithospheric mantle (Wy LM) (Carlson and Irving 1994), a 10% partial melt of Wyoming crustal rocks (Wy Cr) (Frost 1993), a 10% partial melt of average upper crust (Avg UC) (Rudnick and Gao 2003), and a 10% partial melt of average lower crust (Avg LC) (Rudnick and Gao 2003). Tick marks are shown at 0, 5, 10, 20, 50, 75 and 100% of the contaminant. Dashed fields indicate the composition of northern Gunbarrel rocks (Sandeman et al., 2014).

Figure 13. Primitive mantle-normalized (Sun and McDonough, 1989) incompatible element patterns. A. Comparison of examples of northern (black lines and symbols) with central and Southern Gunbarrel rocks (grey lines and symbols). B. Dyke samples from the South China craton (Li et al. 2003) and south Australian Gairdner dykes (Zhao et al. 1994).

Figure 14: Map of western North America showing general location of the 780 Ma Gunbarrel LIP including dykes (red), sills (green) and volcanic rocks (black). Modified from Buchan et al. (2010). MM- Mackenzie Mountains. Bright red star is inferred location of plume head center,

978 surrounded by an proposed magma reservoir (ring). Dark red lines are directions of lateral
979 injection of dykes from the magma reservoir surrounding the plume centre. The plume directly
980 feeds the Irene and Huckleberry volcanic rocks (bright red line).

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Figure 1. Map, sample locations
269x349mm (300 x 300 DPI)

Figure 3, mineral microprobe data
215x279mm (300 x 300 DPI)

Figure 4, geochronology data

215x279mm (300 x 300 DPI)

Figure 5. Major elements

246x181mm (300 x 300 DPI)

Figure 6. Trace elements.

194x255mm (300 x 300 DPI)

Figure 7. Normalized REE plot.
141x94mm (300 x 300 DPI)

Figure 8. Normalized incompatible element plots

407x259mm (300 x 300 DPI)

Figure 9. Tectonic classification diagrams.

158x356mm (300 x 300 DPI)

Figure 10, Nd isotopes

259x329mm (300 x 300 DPI)

Figure 11. Depth of melting models.

116x201mm (300 x 300 DPI)

Figure 12. mantle-crust mixing models.

207x207mm (300 x 300 DPI)

Figure 13. Comparison of normalized incompatible element patterns, northern Gunbarrel and South China/Australia dykes.

213x263mm (300 x 300 DPI)

Figure 14. Plume-dyke injection model.

269x349mm (300 x 300 DPI)

Table 1. Gunbarrel Geochronological Data

Rock type	Age, 2-sigma error	Geochronological System	Reference
Sill, Turah	778.6 ± 0.71 Ma	U-Pb, CA-TIMS, zircon	This study
Sill, Rogers Pass	778.7 ± 0.94 Ma	U-Pb, CA-TIMS, zircon	This study
Sill, Wolf Creek	776 ± 5Ma	U-Pb, baddeleyite	Harlan et al. (1997)
Dykes, TRM (Group B)	1120 ± 185 Ma	Rb-Sr, Whole Rock	Wooden et al. (1978)
Dykes, TRM (Group B)	769 ± 7 Ma	U-Pb, zircon	Harlan (1993)
Dykes, TRM (Group B)	782.4 ± 4.9 Ma	⁴⁰ Ar- ³⁹ Ar, hornblende	Harlan et al. (2003)
Dyke, Christmas Lake	750 Ma	Rb-Sr, whole rock	Mueller and Rogers (1973)
Dyke, Christmas Lake	774 ± 4 Ma	⁴⁰ Ar- ³⁹ Ar	Harlan et al (1997)
Dyke, Christmas Lake	779.5 ± 3 Ma	U-Pb, baddeleyite	Harlan et al (2003)
Dyke, Mount Moran	775 Ma	Rb-Sr, K-Ar	Reed and Zartman (1973)
Dyke, Mount Moran	765 ± 5 Ma	⁴⁰ Ar- ³⁹ Ar	Harlan et al. (1997)
Irene and Huckleberry volcanic rocks Washington	762 ± 44 Ma	Sm-Nd, whole rock and mineral separates	Devlin et al. (1988)
Lava, Little Dal Basalts	778.4 ± 1.8, 775.1 ± 0.5	U-Pb, CA-ID TIMS zircon	Milton et al. (2017)
Sill Tsezotene	779.5 ± 2.5 Ma	U-Pb, baddeleyite	Harlan et al. (2003)
Sill, Concajou	779.5 ± 2.5 Ma	U-Pb, baddeleyite	Harlan et al. (2003)
Sills, Hottah Sheets	780 ± 1 Ma	U-Pb, baddeleyite	Harlan et al. (2003)
Dyke, Muncho	777.3 ± 3 Ma	U-Pb, baddeleyite	Harlan et al. (2003)

