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ZIRCON AS A PROXY FOR "TAKING THE TEMPERATURE" OF GRANITES: AN EXAMPLE USING ZIRCON THERMOMETRY APPLIED TO GRENVILLIAN MID-CRUSTAL MAGMAS IN THE BLUE RIDGE PROVINCE, VIRGINIA

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THESIS

A thesis submitted in partial fulfillment of the
requirements for the degree of Master of Science in the
College of Arts and Sciences
at the University of Kentucky

By

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Lexington, Kentucky

Director: Dr. David P. Moecher, Professor of Geology

Lexington, Kentucky

2017

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ABSTRACT OF THESIS

ZIRCON AS A PROXY FOR “TAKING THE TEMPERATURE” OF GRANITES: AN EXAMPLE USING ZIRCON THERMOMETRY APPLIED TO GRENVILLIAN MID-CRUSTAL MAGMAS IN THE BLUE RIDGE PROVINCE, VIRGINIA

The Grenville orogeny was a protracted (~200 m.y.) series of “hot” magmatic-metamorphic events that contributed to the growth of the Laurentian margin in the late Mesoproterozoic. The granites contain remarkably high Zr content, lack xenocrysts, and become zircon saturated at high temperatures, which are all unusual for felsic magmas. The “hot Grenville granite” hypothesis is tested and use of high-Zr granitoids as potential zones of crustal magma generation through: U-Pb geochronology and cathodoluminescence imaging to assess inherited zircon components; quantitative modeling of zircon crystallization history using rhyolite-MELTS; and Ti-in-zircon thermometry. U-Pb zircon ages for two samples from the Virginia Blue Ridge are 1168 ± 25 Ma (2209 ppm Zr; $T_{\text{Zr}} = 1032^{\circ}\text{C}$) and 1050 ± 13 Ma (918 ppm Zr; $T_{\text{Zr}} = 898^{\circ}\text{C}$). A sample from the NJ – Hudson Highlands has been dated at 1018 ± 11 Ma (1238 ppm Zr; $T_{\text{Zr}} = 960^{\circ}\text{C}$). These samples produce crystallization histories that range over higher temperatures (983–1060°C) than colder, low-Zr counterparts and contain Ti concentrations of 2 to 86 ppm. This analytical approach will further the understanding of zircon’s utility and limitations as a proxy in granite petrogenesis, and constrain thermal models that produced uncommon lithospheric conditions that led to widespread hot granite production at a unique period in Earth history.

KEYWORDS: Blue Ridge Province, Grenville Basement, Ti-in-zircon, Geothermometry, Zircon Saturation

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April 26, 2017

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CHAPTER I. INTRODUCTION

Zircon (ZrSiO_4), a widely used U-Pb geochronometer, is also commonly used as a geothermometer in studies of crustal petrogenesis to determine temperatures of magmatic systems and high-grade metamorphism. Both total zirconium (Zr) concentration of a granitic magma and titanium (Ti) concentration of zircon crystallized from that magma are used to calculate crystallization temperatures. Watson and Harrison (1983) demonstrated experimentally that the solubility of Zr in a range of melt compositions is the key factor in the dissolution of zircon during melting in the source region of magmas. They also calibrated the Zr solubility as a function of temperature and magma composition, potentially allowing for determination of the temperature in the source region. The Ti concentration of zircon is also highly dependent on melt composition and temperature while being weakly dependent on pressure (Watson and Harrison, 2005), permitting calculation of zircon crystallization temperature, and by extension the temperature of the melt.

Recent work has revealed that there are only a few circumstances where zircon begins crystallizing near liquidus temperatures in granitic magmas. More commonly, zircon forms over a range of temperatures during the crystallization sequence in granites (100 – 200 °C; Harrison et al., 2007) and often closer to the solidus. Moecher et al. (2014) demonstrated by modeling of the crystallization sequence of modal silicates and zircon in two granitic magmas with high Zr content (830 and 1201 ppm) that zircon begins to crystallize near the liquidus in high Zr granites (approximately 1000° C). In that same study, the crystallization temperature for granites with more typical Zr contents (100 – 300 ppm) of crustal granites was nearly 200 – 300 °C lower than the liquidus.

Watson and Harrison's (1983) whole-rock zircon saturation thermometer ($^{Zr}T_{sat}$) has pitfalls in its application as well. In their calibration, the calculated zircon saturation temperature doesn't necessarily correspond to the initial temperature of zircon crystallization; it is the temperature at which zircon saturation of the melt occurred, which could be reached at any time and temperature during the crystallization between the liquidus and solidus.

Watson and Harrison's (1983) previous work eventually led to the suggestion of "hot" and "cold" granites (Miller et al., 2003). A "hot" granite is one that has a T_{Zr} of 800 °C or more, generally lacks zircon xenocrysts inherited from the magma source region (because the melt temperature was high enough to dissolve potential xenocrysts), and is consistent with the fractionation of mantle-derived magma (Miller et al., 2003). "Cold" granitic magmas will likely contain zircon xenocrysts because melt temperature is too low ($< \sim 700$ °C) to dissolve inherited zircons, they are generated where crustal thickening occurs, and are present in systems where water can be included in the melt. Both granites may contain zircons with xenocrystic cores, but it is more likely that a high-temperature granite will have complete dissolution of zircon grains under conditions of magma generation. Magmatic conditions will also be more efficient in precipitating new zircons in hot granites because the Zr content of the melt will be high (Moecher and Samson, 2006).

Given these results, zircon chemistry and age do not necessarily yield a correlative temperature and time of crystallization of a magma, as inferred by U-Pb zircon geochronology corresponding to the onset of granite crystallization (i.e., liquidus temperatures). This notion has been explored in young, shallow felsic volcanic systems

where zircon rims were enriched in Ti, presumed to indicate higher temperatures during a later crystallization phase (Pamukcu et al., 2013). This discrepancy has yet to be fully resolved when examining granites originating from middle-to-lower crustal magmatic systems. Further examination of the use of zircon as a geothermometer is required to expand on the initial hot granite research as outlined in Moecher, et al., (2014). In that study, they hypothesized that the Grenville orogeny was an exceptionally hot series of collisional events, with prolonged and/or repeated waves of contributing magmatism (Rivers, 2008, 2009; Rino et al., 2008; Beaumont et al., 2010; Moecher et al., 2014). However, any geologically significant model of these magmatic conditions requires thermal constraints from crystals within rocks from the high-temperature settings. Grenvillian granites typically are Zr-rich, lack inherited zircon constituents (implying hotter magma source region), and have high modeled saturation temperatures, suggesting that these are truly hot granites (Moecher et al., 2014).

This thesis will evaluate the use of zirconium and zircon as a granite geothermometer in Grenvillian mid-crustal magmas from the central Blue Ridge of the Virginian Appalachians as well as the more northerly section in New York (Figure 1.1; Tollo et al., 2004a). More in-depth investigation will help to significantly expand our understanding on the limitations of zircon use for petrogenetic studies, especially for magmas emplaced in the middle to deep crust, and how to better interpret zircon saturation and Ti-in-zircon geothermometry.

Purpose of Study

Calculating geologically meaningful temperatures for felsic magmatic systems is a challenging task. The original study by Watson and Harrison (1983) for constraining magmatic temperatures using zircon has been evaluated more critically in subsequent research (Harrison et al., 2007; Fu et al., 2008, Moecher et al., 2014) to further understand the limitations of zircon thermometry in magmatic systems. Dry, high-Zr granites (1000+ ppm) will crystallize zircon near the liquidus, though moderate-Zr (~320 ppm) rocks will crystallize zircon at approximately 150 °C below liquidus conditions (Moecher et al., 2014). Following this trend, low-Zr (~150 ppm) rocks become zircon saturated at ~275 °C below the liquidus (Miller et al., 2003). This variability in $^{Zr}T_{sat}$ suggests that zircon U-Pb ages and trace element compositions in plutonic systems do not reflect an instant in time, and rarely reflect initial thermal conditions of felsic melts. This thesis will test the hypothesis that various zircon crystallization geothermometers in ultrahigh to lower zirconium granites demonstrate how zircon crystallizes at near-liquidus and at near-solidus temperatures, respectively. For high-Zr granites, zircon saturation will occur sooner in the crystallization history and vice versa for lower-Zr granites. If correct, the $^{Zr}T_{sat}$ thermometer should be in better agreement with the Ti-in-zircon thermometer, and with the modeled onset of zircon crystallization, in high-Zr granites than low-Zr granites.

The first task of this study was to determine if the Grenvillian granites are indeed “hot” granites, by evaluating the presence or absence of an inherited xenocrystic component via cathodoluminescence (CL) imaging of zircon from high-Zr granitoids. The exceptionally high Zr contents of Grenville magmatic rocks in eastern Laurentia

resulted in anomalously high zircon fertility (observed as both relatively high abundance and size of zircons) that introduced an age bias into the detrital zircon record of Neoproterozoic to modern clastic sedimentary systems across much of Laurentia (Moecher and Samson, 2006). Grenville granites with high Zr concentrations produced an abundance of zircon grains with ages at approximately 1.05 and 1.15 Ga and consequently led to other crustal age components (e.g., those of the Taconian, Acadian, and Alleghanian orogenies) being obscured in the detrital zircon record.

The second task of this study, zircon U-Pb geochronology, will expand previous data for geochronologic age distributions in hot granites for the Grenville basement inliers of the Blue Ridge and New Jersey – Hudson Highlands. This project will also build upon the preliminary results found in the pilot study done by Moecher et al., (2014), where magmatic temperatures and crystallization sequences of granitoids with varying Zr content were numerically modeled using rhyolite-MELTS software (Gualda et al., 2012). In that study, Ti-in-zircon thermometry was compared with $^{238}\text{U}/^{206}\text{Pb}$ thermometry (determined from whole rock major and trace element analysis), and the latter temperature was compared with those obtained from zircon crystallization spectra determined from rhyolite-MELTS modeling (Gualda et al., 2012).

Figure 1.1: Generalized map displaying locations of exposed Grenville-aged rocks in the Laurentian Appalachians. Shaded in grey (after Tollo et al., 2004a, modified from Rankin et al., 1990, Horton et al., 1989, and Glover et al., 1994). Red rectangles outline the study areas. HM- Hoosatic massif; HH- Hudson highlands, MP- Manhattan prong; DC- Washington, DC; SMM- Sauratown Mountains massif; GMW- Grandfather Mountain window.

CHAPTER II. GEOLOGIC SETTING

Grenville basement in the Blue Ridge province of the southern and central Appalachians consists of crystalline rocks (ca. 1.35 – 0.95 Ga), spanning the eastern U.S. ~900 km from Georgia to Pennsylvania (Rankin et al., 1989; Aleinikoff et al., 2000, Aleinikoff et al., 2004). During the Grenville orogeny, much of the eastern Laurentian continental crust was accreted to Laurentia and deformed through continental collisional processes (Rivers, 1997). The Elzevirian orogeny (1245 – 1225 Ma) preceded the Grenville orogeny (although some would consider it to represent an early phase of Rodinian assembly), which includes the accretionary phases of the Shawinigan (1190 – 1140 Ma), the Ottawan (1090 – 1020 Ma), and the Rigolet (1000 – 980 Ma; McLelland et al., 1996; Rivers, 1997, 2008).