Table 2. Sample Locations

Sample	Geographic Area	Unit Name	Sample Location, Width (m)	Latitude (°N)	Longitude (°W)
<i>Gunbarrel Intrusions</i>					
12-MT-01	Tobacco Root Mtns	TRM	scree slope (>20m)	45.3673	111.9177
12-MT-02	Tobacco Root Mtns	TRM	near dyke center (>20m)	45.3665	111.9179
12-MT-03	Tobacco Root Mtns	TRM	dyke margin (>20m)	45.3665	111.9179
12-MT-09	Tobacco Root Mtns	TRM	dyke center (50m)	45.4206	112.1116
12-MT-10	Tobacco Root Mtns	TRM	dyke margin (50m)	45.4206	112.1116
13-AM-13	Tobacco Root Mtns	TRM	dyke center (20m)	45.4258	112.1327
13-AM-14	Tobacco Root Mtns	TRM	near dyke margin (10m)	45.4222	112.1086
13-AM-15	Tobacco Root Mtns	TRM	near dyke center (10m)	45.4230	112.1054
13-AM-01	Beartooth Mtns	Christmas Lake	dyke center (5m)	44.9752	109.4339
13-AM-02	Beartooth Mtns	Christmas Lake	dyke margin (5m)	44.9752	109.4339
13-AM-03	Beartooth Mtns	Christmas Lake	near dyke center (10m)	44.9693	109.4360
13-AM-11	Belt Purcell Basin	Wolf Creek Sill	near sill center? (70m)	47.0200	112.2099
13-AM-12	Belt Purcell Basin	Rogers Pass Sill	near sill centre? (75-190m)	47.0841	112.3634
13-AM-26	Belt Purcell Basin	Turah Sill	near sill margin, 2 samples (50m)	46.8754	113.8561
TR-45 [a]	Tobacco Root Mtns	TRM	unknown	45.3500	111.8280
TR-62 [a]	Tobacco Root Mtns	TRM	unknown	45.3689	111.9274
T09-BT15 [c]	Beartooth Mtns	Christmas Lake	Dyke (10m)	44.9692	109.4370
T09-BT12 [c]	Beartooth Mtns	unknown	Dyke (10m)	44.9746	109.4348
91LAAT2-1 [b]	Muskwa Ranges	Muncho Lake	near dyke margin (25-30m)	58.7830	125.6660
91LAAT2-2 [b]	Muskwa Ranges	Muncho Lake	dyke center (25-30m)	58.7830	125.6660
91LAAT2-3 [b]	Muskwa Ranges	Muncho Lake	dyke center (25-30m)	58.7830	125.6660
94LAAT1-2A [b]	Teton Range	Mount Moran	talus block (20m)	43.8334	110.7734
94LAAT003-1A [b]	Teton Range	Mount Moran	Margin (20m)	43.8334	110.7734
BURRPE-04 [d]	Belt Purcell Basin	Rogers Pass Sill	Sill (75-190m)	47.1229	112.3508
<i>Irene and Huckleberry Volcanic rocks</i>					
12-MT-17	NE Washington	I&H	center of outcrop	48.3174	117.8414
12-MT-18	NE Washington	I&H	large flow outcrop	48.3195	117.8171
12-MT-19	NE Washington	I&H	scree	48.3347	117.8272
12-MT-20	NE Washington	I&H	center of outcrop	48.8714	117.1460
12-MT-21	NE Washington	I&H	off of outcrop	48.8748	117.1465
12-MT-22	NE Washington	I&H	center of outcrop	48.8808	117.1498
12-MT-23	NE Washington	I&H	center of outcrop	48.8713	117.1448
12-MT-24	NE Washington	I&H	center of outcrop	48.9455	117.0955