Blue Ridge Province

The Blue Ridge province is interpreted to be an outlier of the Grenville province of Canada, and includes crystalline basement rocks dated at ca. 1.0 – 1.3 Ga (Tollo et al., 2004b; Southworth et al., 2010; Tollo et al., 2010). The Shenandoah and French Broad massifs in the Virginia Blue Ridge (Figure 1.2) represent the largest Mesoproterozoic crustal exposure in the Appalachians, and consist of high-grade granitic orthogneisses and charnockites (Bartholomew and Lewis, 1984; Rankin et al., 1989; Tollo et al., 2004a). The smaller, late Precambrian intrusive igneous plutons are generally undeformed, whereas the larger plutons display foliations near major faults and contacts (Tollo et al., 2004a). The Shenandoah massif also contains Neoproterozoic A-type granites and associated volcanic rocks with ages between 760 and 700 Ma that are interpreted to result from post-Rodinian extension and continental rifting (Rankin, 1968;

Tollo et al., 2004a). In the northern Blue Ridge as well as areas of the southern Appalachians, Neoproterozoic cover rocks overlie the Mesoproterozoic granulite-facies gneisses. Catoclin volcanic units represent the final phase of rifting and the Cambrian metasediments represent the transition to a passive margin “drift” phase for the eastern Laurentian margin bordering Iapetus.

New Jersey – Hudson Highlands

The Mesoproterozoic Mount Eve granite suite is part of the New Jersey – Hudson Highlands section of the central Appalachians, which extend from northwestern New Jersey to southeastern New York (Figure 1.2). The alkali rich, A-type suite contains numerous undeformed plutons with compositions ranging from quartz monzonite to granite. The plutons intrude Mesoproterozoic basement gneiss over an area of approximately 40 km² (Gorring et al., 2004). The suite locally contains xenoliths of basement gneiss and amphibolite, and magmatic flow fabrics that occur proximal to intrusive contacts. The presence of a magmatic flow fabric and lack of a solid state fabric is consistent with an absence of evidence for metamorphic overprinting or deformation (Drake et al., 1991; Gorring et al., 2004). Given field relations, geochronology, and chemical composition, the Mount Eve granite suite was determined to be post-kinematic relative to high-grade metamorphic events preserved in the older Grenville orthogneisses.

CHAPTER III. ANALYTICAL METHODS

U-Pb Geochronology

Zircon U-Pb geochronology was conducted at the University of California Los Angeles (UCLA) on a CAMECA ims1270 secondary ion mass spectrometer (SIMS). Two representative samples from the Blue Ridge province in Virginia and one sample from the New Jersey – Hudson Highlands province were analyzed: VA 15-1, VA 15-2, and NJ 15-1, respectively. Prior to analysis, all samples were prepared at the University of Kentucky. Approximately 3 kg of sample was crushed using a jaw crusher into gravel-sized chips, then milled into fine-grained sand using a Bico disc mill. The samples were wet sieved to remove clay-sized grains using disposable 250, 125, and 53 μm plastic mesh screens to reduce contamination. The 250 – 125 μm and 125 – 53 μm aliquots were rinsed in an ultrasonic bath and dried in an oven. Magnetic iron particles from the disk mill and magnetite were removed using a ceramic block magnet. Heavy minerals were separated from the samples using acetylene tetrabromide (S.G. = 2.96) and methylene iodide (S.G. = 3.32). The remaining magnetic minerals were removed using a Frantz Isodynamic Magnetic Separator Model LB-1 at increasing amperage, not to exceed 1.5 Å. Pyrite, monazite, and other impurities were hand-picked and removed to arrive at a relatively pure zircon concentrate.

For preparing a zircon mount consisting of hundreds of grains for assessing the presence of xenocrysts, a round 1” outer diameter plastic mold was affixed to a ceramic tile with a 2 x 2” square of double-sided tape. The zircon concentrate was poured into the mold and periodically rotated and tapped to evenly distribute the grains. Grains of zircon standard AS3 were mounted with sufficient separating distance from unknowns. An

epoxy was mixed using 5 parts Buehler Epo-Thin[®] epoxy resin with 2 parts Buehler Epo-Thin[®] epoxy hardener, stirred, and ultrasonically agitated to remove air bubbles. The mixture was poured into the mounting ring and left to cure for at least 24 hours. The mounts were sequentially polished using 1200 grit sandpaper, 2000 grit sandpaper, and 0.3 μm alumina powder polish.

Backscatter electron (BSE) and cathodoluminescence (CL) images were collected on the University of Kentucky's CAMECA SX50 electron probe microanalyzer and the JEOL IT-100 scanning electron microscope (SEM). These images were used to help determine the presence of xenocrysts, inclusions, and fractures within the zircon grains. This preliminary assessment was used as a guide to locate ideal spot locations during SIMS and LA-ICP-MS analyses.

The mounts were repolished and washed with 1N HCl to reduce common Pb contamination at UCLA and a 20 – 40 nm thick gold coating was applied after drying. Analytical techniques followed those described in Schmitt et al., (2003), with the exception that the multi-collector was added, allowing for decreased analysis time. The mount was sputtered (in order to remove analysis of common lead in gold coating) prior to each analysis using a primary O_2^- ion beam with a spot size of 30 μm . Zircon standard AS3 (1099 ± 1 Ma: Paces and Miller, 1993; Schmitz et al., 2002) was analyzed following every five unknown grains during analysis. Approximately 50 spots, some grains with two spots, were analyzed for each sample. Raw data reduction, including construction of the calibration curve and calculation of isotopic ratios was conducted using the UCLA in-house program ZIPS. Conventional U-Pb Concordia, Tera-Wasserburg Concordia,

weighted mean, and relative probability plots were created using Isoplot 4.15 (Ludwig, 2011).

Zircons from NJ 15-1 were also dated at the University of Arizona LaserChron Center using laser ablation-inductively coupled plasma-mass spectrometry (LA-ICP-MS) on a Thermo Element2 multicollector ICP-MS. The mount was prepared by hand-picking prismatic zircon crystals. These analyses were used to assess the quality of data collected at UCLA. Operating conditions used for data collection are described by Gehrels et al., (2008). The primary analytical standard was FC-1, which is the same as AS3 (1099 Ma), with zircon standards SL (563 Ma), and R33 (419 Ma) analyzed as secondary standards.

Approximately 110 spots were analyzed for this sample. Prior to analysis, the surface of the grain was ablated with a Photon Machines Analyte G2 excimer laser equipped with a HelEx ablation cell using a spot diameter of 20 μm . Helium was used to transport the ablated material to the Element2 ICP-MS. This process involved 5 seconds of measuring peaks with a non-firing laser in order to collect background intensities followed by 10 seconds of measuring peaks with the laser firing. To purge the system of ablated material and save the analysis file, a 20 second delay was set between each sample. Raw U-Th-Pb data reduction was performed at the University of Arizona using a Python decoding routine and the Excel program “E2agecalc” to calculate concentrations, isotopic ratios, and ages for unknowns. U-Pb Concordia, Tera-Wasserburg, weighted mean, and probably density plots were created using Isoplot 4.15 (Ludwig, 2011).

Whole Rock Geochemistry: X-ray Fluorescence

Whole rock geochemistry using x-ray fluorescence spectrometry (XRF) was performed to determine major, minor, and trace element composition. Six samples from

the Blue Ridge and five samples from the New Jersey – Hudson Highlands were prepped and analyzed at the Kentucky Geological Survey. The samples were washed to remove organic material, and only non-weathered surfaces were selected for analysis. Billets for thin section analysis were cut from a representative block of sample before further preparation. Approximately 3 kg of sample was crushed into gravel-sized chips using a jaw crusher, then an aliquot was powdered using a tungsten carbide ring-and-puck shatterbox to produce 60 mL of very fine powder. Both crusher and ring-and-pucks were cleaned with isopropyl alcohol and compressed air prior to processing a new sample.

Lithium tetraborate glass discs were fused at the Kentucky Geological Survey's X-ray Analytical Lab. A combination of 4.000 ± 0.001 g of sample and 8.000 ± 0.001 g of Fluxite[®] (90 Li₂Br₄O₇:10 LiF) was mixed in a platinum crucible with two drops of 5.8 M LiBr as a non-wetting agent. The crucible was placed into a Katanax K1 Prime electric fluxer, and the discs were fused at a maximum temperature of 1080 °C. The glass discs were analyzed on a 4-kW Bruker S4 Pioneer wavelength dispersive XRF. The chemical compositions of unknowns were calculated by comparing x-ray intensities against standard intensities using Spectra Plus[®]. The software was unable to calculate V, U, Th, and Ga content for the samples due to concentrations below the detection limit; these elements were omitted from the data set. The standards used to construct standard calibration curves are from multiple sources: USGS – (DNC-1, BIR-1, W2a, BCR-2, BHVO-1, BHVO-2, AVG-2, G-2, STM-1, GSP-1), the Irish Geologic Association – (OU-3, OU-4, AMH-1, YG-1, KPT-1), the Canadian Certified References Materials Project – (MRG-1, SY-2, S-3), South African Reference Materials – (SARM 4, SARM 50), Centre de Recherches Pétrographiques et Géochimiques – (BE-N) and Chinese

National Standard – (GBW 07105). Samples were also sent to Washington State University’s GeoAnalytical Lab for verification of concentrations, and both sets of analyses are reported (Appendix A). In general, major, minor, and most trace elements are in good agreement, except for Zr, which tended to be much lower in samples analyzed at the KGS.

Rhyolite-MELTS Modeling

To calculate liquidus compositions and temperatures as the melt crystallizes, multiple crystallization simulations were run using rhyolite-MELTS software (Gualda and Ghiorso, 2012). Rhyolite-MELTS calculates the crystallizing phase assemblage as well as the composition of the remaining melt at each temperature interval. For each sample, the phase assemblage was modeled at 25° intervals starting from the liquidus. The M value, a cation ratio deemed most appropriate to reflect variations in melt composition, is calculated using the melt composition at each temperature interval (Watson and Harrison, 1983). A prediction of zircon saturation temperature can then be calculated for each M at every 25° interval using the relation:

$$Zr_{M,T} = 496000 \exp\{[3.8 + (0.85 * (M - 1))] - 12900T(K)\}$$

$$M = (Na + K + 2Ca)/(Al * Si)$$

The Zr concentration is calculated using:

$$Zr_{melt} = C_0/F$$

where C_0 is the initial bulk rock Zr content and F is the remaining melt fraction at each temperature. The modeling parameters assume that Zr is incompatible in all other phases until zircon saturation is reached. The predicted temperature at which zircon begins crystallizing is when $Zr_{M,T} = Zr_{melt}$.

Ti-in-Zircon Thermometry

In order to further constrain the temperature of zircon formation, we performed Ti-in-zircon geothermometry using Ti concentrations collected in-situ using the Stanford-USGS sensitive high-resolution ion microprobe with reverse geometry (SHRIMP-RG). Trace element analyses (REE) were collected using a 1.5-2.5 nÅ O₂⁻ ion primary beam with a spot diameter of ~23 µm and sputter depth of ~1 µm. Similar analytical methods are further explained in Padilla et al., (2016). The calibration of the Ti-in-zircon thermometer was conducted with quartz and rutile present in the melt during zircon crystallization ($a_{\text{SiO}_2} = 1$, $a_{\text{TiO}_2} = 1$) (Watson et al., 2006; Ferry and Watson, 2007). Both quartz and rutile may be absent from the melt in natural systems while zircon is crystallizing, therefore estimates of a_{SiO_2} and a_{TiO_2} are required for temperature calculations. Values of $a_{\text{SiO}_2} = 1$ (as quartz is present in all samples) and $a_{\text{TiO}_2} = 0.7$ (Ghiorso and Gualda, 2013) were used for all T calculations in this study. The corresponding range of temperatures for $a_{\text{TiO}_2} = 0.6 - 0.8$ is 30 – 45°C and $a_{\text{SiO}_2} = 0.8 - 1.0$ is 20 – 35°C. The temperature will be underestimated when a_{TiO_2} is overestimated, so $a_{\text{TiO}_2} = 0.7$ is conservative.

CHAPTER IV. SAMPLE DESCRIPTIONS AND PETROLOGY

Hand samples were collected from the Shenandoah massif in the Virginia Blue Ridge province and the Mount Eve granite suite in New York. Polished thin sections for petrographic descriptions were prepared for each of the samples. The Blue Ridge samples (VA 15-1, VA 15-2, VA 15-3, VA 15-4, VA 15-5, VA 15-6) were collected in June 2015 and the Mount Eve samples (NJ 15-1, NJ 15-2, NJ 15-3, NJ 15-4, NJ 15-5) were collected in August 2015 by Dr. Dave Moecher.

Samples VA 15-1, VA 15-2, and NJ 15-1 were selected from the Virginia samples for geochronology because of their relatively high Zr concentrations and zircon yields. These samples are petrologically representative of both the Blue Ridge and Mount Eve study areas. Several previous studies have thoroughly documented the geochemical, petrologic, and structural character of these samples (Tollo et al., 2004a; Tollo et al., 2006; Hughes et al., 1997; Hughes et al., 2004; and Gorrington et al., 2004), therefore this section will only provide brief petrologic characteristics of the three analyzed samples.

Blue Ridge Province

1. VA 15-1, which was collected from the Stage Road Suite of the Lovingsston massif is a leucocratic, medium-to-coarse grained gneissic granite, with flattened quartz and feldspar grains and biotite folia defining the gneissic fabric. This sample has greenschist facies metamorphic overprinting characterized by white mica replacing quartz. The sample contains quartz, plagioclase, minor biotite, muscovite, and ilmenite. Potassium feldspar in this sample is dominantly perthitic and the sample lacks pyroxene (Figures 4.1a, 4.1b). Accessory minerals include apatite and zircon.

2. VA 15-2 was collected from the Pedlar River Charnockite Suite of the Pedlar massif and is a dusky-green, mesocratic, coarse-to-very-coarse grained granite to granodioritic charnockite. The sample is nonfoliated to weakly foliated and contains both ortho- and clinopyroxene, intermediate plagioclase, potassium feldspar, and blue quartz. Red-brown biotite, hornblende, and poikilitic garnet are also present and accessory minerals include rutile, apatite, zircon, magnetite, and ilmenite (Figures 4.2a, 4.2b).

New Jersey – Hudson Highlands

1. NJ 15-1, which was collected from the Mount Eve granite suite is a pink to light-grey, medium-to-coarse-grained biotite-hornblende granite that lacks foliation or any other observed fabric. The sample is composed dominantly of microperthite, quartz, and oligoclase with minor magnetite and ilmenite and accessory zircon, apatite, and titanite (Figures 4.3a, 4.3b).

Figure 4.1a: Photomicrograph of VA 15-1 in plane-polarized light. Annotated to show dominant mineral assemblage of gneissic biotite granite with flattened quartz and biotite folia defining fabric.

Figure 4.1b: Photomicrograph of VA 15-1 in cross-polarized light. Annotated to show dominant mineral assemblage of gneissic biotite granite and white mica replacing quartz to left of image.

Figure 4.2a: Photomicrograph of VA 15-2 in plane-polarized light. Annotated to show dominant mineral assemblage of granodioritic charnockite and coarseness of grains.

Figure 4.2b: Photomicrograph of VA 15-2 in cross-polarized light. Annotated to show dominant mineral assemblage of granodioritic charnockite, particularly the presence of pyroxenes.

Figure 4.3a: Photomicrograph of NJ 15-1 in plane-polarized light. Annotated to show dominant mineral assemblage of granite and lack of observed fabric.

Figure 4.3b: Photomicrograph of NJ 15-1 in cross-polarized light. Annotated to show dominant mineral assemblage of granite and perthitic textures.

CHAPTER V. RESULTS OF U-PB GEOCHRONOLOGY

Zircon grains separated from both the Blue Ridge province (VA 15-1, VA 15-2) and the Mount Eve granite suite (NJ 15-1) range from 125 μm to 250 μm in their longest dimension and were analyzed for U and Pb isotopes at the University of California Los Angeles on the CAMECA IMS-1270 multi-collector secondary ion mass spectrometer (SIMS). These analyses were used to both evaluate the presence of xenocrysts, or any other inherited zircon component that would be significantly older than the Grenville component, and to determine magmatic crystallization ages. A description of analytical procedures is found in Chapter III. Raw isotopic ratios, U-Pb ages, and multi-collector gain factor corrections are compiled in Appendix B. To ensure proper calibration and consistency among the three sample mounts, a new calibration of the AS3 zircon standard was conducted for each sample (Figures 5.1, 5.2, 5.3). The accepted crystallization age of AS3 is 1099 ± 1 (Paces and Miller, 1993; Schmitz et al., 2002). The weighted mean age of AS3 for each sample run is within 2σ error of the accepted age, so no additional age corrections were applied.

Sample “best ages” were calculated from $^{206}\text{Pb}/^{238}\text{U}$ ages with a precision of 1 standard error. These ages are considered the best estimate for each sample age, as the zircons were very low in U and thus low in ^{207}Pb . The common Pb correction thus overestimates the amount of common ^{207}Pb in these samples. $^{207}\text{Pb}/^{235}\text{U}$ ages are consequently too young, and the individual multi-collector counts for ^{207}Pb are low. When data were processed with the common Pb correction, the ages became reversely discordant. Therefore, only uncorrected data are included in the results below (Figure 5.4). The zircons for each sample display variable degrees of discordancy, and it is

possible that this effect is artificial. It is also possible that normal discordance could result from lead loss during recrystallization of zircon grains at high temperatures. However, the Mount Eve pluton is unmetamorphosed and the Blue Ridge plutons experienced only greenschist facies Paleozoic metamorphism, potentially indicating the introduction of geochronological lab error.

An age confirmation for sample NJ 15-1 was made at the University of Arizona LaserChron Center on the Thermo Element2 multicollector inductively-coupled plasma-mass spectrometer for comparison of age data collected from UCLA. A description of LA-ICP-MS analytical procedures can be found in Chapter III. Calculated isotopic ratios and U-Pb ages are compiled in Appendix B. The “best ages” for solely this sample were determined from $^{206}\text{Pb}/^{207}\text{Pb}$ as all grains were older than 900 Ma, and the $^{206}\text{Pb}/^{207}\text{Pb}$ ages are more precise for rocks that are older than ca. 800 Ma (Gehrels et al., 2008). However, these are only “best ages” as long as the ages are nearly concordant.

Blue Ridge Province

Orthogneiss sample VA 15-1 contains euhedral to subhedral zircons displaying oscillatory or sector magmatic growth zonation (Figure 5.5). The 33 zircons analyzed included many fractured grains. Most grains are narrowly, albeit faintly, zoned along the edges with broader zones preserved in the cores. This type of zonation pattern is typical for magmatic rocks (Corfu et al., 2003). Greenschist facies metamorphism that postdates crystallization has potentially affected the zonation patterns in this sample, and the secondary textures are more difficult to interpret. Convolute zoning and oscillatory zoning that is cut off by recrystallization and re-homogenization of grains as well as the

development of microvein systems is common. Nonetheless, these are probably high temperature (magmatic or subsolidus) modifications to zircon growth textures.

Single spot $^{206}\text{Pb}/^{238}\text{U}$ ages range from 1088 to 1259 Ma with a weighted mean of 1168 ± 25 Ma (Figure 5.6; MSWD = 0.36, probability = 1.00). Although the Concordia and Tera-Wasserburg plots show variable discordancy, ages were obtained from apparent cores (potential xenocrysts) and rims. The ages are generally within error of one another and it is concluded that these are not true inherited components as a significantly older population is not seen.

Zircons from sample VA 15-2 from the Pedlar River Charnockite Suite are subhedral to anhedral. The grains display internal oscillatory magmatic growth zonation as well as unzoned rim overgrowths (Corfu et al., 2003). The forty zircon grains analyzed include few grains with fractures, and some grains are completely and homogeneously recrystallized, although in most grains recrystallization is heterogeneous and localized with convoluted zoning (Figure 5.7). Single spot $^{206}\text{Pb}/^{238}\text{U}$ ages range from 995 to 1134 Ma. A weighted mean “best age” plot yields an age of 1050 ± 13 Ma (Figure 5.8; MSWD = 2.8, probability = 0.00). The MSWD is consistent with more than one age population. Due to the inability to differentiate significant age variation between the core and rim of these grains, this sample is interpreted to lack xenocrysts, although this is discussed further below.

New Jersey – Hudson Highlands

Zircon in granite sample NJ 15-1 is euhedral to subhedral and display typical oscillatory magmatic zonation, occasionally faint. The 52 zircon grains analyzed contain few grains with irregular internal mixing as well as sector zoning (Corfu et al., 2003)

(Figure 5.9). Many zircons are fractured. Most grains are heterogeneous and generally lack thick rim overgrowths, though some grains do have overgrowths. Single spot $^{206}\text{Pb}/^{238}\text{U}$ ages range from 937 Ma to 1095 Ma. A weighted mean “best age” plot yields an age of 1018 ± 11 Ma (Figure 5.10a; MSWD = 1.2, probability = 0.14). Analyses were taken from all areas on grains and the core versus rim ages do not indicate the presence of any xenocrystic (inherited) component.

The separate mount examined at the University of Arizona’s LaserChron Center contains 96 analysis spots and only those above 95% concordance are included in the data set (80 spots). Single spot best ages range from 945 Ma to 1055 Ma. A weighted mean “best age” plot yields an age of 1017 ± 4 Ma (Figure 5.10b; MSWD = 1.07, probability = 0.14). Analyses were taken from all areas on grains and the core versus rim ages again show no evidence for xenocrysts.

Discussion

The purpose of conducting U-Pb geochronology for multiple zircons in each sample was to assess the presence of xenocrystic cores and older inherited components. If xenocrysts were found, further analytical work cannot be continued on those grains because we have no way to identify the initial magmatic conditions under which the original xenocryst formed. Additionally, whole-rock Zr content may be an overestimate of parent magma composition when xenocrysts are abundant. Zircons from the three samples are lacking inherited components, leading to the conclusion that these high-Zr granitoids have been crystallized at high temperatures and are “hot” granites.