12-MT-25	NE Washington	I&H	center of outcrop	48.9453	117.0917
12-MT-26	NE Washington	I&H	large flow outcrop	48.7679	117.2923
12-MT-27	NE Washington	I&H	small outcrop	48.3347	117.8272

Notes: Coordinate system NAD27. TRM –Tobacco Root Mountains, Mtns-Mountains, I&H –Irene and Huckleberry metavolcanic rocks. [a] samples obtained from S. Harlan, [b] samples obtained from A. LeCheminant, [c] Sample from T. Kilian, [d] Sample from E. Burtis (Burtis et al., 2007). Approximate sill and dyke widths are shown in brackets under “Sample Location, Width (m)”, in metres.

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Table 3. U-Pb CA-TIMS zircon data

Table 5: U-Pb on Pb-zircon data

Sample	Weight (μg)	U (ppm)	sample Pb (ppm)	Pb (pg)	Pb* (pg)	Pbc (pg)	Corrected atomic ratios												Rho % disc.
							Th	²⁰⁶ Pb/ ²⁰⁸ Pb	²⁰⁶ Pb/238U	²⁰⁷ Pb/235U	²⁰⁷ Pb/206Pb	²⁰⁶ Pb/238	²⁰⁷ Pb/235	²⁰⁷ Pb/206	Date (Ma)	err	ate (Ma)	ate (Ma)	
							U/204Pb	²⁰⁶ Pb	(rad.)	%err	(rad.)	%err	(rad.)	%err	Date (Ma)	err	ate (Ma)	ate (Ma)	
Rogers Pass sill RPKRC02-1 47°07'22.4"N, 112°21'03.3"W zircon crystallization age = 778.68±0.94 Ma (MSWD=0.08) 3 point weighted ²⁰⁶ Pb/238U date, 95% conf.																			
sE	0.41	161.4	25	###	1.1	8.9	##	490	0.32	0.1284 (0.21)	1.1661	####	0.0658 (1.61)	778.9 ±1.6	784.8	801.5	0.50	2.99	
sA	1.40	43	6	8.3	0.8	###	##	612	0.19	0.1284 (0.19)	1.1610	####	0.0656 (1.20)	778.6 ±1.5	782.4	793.3	0.43	1.97	
sC	0.27	231	34	9.3	0.6	###	##	841	0.28	0.1284 (0.25)	1.1461	####	0.0648 (1.46)	778.5 ±2.0	775.4	766.5	0.50	-1.66	
sB*	0.27	207	30	8.0	1.2	6.5	##	384	0.23	0.1280 (0.18)	1.1606	####	0.0658 (1.94)	776.3 ±1.4	782.2	799.1	0.58	3.02	
Turah sill MTU-1 46°49'39.13"N, 113°48'20.32"W zircon crystallization age = 778.58±0.71 Ma (MSWD=0.9) 4 point weighted ²⁰⁶ Pb/238U date, 95% conf.																			
sA	1.40	42.5	5.9	8.3	0.8	###	##	612	0.19	0.1285 (0.17)	1.1624	####	0.0656 (1.20)	779.5 ±1.3	783.1	793.3	0.45	1.84	
sD	0.72	99.6	13.2	9.5	1.5	6.4	##	413	0.13	0.1283 (0.20)	1.1611	####	0.0656 (1.83)	778.4 ±1.6	782.5	794.3	0.52	2.13	
sC	1.26	69.4	9.3	###	0.7	###	##	982	0.15	0.1283 (0.17)	1.1484	####	0.0649 (0.82)	778.2 ±1.3	776.5	771.4	0.42	-0.93	
sB	1.08	123.5	16.7	###	0.7	###	##	1537	0.16	0.1283 (0.22)	1.1454	####	0.0648 (0.55)	778.0 ±1.7	775.1	766.7	0.46	-1.56	

Notes: sample: sm=small, euh=euhedral, s_=single grain, * excluded from date calculation

Weight: represents estimated weight prior to first step of CA-TIMS dissolution. U and Pb concentrations are based on this weight using the U and Pb atoms measured from the second dissolution step only. The U and Pb concentrations may be underestimations, depending on how much material was dissolved and leached in the first step. They are useful for internal comparisons however. Picograms (pg) sample and initial Pb from the second dissolution step were measured directly.

sample Pb: sample Pb (radiogenic + initial) corrected for laboratory blank

TcPb: total common Pb. All assigned to blank.