Previous studies have dated a similar Stage Road Suite sample (VA 15-1) using U-Pb and determined that this suite of rocks is representative of Lovington massif

country rock that formed ca. 1150 Ma (Aleinikoff et al., 2000; Hughes et al., 2004). Data from the current study suggest a more refined age of 1168 ± 25 Ma. The Stage Road Suite is also possibly equivalent to a metamorphic episode that led to the development of the gneissic foliations at 1160 – 1140 Ma and high-silica charnockite formation in the northern Pedlar massif (Tollo et al., 2004a).

Sample VA 15-2 has also been dated using U-Pb and because of complex isotopic systematics, the date of >1145 Ma (Aleinikoff et al., 2000) is unreliable. As shown in Figure 5.7, the zircons display very heterogeneous zoning patterns and various degrees of recrystallization. Though this study indicates that the charnockite sample is Mesoproterozoic and 1050 ± 13 Ma in age, no xenocrysts were found. There remains uncertainty with regard to grain textures and age. It is possible that the seemingly bimodal population within best ages is due to recrystallization or dissolution of antecrysts during metamorphism, but because the sample lacks a significantly older component we do not believe these analyses to be indicative of true xenocrysts.

Sample NJ 15-1 has been previously dated using U-Pb to have an age of 1020 ± 4 Ma (Drake et al., 1991) and the Mesoproterozoic date coincides with this study's SIMS age of 1018 ± 11 Ma. The sample dated using LA-ICP-MS at the University of Arizona has a similar age of 1017 ± 5 Ma and confirms this age estimate. This sample contains zircons with similar morphologies to VA 15-1: mostly homogenous and typical magmatic zonation patterns. We do see large (up to $\sim 15 \mu\text{m}$), thick dark CL overgrowths on a handful of grains, and the general morphologies are comparable to those seen in Siebel et al. (2012), where they are interpreted as indicators of UHT metamorphic conditions and intracrustal recycling.

Figure 5.1: Results of SIMS analysis of AS3 zircon standard from sample VA 15-1. Data were not corrected for common Pb. (a) Weighted mean age plot of $^{206}\text{Pb}/^{238}\text{U}$ ages with 1σ errors. (b) Tera-Wasserburg diagram of all data. (c) Concordia diagram of all data.

Figure 5.2: Results of SIMS analysis of AS3 zircon standard from sample VA 15-2. Data were not corrected for common Pb. (a) Weighted mean age plot of $^{206}\text{Pb}/^{238}\text{U}$ ages with 1σ errors. (b) Tera-Wasserburg diagram of all data. (c) Concordia diagram of all data.

Figure 5.3: Results of SIMS analysis of AS3 zircon standard from sample NJ 15-1. Data were not corrected for common Pb. (a) Weighted mean age plot of $^{206}\text{Pb}/^{238}\text{U}$ ages with 1σ errors. (b) Tera-Wasserburg diagram of all data. (c) Concordia diagram of all data.

Figure 5.4: Pb-corrected results of SIMS analysis of grains from sample NJ 15-1. Ages are reversely discordant when applying the UCLA common Pb correction.

Figure 5.5: CL images of VA 15-1 zircon grains. Yellow ellipses represent 30 μm analysis spot locations. Ages with 1 standard error are shown beside each spot.

Figure 5.6: Results of SIMS analysis of zircon grains from sample VA 15-1. Data were not corrected for common Pb. (a) Weighted mean age plot of $^{206}\text{Pb}/^{238}\text{U}$ ages with 1σ errors. (b) Tera-Wasserburg diagram of all data. (c) Concordia diagram of all data.

Figure 5.7: CL images of VA 15-2 zircon grains. Yellow ellipses represent 30 μm analysis spot locations. Ages with 1 standard error are shown beside each spot.

Figure 5.8: Results of SIMS analysis of zircon grains from sample VA 15-2. Data were not corrected for common Pb. (a) Weighted mean age plot of $^{206}\text{Pb}/^{238}\text{U}$ ages with 1σ errors. (b) Tera-Wasserburg diagram of all data. (c) Concordia diagram of all data.

Figure 5.9: CL images of NJ 15-1 zircon grains. Yellow ellipses represent 30 μm analysis spot locations. Ages with 1 standard error are shown beside each spot.

NJ 15-1
1238 ppm Zr

Mount Eve
Granite
box heights are 1 σ

Figure 5.10a: Results of SIMS analysis of zircon grains from sample NJ 15-1. Data were not corrected for common Pb. (a) Weighted mean age plot of $^{206}\text{Pb}/^{238}\text{U}$ ages with 1 σ errors. (b) Tera-Wasserburg diagram of all data. (c) Concordia diagram of all data.

NJ 15-1
1238 ppm Zr

Mount Eve
Granite
box heights are 1σ

Figure 5.10b: Results of LA-ICP-MS analysis of zircon grains from sample NJ 15-1. Data were corrected for common Pb. (a) Weighted mean age plot of $^{206}\text{Pb}/^{207}\text{Pb}$ ages with 1σ errors. (b) Tera-Wasserburg diagram of all data. (c) Concordia diagram of all data.

CHAPTER VI. RESULTS OF CRYSTALLIZATION MODELING

In order to predict crystallization histories and the evolution of Zr concentration throughout crystallization of a zircon-bearing granite, this study used rhyolite-MELTS (Gualda et al., 2012) quantitative thermodynamic and geochemical modeling software. This program was chosen over MELTS (Ghiorso and Sack, 1995) because rhyolite-MELTS is calibrated to handle quartz-feldspar saturation concurrently with pressure in high-silica systems. The three samples chosen for geochronology (VA 15-1, VA 15-2, NJ 15-1) were modeled using whole-rock elemental data from XRF analyses (Appendices A and C). Details of modeling parameters are presented in Chapter III. Rhyolite-MELTS allows users to derive simulated temperatures at which zircon saturation in the melt is reached, or the upper limit of the range over which zircon will crystallized. This temperature can then be compared with the zircon saturation temperature (T_{Zr}) calculated from whole-rock bulk compositions as well as Ti-in-zircon temperatures to be discussed in the following section.

Two simulations were run for each of the three samples using variable bulk-rock H₂O contents: original H₂O wt. % measured by LOI as a lower control and 1.0% H₂O as an upper control to assess the effect of fluid saturation conditions in the initial melt. Realistically, initial melt conditions are likely to be wetter than these nominal anhydrous values and this is a key drawback when using rhyolite-MELTS (models cannot be run with 0% H₂O). Typical A-type granites generated in crustal environments have much higher water contents than previously considered: at 500 MPa and a temperature of 800 °C, various granitic compositions have been experimentally found to contain approximately 10 wt. % H₂O (Holtz et al., 2001). As such, rhyolite-MELTS may

underestimate initial magmatic temperatures at the source. In addition to calculating the crystallizing phase assemblage compositions (Figure 6.1), rhyolite-MELTS also calculates the composition of the remaining melt for each temperature step (in this case, 25 °C for internal precision). The remaining melt compositions are then used to calculate the M value at each temperature, and a predicted zircon saturation temperature was calculated for each M using the equation (Watson and Harrison, 1983):

$$D^{Zr,zircon/melt} = \{-3.8 - [0.85(M - 1)]\} + 12,900/T ,$$

where $D^{Zr,zircon/melt}$ is the ratio of Zr ppm in zircon (~476,000 ppm) to the concentration of Zr in the saturated melt and M is a cation ratio $[(Na+K+2Ca)/(Al*Si)]$ that is dependent on the degree to which the melt is peraluminous, metaluminous, or peralkaline. T is in Kelvin but will be reported as °C. When rearranged to solve for T, our geothermometer, the equation yields:

$$T_{Zr} = 12,900/[2.95 + 0.85M + \ln(496,000/Zr_{melt})].$$

Zr concentration of the evolving melt is calculated using:

$$Zr_{melt} = C_0/F,$$

where C_0 is the initial bulk-rock Zr concentration and F is the fraction of remaining melt at each temperature, calculated from rhyolite-MELTS. The melt is saturated in zircon at the temperature at which $Zr_{T,M} = Zr_{melt}$, the point of intersection of the two respective curves, which is the predicted onset of zircon crystallization (Figure 6.2).

Blue Ridge Province

Orthogneiss sample VA 15-1 contains 61.85% SiO₂, 0.62% LOI, and 2209 ppm Zr (Appendices A and C). The first simulation at 0.60 wt. % H₂O yields a liquidus temperature of ~1060 °C (M = 1.79, Figure 6.2). The second simulation at 1.0 wt. % H₂O

yields a crystallization temperature of ~1043 °C (Figure 6.2), decreasing the liquidus temperature by approximately 17 °C. The modeled onset of zircon crystallization is ~28 °C higher than T_{Zr} .

Granodioritic charnockite sample VA 15-2 contains 58.18% SiO₂, 0% LOI, and 918 ppm Zr (Appendices A and C). The first simulation at 0.1 wt. % H₂O yields a liquidus temperature of ~1024 °C ($M = 2.09$, Figure 6.2). The second simulation at 1.0 wt. % H₂O yields a liquidus temperature of ~996 °C (Figure 6.2), decreasing the liquidus temperature by approximately 28 °C. The modeled onset of zircon crystallization is ~126 °C higher than T_{Zr} .

New Jersey – Hudson Highlands

Granite sample NJ 15-1 contains 66.97% SiO₂, 0.37% LOI, and 1238 ppm Zr (Appendices A and C). The first simulation at 0.37 wt. % H₂O yields a liquidus temperature of ~983 °C ($M = 1.79$, Figure 6.2). The second simulation at 1.0 wt. % H₂O yields a liquidus temperature of ~979 °C, decreasing the liquidus temperature by approximately 4 °C. The modeled onset of zircon crystallization is ~23 °C higher than T_{Zr} .

Discussion

In the models, liquidus temperatures for the three samples range from 983 – 1060 °C. The first crystallizing phase for VA 15-1 is orthopyroxene. The first crystallizing phase for VA 15-2 is quartz with orthopyroxene at nearly the same time. The first crystallizing phase for NJ 15-1 is orthopyroxene. The highest M value calculated was VA 15-2 at 2.09. This sample also has the lowest Zr ppm at 918 and largest difference in modeled Zr_{sat} and T_{Zr} (Figure 6.2). This phenomenon has been rationalized by Miller et

al. (2003) to be caused by cumulate crystals (other than zircon) leading to a more mafic composition than the coexisting melt, which in turn creates higher M values and lower T_{Zr} . As this sample is a granodioritic charnockite with a lower Zr ppm, the overall composition is more mafic (58.18 wt. % SiO_2 vs. 61.85 wt. % and 66.97 wt. %, Appendices A and C) than other included samples and could be a reason for the large discrepancy. In all cases, T_{Zr} is lower than the rhyolite-MELTS modeled temperature, which is consistent with T_{Zr} being a minimum estimate of magma temperature. Sample NJ 15-1 shows an abundance of alkali feldspar at the modeled temperature (Figure 6.1) and this is supported with the presence of microperthite in thin section (Figure 4.3b).

There are limitations involved when using the rhyolite-MELTS modeling technique to estimate zircon saturation temperatures. Firstly, hydrous phases such as biotite and hornblende are not well modeled and therefore the program perhaps introduces a degree of inaccuracy for intermediate compositions like samples VA 15-1 and VA 15-2. Secondly, many bulk-rock compositions of plutonic rocks are not initial melt compositions (Miller et al., 2003). Both simulations were performed keeping pressure static at 500 MPa as the depth of emplacement and crystallization is unknown. Though previous research shows that zircon solubility is unaffected by pressure, zircon solubility may be affected by dry (<1.5 wt. % H_2O) peralkaline melt compositions (Watson and Harrison, 1983), and the samples selected for this study are assumed to be relatively anhydrous. We assume that the models are not overestimating zircon saturation temperatures because all samples lack xenocrystic inherited components as demonstrated in Chapter V by CL imaging and U-Pb geochronology.

Figure 6.1: Sequence of melt crystallization output from rhyolite-MELTS at bulk-rock LOI H₂O conditions and 25 °C temperature increments. Red dashed line indicates modeled temperature Zr_{sat} .

VA 15-1
2209 ppm Zr

VA 15-2
918 ppm Zr

NJ 15-1
1238 ppm Zr

Figure 6.2: Results of crystallization modeling from rhyolite-MELTS. Blue line and diamonds show decrease in Zr concentration calculated from M at each temperature (T). Green line and squares show increasing Zr concentration in residual melt, initial conditions from bulk-rock composition. Vertical dashed line represents intersection of two curves: the temperature at which Zr_{sat} is reached. Yellow arrow is bulk-rock T_{Zr} . Note: VA 15-2 T_{Zr} is 898 °C but is placed at 925 °C for visual comparison.

CHAPTER VII. RESULTS OF TI-IN-ZIRCON THERMOMETRY

Zircons from all three samples (VA 15-1, VA 15-2, NJ 15-1) were analyzed for Ti and other trace elements (Fe, Y, La, Ce, Nd, Sm, Eu, Gd, Dy, Er, Yb, Hf, U, Th) in situ at Stanford University's SHRIMP-RG ion microprobe lab in order to obtain high mass resolution concentrations (Appendix D). Emphasis was placed on Ti concentration in order to evaluate Ti-in-zircon thermometry. Details of analytical methods and instrument configuration are presented in Chapter III. Measured Ti concentrations are estimated to be precise to ± 0.1 ppm based on repeated measurement of the Ti standard. Trace element concentrations were calculated relative to MADDER, a well-characterized, homogeneous Madagascar Green in-house zircon standard whose values are calibrated relative to 91500 (Wiedenbeck et al., 1995, 2004) for all elements except Ti. Ti concentrations were calculated relative to zircon standard SL13 using $Ti = 6.14 \pm 0.01$ ppm (Hiess et al., 2008) for comparison with sample Ti-in-zircon values. Our analyses in this study return $Ti = 6.26 \pm 0.09$ for SL13 (Appendix D). Standards were analyzed at the beginning of initial setup and mounted on a separate mount. All trace element measurements have been normalized to $^{30}Si^+$. Elemental ratios were calculated using SQUID2.51, a Microsoft Excel add-in program (Ludwig, 2009).

Estimates of crystallization temperatures were calculated using Ferry and Watson's (2007) calibration of the Ti-in-zircon thermometer:

$$\log (\text{ppm Ti-in-zircon}) = (5.711 \pm 0.0772) - ((4800 \pm 86)/T) - \log a_{SiO_2} + \log a_{TiO_2},$$

where T is in Kelvin but will be reported hereafter as Celsius. Rearranging and solving for T (in °C) yields the expression:

$$T (^{\circ}C) = (-4800 \pm 86 / ((\log(\text{ppm Ti-in-zircon}) - (5.711 \pm 0.0772) + \log a_{SiO_2} - \log a_{TiO_2})) - 273$$

This method requires accurate Ti measurements and well constrained activities of titania and silica in the melt, a_{TiO_2} and a_{SiO_2} , respectively. Titania activity is dependent on degree of rutile saturation and silica activity is dependent on quartz saturation. Quartz is present in all samples, and therefore, by definition, $a_{\text{SiO}_2} = 1.0$ for temperature calculations. Rutile (TiO_2) is not present in the samples for this study but both ilmenite and titanite are found as accessory phases, so we assume that $a_{\text{TiO}_2} < 1.0$ during crystallization of zircon and use 0.7 for calculations, as recommended by Ghiorso and Gualda, (2013). Sample NJ 15-1 had an abundance of titanite, and when a_{TiO_2} was increased to 0.9 with $a_{\text{SiO}_2} = 1.0$, temperature estimates for all samples decreased by 26 – 29 °C on average.

Blue Ridge Province

Zircon in orthogneiss sample VA 15-1 contains a range of Ti concentrations from 7 – 86 ppm (Figure 7.1) and estimated temperatures range from 749 – 1053 °C. Inner growth zones (apparent “cores”) range from 7 – 86 ppm Ti. Outer growth zones (apparent “rims”) range from 12 – 40 ppm Ti.

Granodioritic charnockite sample VA 15-2 contains a range of Ti concentrations from 7 – 36 ppm (Figure 7.1). This collection is skewed by the large population of values less than 20 ppm. Estimated temperatures range from 750 – 928 °C. Inner growth zones range from 7 – 36 ppm Ti, and outer growth zones range from 8 – 27 ppm Ti.

New Jersey – Hudson Highlands

Granite sample NJ 15-1 contains a range of Ti concentrations from 2 – 38 ppm (Figure 7.1) and estimated temperatures range from 656 – 935 °C. Inner growth zones range from 4 – 38 ppm Ti, and outer growth zones range from 2 – 14 ppm Ti.

Discussion

Ti-in-zircon concentrations are highly dependent on temperature in experimental studies (Watson and Harrison, 2005; Watson et al., 2006; Ferry and Watson, 2007) and yield a precision of ± 5 °C, though the accuracy of this geothermometer has geologic limitations with regard to natural zircons and their petrologic context (Fu et al., 2008). This study was designed to further evaluate accuracy and geologic limitations of the zircon thermometers. For the samples selected, there remains a degree of Ti variability within individual grains, especially when including both “core” and “rim” values into an average temperature and concentration.

In interpretation of the Ti measurements, and inter- and intragrain (core vs. rim measurements) variations in Ti concentration for each sample, it is important to take into consideration the likelihood that zircon crystallizes over a temperature interval between the liquidus and solidus (the “zircon crystallization spectrum”: Harrison et al., 2007) (Figure 7.2) as the magmatic conditions evolve. High-Zr (850 – 1050 °C, hot) granitoids should yield zircon crystallization spectra that encompass a higher range of temperatures than spectra for low-Zr (650 – 750 °C, cold) granitoids (Miller et al., 2003; Moecher et al., 2014).

Sample VA 15-1 has a high degree of zircon homogeneity, in that the grains do not have rim overgrowths, or the rims are very thin, and are proposed to be metamorphic (Figure 7.2). Zircons from sample VA 15-2 have a much different style of growth zonation, although two distinct types of zircon are evident in CL, both of which are thick enough to analyze (Figure 7.2). Zircons from sample NJ 15-1 have very dark, thick rim overgrowths as well as fully homogenous grains (Figure 7.2).

Variations in CL zoning in zircon relate to variations in trace element composition of grains that develop during crystallization, and are controlled by the K_D between melt and zircon as melt composition and temperature evolve (Hanchar and Miller, 1993). Intragrain variation in CL (apparent cores vs. rims in CL) may indicate partial mixing or assimilation with a mafic component, especially in sample VA 15-2 where grains display a large degree of heterogeneity (Figure 7.2) (Padilla et al., 2016). This sample also has the greatest variability in trace element enrichment with regard to intragrain REE scatter (Figure 7.3). Note that all samples are depleted in Eu, with VA 15-1 and VA 15-2 more than NJ 15-1, possibly a product of their greenschist metamorphic overprinting. Ce anomalies are positive and Eu-negative, and these are common anomaly patterns in igneous zircons, but a negative Eu anomaly is not expected for crustal zircon (Hoskin and Schaltegger, 2003). This paradox is explained by plagioclase fractionation which depletes Eu before or during zircon crystallization (Hoskin and Schaltegger, 2003). Plagioclase is a crystallizing phase at modeled temperature from rhyolite-MELTS (Figure 6.1).

Variability in Ti-in-zircon concentrations does not correlate with CL zoning. For example, VA 15-1 cores average Ti = 31 ppm, where rims average Ti = 22 ppm. VA 15-2 Ti averages are equal at 15 ppm. We see the greatest difference in Ti concentration between cores and rims in NJ 15-1 (17 ppm vs. 7 ppm) paired with extreme contrast in CL color. CL contrast is not definitively correlated with Ti concentration, though this cannot be fully ruled out and further clarification of relationships is needed as REE enrichment is seemingly linked to CL color (Figure 7.3). Fu et al., (2008) have reported lower Ti concentrations in zircon than predicted for natural zircons.

Figure 7.1: Histogram of Ti-in-zircon concentration for all analyzed spots. VA 15-1 ranges from 7-86 ppm. VA 15-2 ranges from 7-36 ppm. NJ 15-1 ranges from 2-38 ppm.

VA 15-1

VA 15-2

NJ 15-1

Figure 7.2: SEM images of selected SHRIMP-RG analysis spots. Images show differences between zircon zonation, CL color variations, and their corresponding Ti-in-zircon concentrations and associated temperature estimations.

Figure 7.3: REE plot normalized to CI chondrite (McDonough and Sun, 1995). VA 15-1 displays dark CL at lower concentrations in trace elements. VA 15-2 displays variability in trace element with regard to CL color (more scatter). NJ 15-1 displays a stark separation of CL color and trace elements, again with dark colors having lower levels of REE concentration.

CHAPTER VIII. CONCLUSIONS

Three granitoids collected from the Blue Ridge province and the New Jersey – Hudson Highlands were examined using U-Pb geochronology, whole-rock geochemistry, zircon saturation thermometry, rhyolite-MELTS quantitative modeling, and Ti-in-zircon trace element analyses to evaluate the use of zirconium and zircon as granite geothermometers in Grenvillian mid-crustal magmas. Calculating geologically meaningful temperatures for felsic magmatic systems is a challenging task, and this thesis provides new data that further explain the difficulties and limitations when determining initial crystallization temperatures and conditions using zircon geothermometers, which are considered among the most reliable methods available for doing so (Watson and Harrison, 1983; Miller et al., 2003; Ferry and Watson, 2007; Harrison et al., 2007).

Sample VA 15-1, an orthogneiss from the Lovington massif in the Blue Ridge province, has a calculated zircon saturation temperature (T_{Zr}) of 1032 °C when using Watson and Harrison's (1983) bulk-rock zircon saturation thermometer. The rhyolite-MELTS modeled temperature for onset of zircon crystallization is estimated at 1060 °C, exceeding T_{Zr} by approximately 30 °C. The highest Ti-in-zircon temperature range (749 – 1053 °C) agrees well with the rhyolite-MELTS temperature (Figure 8.1).