Pb*/Pbc: radiogenic Pb to total common Pb (blank + initial)

Corrected atomic ratios: ²⁰⁶Pb/²⁰⁴Pb corrected for blank, mass discrimination and tracer, all others corrected for blank, mass discrimination, tracer and initial Pb, values in parentheses are 2 sigma errors in percent.

Rho: ²⁰⁶Pb/²³⁸U vs ²⁰⁷Pb/²³⁵U error correlation coefficient

% disc.: percent discordant

Table 4. Sm-Nd Isotopic Data

Sample	Location	¹⁴³ Nd/ ¹⁴⁴ Nd _m	¹⁴⁷ Sm/ ¹⁴⁴ Nd	¹⁴³ Nd/ ¹⁴⁴ Nd ⁷⁸⁰	ε _{Nd} ⁷⁸⁰
12-MT-01	Tobacco Root Mountains	0.512516	0.1554	0.511722	+1.75
12-MT-09	Tobacco Root Mountains	0.512520	0.1563	0.511721	+1.74
13-AM-13	Tobacco Root Mountains	0.512517	0.1560	0.511719	+1.70
13-AM-14	Tobacco Root Mountains	0.512543	0.1566	0.511742	+2.15
13-AM-15	Tobacco Root Mountains	0.512531	0.1565	0.511730	+1.92
TR-45	Tobacco Root Mountains	0.512530	0.1565	0.511730	+1.92
TR-62	Tobacco Root Mountains	0.512500	0.1493	0.511730	+1.92
91LAAT2-2	Mount Moran	0.512602	0.1643	0.511761	+2.53
94LAAT1-2A	Mount Moran	0.512588	0.1604	0.511767	+2.65
13-AM-01	Christmas Lake	0.512574	0.1556	0.511778	+2.86
13-AM-03	Christmas Lake	0.512528	0.1560	0.511730	+1.91
T09-BT15*	Christmas Lake	0.512510	0.1564	0.511710	+1.52
13-AM-11	Wolf Creek Sill	0.512691	0.1711	0.511816	+3.60
13-AM-26B	Turah Sill	0.512674	0.1692	0.511808	+3.45
12-MT-17	Irene and Huckleberry	0.512732	0.1570	0.511929	+5.80
12-MT-18	Irene and Huckleberry	0.512678	0.1473	0.511925	+5.73
12-MT-19	Irene and Huckleberry	0.512740	0.1593	0.511925	+5.74
12-MT-20	Irene and Huckleberry	0.512437	0.1287	0.511779	+2.88
12-MT-21	Irene and Huckleberry	0.512615	0.0140	0.512543	+17.81
12-MT-22	Irene and Huckleberry	0.512683	0.1496	0.511918	+5.59
12-MT-23	Irene and Huckleberry	0.512782	0.1626	0.511950	+6.21
12-MT-24	Irene and Huckleberry	0.512762	0.1589	0.511949	+6.20
12-MT-25	Irene and Huckleberry	0.512794	0.1634	0.511958	+6.38
12-MT-26	Irene and Huckleberry	0.512509	0.1377	0.511805	+3.38
12-MT-27	Irene and Huckleberry	0.512603	0.1391	0.511891	+5.07

Notes: “m” = measured ratio, “780” = calculated initial ratio at 780 Ma. The average ¹⁴³Nd/¹⁴⁴Nd and precision for 115 runs of the in-house Ames metal between 2008-2012 = 0.511826 +/-0.000014, equivalent to a La Jolla standard value of 0.511856, based on in-house calibration of the two standards. ε_{Nd}^T calculated using ¹⁴³Nd/¹⁴⁴Nd = 0.512638 and ¹⁴⁷Sm/¹⁴⁴Nd = 0.1967 for CHUR. *Analysis from Sandeman et al. (2014) analyzed in our laboratory.