Sample VA 15-2, a granodioritic charnockite from the Pedlar massif in the Blue Ridge province, has a T_{Zr} of 898 °C. The rhyolite-MELTS modeled temperature greatly exceeds this value by approximately 130 °C, and is estimated at 1024 °C. The Ti-in-zircon temperatures range from 750 – 928 °C and are more comparable to the T_{Zr} value than with rhyolite-MELTS (Figure 8.1).

Sample NJ 15-1, a granite from the New Jersey – Hudson Highlands, has a T_{Zr} of 960 °C. The rhyolite-MELTS modeled temperature is similar, estimated at 983 °C. The Ti-in-zircon apparent temperatures range from 656 – 935 °C and agree well with our rhyolite-MELTS and T_{Zr} geothermometers (Figure 8.1). Furthermore, previous data from Moecher et al., (2014), show that for two samples (VA 12-1 and VA 12-2, an orthogneiss and charnockite from the Virginia Blue Ridge, respectively), modeled results agree with the orthogneiss and we again see a discrepancy in temperatures for the charnockite.

The sample with the least variability between each geothermometer is NJ 15-1 (~159 °C). This is likely due to the lack of greenschist metamorphic overprinting that has occurred in both VA 15-1 and VA 15-2. VA 15-2 has the lowest Zr ppm (918) and the greatest difference in temperature estimates (~204 °C). In all cases, rhyolite-MELTS predicts zircon saturation to begin at the highest Ti-in-zircon temperature (Figure 8.1). As previously mentioned in Chapter VI, rhyolite-MELTS cannot accurately account for hydrous phases such as hornblende and biotite, and this may affect crystallization sequences. The two samples with the highest bulk rock Zr concentration (VA 15-1 and NJ 15-1) have the least difference in rhyolite-MELTS and T_{Zr} temperatures. Both samples also contain a substantial amount of homogenous, recrystallized zircon grains that lack, or have very thin, rims in CL. The Ti-in-zircon temperatures range on the lowest end from 656 – 750 °C and on the highest end from 928 – 1053 °C. These values are consistently among the highest apparent temperatures previously reported for felsic to intermediate rocks (653 – 758 °C) (Fu et al., 2008).

The data show that the agreement between two widely used and well calibrated zircon geothermometers (T_{Zr} and Ti-in-zircon) lends confidence to the interpretation that

they are yielding geologically meaningful temperature results. Though there are discrepancies between each temperature estimate, they still qualify as hot (Miller et al., 2003) and thus are ancillary supporting evidence for the hot Grenville granite hypothesis (Moecher et al., 2014). In the latter study, crystallization of dry, hot Grenville granites with varying Zr concentrations began to precipitate zircon near the liquidus at ~1050 – 1125 °C when modeled using rhyolite-MELTS. Ti-in-zircon thermometry yielded temperatures that ranged from ~781 – 1035 °C and T_{Zr} calculations yielded temperatures ranging from ~835 – 998 °C. The data in this thesis are similar to the Moecher et al., (2014), study in that the Ti-in-zircon temperatures are among the highest reported, though they have a larger range (~656 – 1053 °C). T_{Zr} temperatures are hotter (~960 – 1032 °C) and rhyolite-MELTS modeled temperatures are cooler (~983 – 1060 °C).

Although mineral grains crystallizing from a magma (e.g., plagioclase, quartz, zircon) must crystallize over some time interval between liquidus and solidus (i.e., not all grains of any mineral crystallized at the same instance in time), zircon from ca. 1 Ga plutonic systems cannot be used to resolve the time of crystallization of individual zircon grains, because we cannot resolve with sufficient precision via SIMS, SHRIMP-RG, or LA-ICP-MS, differences in U and Pb isotope ratios. Since Ti concentrations can be measured with much higher precision (± 0.1 ppm), Ti-in-zircon can be used not only for calculating temperature at the instant a particular zircon grain crystallized, but to also track the crystallization of the bulk of the zircon grains in a granite. The highest Ti concentrations for each sample are consistent with a high temperature (near liquidus) for the onset of zircon saturation. However, for all samples the majority of Ti concentrations indicate the bulk of the zircon crystallized at temperatures lower than the liquidus (Figure

8.1). It may be that bulk melt Zr contents became critically undersaturated, at which point the rate of zircon crystallization increased substantially.

Quantitative tectonic evolution models for the western margin of the Grenville orogeny in Canada do not take into account any crustal heat generation caused by mantle or magmatic influx, but rather account for heating by stacking of multiple crustal-scale thrust zones (Jamieson et al., 2010). Equivalent eastern margin Grenvillian rocks in the Appalachians cannot be explained by a similar model, as the basement granitoids display weaker degrees of deformation and are exceptionally Zr-rich (Tollo et al., 2004a; Moecher and Samson, 2006; Burton and Southworth, 2010). Because zircon solubility is directly related to temperature, an interpretation that allows for increased crustal temperatures is required for production of granitoids with temperatures ranging from ~900 to ~1000 °C. Extensive melting of continental crust may be explained by ultrahigh-temperature (UHT) magmatic regimes analogous to the granulite province of southern India where individual terranes were accreted during the Proterozoic (Brown and Raith, 1996). Pressure and temperature conditions in this region suggest temperatures on the order of 900 – 1000 °C at 12 kbar (Brown and Raith, 1996). Field settings indicate that these high-grade, intensely deformed granulites occurred in overthickened crust, and the high temperatures may have increased magmatic events in the area (Brown and Raith, 1996).

Previous research shows that in lower crustal zones affected by lithospheric delamination or basaltic underplating at high temperatures ranging from 1000 – 1200 °C (Annen et al., 2006), the melt may become undersaturated in Zr and thus zircon. This scenario would result in low T_{Zr} temperatures even if high melting temperatures were

involved, because the bulk-rock composition would not directly correlate with initial melt conditions where zircon crystallization began. The granitoids in this study are primarily A-type, and they are likely to be created from mantle-derived intermediate magmas (Bonin, 2007). Smithies et al., (2011), propose a model using UHT underplating to explain the Mesoproterozoic Musgrave Orogeny in Australia that may indicate a similar situation for the Grenville Orogeny: granitoids, including charnockites, were emplaced under high temperatures ($\geq 1000\text{ }^{\circ}\text{C}$) and resulted from under- and intraplated mafic magmas that provided a constant supply of heat to melt the available felsic crust. Smithies et al., (2011), proposed that mantle plumes would not be consistent with a long, prolonged orogeny, such as the Grenville.

Ultrahigh-temperature metamorphism is a thermal extreme when compared to typical regional metamorphism. Thermal models from Kelsey and Hand, (2014), indicate that regional UHT metamorphic regimes can be created when subduction zones (for example, during a collisional orogeny) occur simultaneously with elevated rates of radiogenic heat generation in the crust. This study also compiled Ti-in-zircon thermometry data from multiple sources and found that there are two distinct temperature peaks at $\sim 810\text{ }^{\circ}\text{C}$ and $\sim 925\text{ }^{\circ}\text{C}$, and a handful of analyses over $1000\text{ }^{\circ}\text{C}$, with a dry granitic liquidus (the maximum temperature limit) at $1140\text{ }^{\circ}\text{C}$ and 8 kbar. The average temperatures in our investigation range from approximately $900\text{ }^{\circ}\text{C}$ to $1000\text{ }^{\circ}\text{C}$ and fall directly in line with values compiled by Kelsey and Hand, (2014), indicating a possible connection between UHT metamorphism, crustal melting, and crustal metamorphism during periods of the Grenville orogeny.

Figure 8.1: Estimated whole-rock zircon saturation temperatures (T_{Zr}) calculated using the Watson and Harrison (1983) thermometer, plotted against estimated Ti-in-zircon (Ferry and Watson, 2007) crystallization temperatures. Large, filled symbols represent mean (+ 1 standard deviation) Ti-in-zircon temperatures for each sample. Red stars represent rhyolite-MELTS zircon crystallization temperature for each sample. Solid line indicates a ratio of 1. Note how both charnockites have rhyolite-MELTS modeled temperature discrepancies (Figure after Padilla et al., 2016).

APPENDICES

Appendix A: Whole-rock X-Ray Fluorescence Spectrometric Analysis

Sample	VA 15-01 †		WSU	VA 15-02 †	WSU	VA 15-03	WSU	VA 15-04	WSU	VA 15-05	WSU	VA 15-06	WSU	NJ 15-01 †	WSU	NJ 15-02	WSU	NJ 15-03	WSU	NJ 15-04	WSU	NJ 15-05
Al2O3 (wt. %)	13.44	13.43	14.54	14.47	14.81	14.66	11.84	11.56	13.82	13.50	14.74	14.82	13.56	13.71	13.93	13.93	14.11	14.18	14.22	14.26		
SiO2 (wt. %)	61.74	61.85	58.91	58.18	65.9	65.89	72.95	73.49	72.49	72.69	66.73	66.53	67.12	66.97	65.75	66.06	65.75	67.32	66.44	66.62		
Fe2O3 (wt. %)	9.93	9.53	10.03	9.49	5.66	5.30	4.29	4.00	3.49	3.25	5.23	5.11	4.9	4.67	3.78	3.78	3.70	4.64	5.11	4.84		
MnO (wt. %)	0.15	0.16	0.14	0.14	0.07	0.078	0.06	0.066	0.02	0.025	0.06	0.066	0.10	0.108	0.08	0.08	0.088	0.08	0.09	0.099		
TiO2 (wt. %)	1.71	1.641	2.32	2.19	1.25	1.073	0.39	0.242	0.11	0.117	1.17	0.785	0.74	0.752	0.64	0.64	0.689	0.61	0.71	0.749		
CaO (wt. %)	3.85	3.94	5.53	5.53	2.06	2.06	0.77	0.77	0	0.03	2.62	2.78	2.73	2.72	3.29	3.29	3.37	1.81	2.2	2.28		
K2O (wt. %)	3.45	3.47	3.31	3.28	2.59	2.61	4.02	4.03	5.12	5.10	4.66	4.44	5.41	5.55	6.48	6.48	6.52	5.45	5.37	5.42		
Na2O (wt. %)	2.67	2.82	2.74	2.87	4.74	4.69	4.22	4.13	4.09	4.04	2.78	2.98	3.04	3.16	3.13	3.13	3.21	3.71	3.47	3.55		
MgO (wt. %)	0.97	0.93	1.7	1.67	1.15	1.10	0.15	0.10	0.11	0.03	1.04	1.11	0.74	0.69	0.72	0.72	0.69	0.62	0.78	0.74		
P2O5 (wt. %)	0.75	0.767	1.04	1.064	0.45	0.439	0.04	0.033	0.02	0.011	0.23	0.216	0.19	0.184	0.15	0.15	0.143	0.15	0.17	0.166		
% LOI	0.74	0.62	0.1	0	1.33	1.07	0.58	0.29	1.04	0.69	0.85	0.73	0.61	0.37	0.94	0.94	0.71	0.68	0.7	0.41		
Total % Oxides	99.44	98.54	100.4	98.9	100.03	97.9	99.28	98.42	100.34	98.79	100.15	98.83	98.5	98.52	98.3	98.3	98.09	98.5	98.5	98.68		
Pb (ppm)	17	32	13	22	10	7	83	149	14	14	19	24	11	12	14	14	17	12	12	13		
Cu (ppm)	<2	11	<2	12	162	296	<2	9	<2	2	<2	9	<2	13	<2	<2	8	<2	<2	6		
Co (ppm)	2	n/a	7	n/a	5	n/a	<2	n/a	<2	n/a	9	n/a	3	n/a	4	n/a	n/a	<2	<2	n/a		
Ni (ppm)	11	5	11	7	14	5	64	4	18	2	22	13	55	7	45	7	35	38	6	40		
Cr (ppm)	51	53	80	82	33	34	53	59	64	68	77	78	186	188	128	141	152	132	153	159		
Ce (ppm)	282	214	217	238	203	192	448	358	150	67	119	110	249	311	276	397	186	227	270	266		
V (ppm)	35	43	131	90	186	44	146	7	212	2	245	57	null	16	null	16	16	null	null	17		
La (ppm)	63	97	72	105	61	85	129	170	18	23	38	57	null	113	null	113	200	null	104	null		
Ba (ppm)	3281	2502	1786	1780	998	979	17	52	10	57	1014	980	1842	1945	1844	1945	1960	1897	2242	2313		
Nb (ppm)	28	33.5	31	30.4	27	22.5	29	230	50	209.5	18	15.2	65	64.7	57	64.7	57	54.9	47	44		
Zr (ppm)	1013	2209	647	918	615	730	1016	1983	885	1189	408	417	865	1238	793	1079	1079	783	850	1195		
Y (ppm)	60	69	61	77	64	66	289	261	72	48	55	34	136	152	118	127	127	92	97	110		
Sr (ppm)	362	348	601	564	285	226	3	8	<2	4	241	199	438	371	563	462	462	427	500	420		
Rb (ppm)	63	93	52	74	62	72	150	170	161	183	136	167	104	132	127	162	127	115	91	114		
U (ppm)	<2	2	<2	2	2	1	3	9	3	6	2	1	null	3	null	3	null	4	null	3		
Th (ppm)	8	2	9	2	7	2	38	33	16	10	5	1	null	8	null	8	null	12	null	2		
Ga (ppm)	25	26	24	25	22	22	43	50	42	49	21	21	null	23	null	22	null	22	null	24		
Zn (ppm)	222	227	203	213	174	147	381	386	92	67	116	105	165	145	140	156	145	130	173	160		

† Samples selected for U-Pb dating, SHRIMP-RG, and rhyolite-MELTS modeling

Appendix B: SIMS Data. Presented in order of analysis, though AS3 (reported value of 1099 ± 1 Ma) block moved to top for ease of calculations.

Name	206Pb/238U Age (Ma)	206Pb/238U Age (m.y.) (1σ)	Ratio 206Pb/238U	Ratio 207Pb/235U	Ratio 207Pb/235U error (1σ)	207Pb/206Pb Age (Ma)	207Pb/206Pb Age (m.y.) (1σ)	Ratio 207Pb/206Pb	Ratio 207Pb/206Pb error (1σ)	Correlation of Concordia Ellipses	Common 206Pb/204Pb	Common 207Pb/204Pb	Common 208Pb/204Pb	Pb correction	Block Size	True 206Pb/238U	True 207Pb/235U	True 207Pb/235U Unknowns (1σ)	True 206Pb/238U Unknowns (1σ)	True 206Pb/238U Unknowns	True 207Pb/206Pb Unknowns	True 206Pb/238U True Age (Ma)	207Pb/235U True Age (Ma)	207Pb/235U True Age (m.y.) (1σ)							
VA15-1_A33@1.a16	1098	37.11	0.1856	6.83E-03	1090	24.79	1.924	7.14E-02	1074	4.305	7.52E-02	1.61E-04	0.9984	18.86	15.62	38.34	0.9884	0.9857	0.9870	1.8856	0.0714	0.1835	0.0068	0.0746	0.0002	1086	37.11	1076	24.79		
VA15-1_A33@5.a16	1075	38.74	0.1814	7.10E-03	1078	26.55	1.892	7.56E-02	1085	8.773	7.56E-02	3.31E-04	0.9941	18.86	15.62	38.34	(None)	9	0.9758	0.9930	1.8543	0.0756	0.1794	0.0071	0.0750	0.0003	1064	38.74	1065	26.55	
VA15-1_A33@6.a16	1160	30.98	0.1971	5.75E-03	1149	21.22	1.921	6.48E-02	1129	12.76	7.73E-02	4.95E-04	0.9947	18.86	15.62	38.34	(None)	9	1.0602	1.0938	1.0200	2.0591	0.0648	0.1949	0.0058	0.0766	0.0005	1148	30.98	1135	21.22
VA15-1_A33@9.a16	1138	35.47	0.1931	6.57E-03	1160	27.32	2.135	8.44E-02	1202	27.71	8.02E-02	1.13E-03	0.9976	18.86	15.62	38.34	(None)	9	1.0387	1.0938	1.0500	2.0924	0.0844	0.1910	0.0066	0.0795	0.0011	1127	35.47	1146	27.32
VA15-1_A33_new@3.a16	1114	31.34	0.1886	5.78E-03	1130	21.79	2.092	6.93E-02	1160	8.798	7.85E-02	3.48E-04	0.9969	18.86	15.62	38.34	(None)	9	1.0405	1.0461	1.0300	2.0013	0.0653	0.1885	0.0058	0.0778	0.0003	1102	31.34	1116	21.79
VA15-1_A33_new@4.a16	1080	33.85	0.1823	6.21E-03	1113	24.19	1.992	7.07E-02	1178	38.16	7.92E-02	7.28E-04	0.9966	18.86	15.62	38.34	(None)	9	0.9865	1.0205	1.0400	1.9523	0.0707	0.1803	0.0062	0.0786	0.0007	1068	33.85	1069	24.19
VA15-1_A33_new@5.a16	1082	33.25	0.1828	6.18E-03	1082	22.21	1.981	6.93E-02	1081	24.45	7.52E-02	9.25E-05	0.9983	18.86	15.62	38.34	(None)	9	0.9836	0.9810	1.0320	1.8631	0.0635	0.1808	0.0061	0.0781	0.0001	1071	33.25	1068	22.21
VA15-1_A33_new@6.a16	1084	33.28	0.1830	6.18E-03	1084	22.21	1.981	6.93E-02	1081	24.45	7.52E-02	9.25E-05	0.9983	18.86	15.62	38.34	(None)	9	0.9836	0.9810	1.0320	1.8631	0.0635	0.1808	0.0061	0.0781	0.0001	1071	33.28	1068	22.21
VA15-1_A33_new@7.a16	1104	33.22	0.1827	6.18E-03	1104	22.21	1.981	6.93E-02	1081	24.45	7.52E-02	9.25E-05	0.9983	18.86	15.62	38.34	(None)	9	0.9836	0.9810	1.0320	1.8631	0.0635	0.1808	0.0061	0.0781	0.0001	1071	33.22	1068	22.21
VA15-1_A33_new@8.a16	1104	46.96	0.1971	8.65E-03	1112	31.37	1.988	9.21E-02	1123	16.43	7.71E-02	6.35E-04	0.9942	18.86	15.62	38.34	(None)	9	1.0065	1.0384	1.0100	1.9484	0.0922	0.1850	0.0087	0.0764	0.0006	1094	46.96	1098	31.37
VA15-1_A33_new@9.a16	1117	55.55	0.1892	1.03E-02	1114	37.84	1.995	0.1116	1107	21.23	7.65E-02	1.32E-04	0.9943	18.86	15.62	38.34	(None)	9	1.0788	1.0220	1.0000	1.9552	0.1116	0.1871	0.0103	0.0758	0.0008	1106	55.55	1109	37.84
VA15-1_A33_new@10.a16	1111	54.43	0.1895	1.00E-02	1102	35.54	1.96	0.1036	1099	4.02	7.50E-02	1.30E-04	0.9993	18.86	15.62	38.34	(None)	9	1.0194	1.0041	0.9850	1.9209	0.1036	0.1871	0.0103	0.0744	0.0004	1107	54.43	1098	35.54
VA15-1_A33_new@11.a16	1111	73.34	0.1881	1.35E-02	1104	48.45	1.966	0.1415	1096	11.75	7.58E-02	4.45E-04	0.9967	18.86	15.62	38.34	(None)	9	1.0118	1.0072	0.9850	1.9209	0.1036	0.1871	0.0103	0.0744	0.0004	1100	73.34	1098	48.45
VA15-1_A33_new@12.a16	1193	63.67	0.1866	1.17E-02	1100	42.12	1.955	0.1226	1094	14.28	7.60E-02	5.42E-04	0.9935	18.86	15.62	38.34	(None)	9	1.0038	1.0105	0.9980	1.9160	0.1226	0.1845	0.0117	0.0753	0.0005	1092	63.67	1087	42.12
VA15-1_A33_new@13.a16	1193	64.6	0.2034	1.21E-02	1181	42.52	2.199	8.91E-02	1253	7.84E-02	7.84E-02	4.91E-04	0.9825	18.86	15.62	38.34	(None)	9	1.0941	1.1265	1.0300	2.1552	0.1340	0.2011	0.0121	0.0777	0.0009	1181	64.6	1167	42.52
VA15-1_A33_new@14.a16	1161	67.44	0.1973	1.25E-02	1154	58.57	2.424	0.2563	2051	63.86	1.27E-01	2.08E-03	0.8743	18.86	15.62	38.34	(None)	9	1.0613	1.7643	1.6600	3.3753	0.2563	0.1951	0.0125	0.1260	0.0046	1149	67.44	1499	58.57
VA15-1_Zc@6.a16	1130	57.27	0.1916	1.06E-02	1388	46.7	2.904	1.805E-01	1311	33.82	1.11E-01	2.96E-03	0.9533	18.86	15.62	38.34	(None)	9	1.0307	1.4980	1.4500	2.8657	0.1805	0.1895	0.0106	0.1100	0.0021	1118	57.27	1373	46.7
VA15-1_Zc@7.a16	1099	57.1	0.1859	1.05E-02	1083	38.46	1.906	0.1101	1052	18.75	7.44E-02	6.92E-04	0.987	18.86	15.62	38.34	(None)	9	1.0000	0.9764	0.9770	1.8680	0.1101	0.1838	0.0105	0.0737	0.0007	1088	57.1	1070	38.46
VA15-1_Zc@8.a16	1166	65.95	0.1983	1.23E-02	1414	53.67	3.026	0.2128	1811	49.24	1.11E-01	3.00E-03	0.9238	18.86	15.62	38.34	(None)	9	1.0657	1.5502	1.4500	2.9657	0.2128	0.1961	0.0123	0.1100	0.0030	1154	65.95	1399	53.67
VA15-1_Zc@9.a16	1227	68.01	0.2096	1.28E-02	1504	52.62	3.3	0.228	1921	56.53	1.18E-01	3.71E-03	0.8829	18.86	15.62	38.34	(None)	9	1.1275	1.7418	1.5500	3.3322	0.2280	0.2073	0.0128	0.1170	0.0037	1214	68.01	1489	52.62
VA15-1_Zc@10.a16	1132	59.31	0.192	1.10E-02	1193	43.67	2.238	0.1393	1305	40.67	8.45E-02	1.77E-03	0.942	18.86	15.62	38.34	(None)	9	1.0328	1.1465	1.1100	2.1934	0.1393	0.1899	0.0110	0.0838	0.0018	1121	59.31	1179	43.67
VA15-1_Zc@11.a16	1194	67.8	0.2034	1.27E-02	1364	55.69	2.28	0.2027	1643	56.51	1.01E-01	3.08E-03	0.9056	18.86	15.62	38.34	(None)	9	1.1001	1.4518	1.3300	2.7775	0.2027	0.2011	0.0127	0.1000	0.0031	1181	67.8	1350	53.69
VA15-1_Zc@12.a16	1200	70.16	0.2045	1.31E-02	1422	60.02	3.07	0.2405	1780	59.59	1.09E-01	3.58E-03	0.934	18.86	15.62	38.34	(None)	9	1.1001	1.5727	1.4300	3.0088	0.2405	0.2022	0.0131	0.1080	0.0036	1187	70.16	1410	60.02
VA15-1_Zc@13.a16	1115	62.89	0.1888	1.16E-02	1202	45.4	2.267	0.1462	1362	40.11	8.71E-02	1.81E-03	0.9465	18.86	15.62	38.34	(None)	9	1.0156	1.1614	1.1400	2.2218	0.1462	0.1867	0.0116	0.0883	0.0018	1103	62.89	1188	45.4
VA15-1_Zc@14.a16	1155	60.57	0.1963	1.31E-02	1386	47.3	2.246	0.1351	1269	39.58	8.50E-02	1.68E-03	0.953	18.86	15.62	38.34	(None)	9	1.0359	1.1566	1.0800	2.0212	0.1351	0.1911	0.0131	0.0842	0.0017	1181	60.57	1181	47.3
VA15-1_Zc@15.a16	1155	60.57	0.1963	1.31E-02	1386	47.3	2.246	0.1351	1269	39.58	8.50E-02	1.68E-03	0.953	18.86	15.62	38.34	(None)	9	1.0359	1.1566	1.0800	2.0212	0.1351	0.1911	0.0131	0.0842	0.0017	1181	60.57	1181	47.3
VA15-1_Zc@16.a16	1155	60.57	0.1963	1.31E-02	1386	47.3	2.246	0.1351	1269	39.58	8.50E-02	1.68E-03	0.953	18.86	15.62	38.34	(None)	9	1.0359	1.1566	1.0800	2.0212	0.1351	0.1911	0.0131	0.0842	0.0017	1181	60.57	1181	47.3
VA15-1_Zc@17.a16	1155	60.57	0.1963	1.31E-02	1386	47.3	2.246	0.1351	1269	39.58	8.50E-02	1.68E-03	0.953	18.86	15.62	38.34	(None)	9	1.0359	1.1566	1.0800	2.0212	0.1351	0.1911	0.0131	0.0842	0.0017	1181	60.57	1181	47.3
VA15-1_Zc@18.a16	1117	56.04	0.1893	1.03E-02	1149	41.36	2.171	0.1163	1210	40.25	8.05E-02	1.55E-03	0.9409	18.86	15.62	38.34	(None)	9	1.0178	1.0763	1.0600	2.0591	0.1163	0.1871	0.0103	0.0799	0.0017	1106	56.04	1135	41.36
VA15-1_Zc@19.a16	1182	69.5	0.2012	1.30E-02	1299	51.99	2.579	0.1833	1488	64.2	9.06E-02	3.15E-03	0.8793	18.86	15.62	38.34	(None)	9	1.0823	1.3212	1.2200	2.5276	0.1833	0.1990	0.0130	0.0922	0.0032	1170	69.5	1280	51.99
VA15-1_Zc@20.a16	1187	72.16	0.2021	1.35E-02	1497	64.86	3.68	0.279	1969	69.51	1.21E-01	4.71E-03	0.8862	18.86	15.62	38.34	(None)	9	1.0871	1.7254	1.5900	3.3008	0.2790	0.1999	0.0135	0.1200	0.0047	1175	72.16	1481	64.86
VA15-1_Zc@21.a16	1125	83.64	0.1906	1.55E-02	1323	67.33	2.681	0.2441	1661	55.39	1.21E-01	3.05E-03	0.9461	18.86	15.62	38.34	(None)	9	1.0353	1.3405	1.2400	2.6075	0.2441	0.1885	0.0155	0.1010	0.0031	1113	83.64	1308	67.33
VA15-1_Zc@22.a16	1181	82.78	0.2011	1.54E-02	1329	73.29	3.06	0.3252	2049	68.2	1.26E-01	4.48E-03	0.9134	18.86	15.62	38.34	(None)	9	1.0818	1.7961	1.6600	3.4361	0.3252	0.1989	0.0154	0.1250	0.0049	1169	82.78	1513	73.29
VA15-1_Zc@30.a16	1231	89.71	0.2105	1.69E-02	1425	63.08	3.069	0.2528	1728	33.01	1.06E-01	1.90E-03	0.9759	18.86	15.62	38.34	(None)	9	1.1323	1.5722	1.3900	3.0078	0.2528	0.2082	0.0169	0.1050	0.0019	1219	89.71	1410	63.08
VA15-1_Zc@32.a16	1198	82.71	0.2043	1.55E-02	1475	71.07	3.274	0.2991	1899	80.56	1.16E-01	2.40E-03	0.8726	18.86	15.62	38.34	(None)	9	1.0990	1.6773	1.5300	3.2087	0.2991	0.2020	0.0155	0.1150	0.005				

Appendix B: SIMS Data. Presented in order of analysis, though AS3 (reported value of 1099 + 1 Ma) block moved to top for ease of calculations.

Name	206Pb/238U Age (Ma)	206Pb/235U Age (m.y.) _(1σ)	Ratio 206Pb/238U	Ratio 206Pb/235U error (1σ)	207Pb/235U Age (Ma)	Ratio 207Pb/235U error (1σ)	207Pb/206Pb Age (Ma)	207Pb/206Pb Age (m.y.) _(1σ)	Ratio 207Pb/206Pb	Ratio 207Pb/206Pb error (1σ)	Correlation of Concordia Ellipses	Common 206Pb/204Pb	Common 207Pb/204Pb	Common 208Pb/204Pb	Pb correction	Block Size	True 206Pb/238U	True 206Pb/235U	True 207Pb/206Pb	True 207Pb/235U Unknowns (1σ)	True 206Pb/238U Unknowns (1σ)	True 206Pb/206Pb Unknowns	True 207Pb/206Pb Unknowns (1σ)	206Pb/238U True Age (Ma)	207Pb/235U True Age (m.y.) _(1σ)	207Pb/235U True Age (Ma)	207Pb/235U True Age (m.y.) _(1σ)			
VA15-2_A53_#4@93.ais	1100	20.88	0.1861	3.84E-03	1.093	14.02	1.935	4.56E-02	1080	6.907	7.54E-02	2.48E-04	0.9076	18.86	15.62	38.34	9	1.0011	0.9913	0.9063	1.9221	0.0405	0.1858	0.0038	0.00751	0.0002	1.098	20.88	1089	14.02
VA15-2_A53_#4@94.ais	1092	19.84	0.1846	3.65E-03	1.088	13.27	1.921	3.82E-02	1081	5.162	7.55E-02	1.94E-04	0.9016	18.86	15.62	38.34	9	0.9930	0.9841	0.9930	1.9082	0.0387	0.1843	0.0037	0.00751	0.0003	1.090	19.84	1084	13.27
VA15-2_A53_#4@95.ais	1121	31.91	0.1899	5.09E-03	1121	22.44	2.017	6.97E-02	1122	6.186	7.59E-02	2.69E-04	0.9961	18.86	15.62	38.34	9	1.0215	1.0333	1.0115	2.0036	0.0687	0.1896	0.0059	0.00766	0.0003	1.119	31.91	1117	22.44
VA15-2_A53_#4@96.ais	1117	18.19	0.1868	3.91E-03	1111	15.35	1.980	4.92E-02	1112	12.36	7.70E-02	1.69E-04	0.9933	18.86	15.62	38.34	9	1.0221	1.0333	1.0115	2.0036	0.0687	0.1896	0.0059	0.00766	0.0003	1.119	18.19	1117	15.35
VA15-2_A53_#4@97.ais	1123	18.19	0.1868	3.91E-03	1111	15.35	1.980	4.92E-02	1112	12.36	7.70E-02	1.69E-04	0.9933	18.86	15.62	38.34	9	1.0221	1.0333	1.0115	2.0036	0.0687	0.1896	0.0059	0.00766	0.0003	1.119	18.19	1117	15.35
VA15-2_A53@98.ais	1095	17.81	0.1851	3.27E-03	1099	12.12	1.951	3.92E-02	1106	6.111	7.64E-02	2.34E-04	0.9866	18.86	15.62	38.34	9	0.9957	0.9955	1.0095	1.9759	0.0352	0.1848	0.0033	0.00760	0.0003	1.093	17.81	1094	12.12
VA15-2_A53@99.ais	1096	18.96	0.1854	3.49E-03	1112	14.76	1.998	4.91E-02	1151	15.27	7.82E-02	6.01E-04	0.9424	18.86	15.62	38.34	9	0.9973	1.0236	1.0266	1.9847	0.0443	0.1851	0.0035	0.00778	0.0006	1.095	18.96	1101	14.76
VA15-2_A53@100.ais	1089	17.71	0.1841	3.25E-03	1112	14.76	1.998	4.91E-02	1151	15.27	7.82E-02	6.01E-04	0.9424	18.86	15.62	38.34	9	0.9973	1.0236	1.0266	1.9847	0.0443	0.1851	0.0035	0.00778	0.0006	1.095	17.71	1108	14.76
VA15-2_A53@101.ais	1071	18.53	0.1807	3.39E-03	1081	13.8	1.944	3.91E-02	1102	10.82	7.69E-02	4.13E-04	0.9973	18.86	15.62	38.34	9	0.9903	1.0200	1.0299	1.9777	0.0435	0.1838	0.0033	0.00780	0.0006	1.088	17.71	1108	14.76
VA15-2_A53@102.ais	1081	18.53	0.1807	3.39E-03	1081	13.8	1.944	3.91E-02	1102	10.82	7.69E-02	4.13E-04	0.9973	18.86	15.62	38.34	9	0.9903	1.0200	1.0299	1.9777	0.0435	0.1838	0.0033	0.00780	0.0006	1.088	17.71	1108	14.76
VA15-2_A53@103.ais	1081	18.53	0.1807	3.39E-03	1081	13.8	1.944	3.91E-02	1102	10.82	7.69E-02	4.13E-04	0.9973	18.86	15.62	38.34	9	0.9903	1.0200	1.0299	1.9777	0.0435	0.1838	0.0033	0.00780	0.0006	1.088	17.71	1108	14.76
VA15-2_A53@104.ais	1093	19.06	0.1868	3.80E-03	1094	13.06	1.937	3.78E-02	1096	8.007	7.60E-02	1.29E-04	0.9848	18.86	15.62	38.34	9	0.9941	0.9923	1.0085	1.9241	0.0378	0.1845	0.0035	0.00757	0.0003	1.091	19.06	1089	13.06
VA15-2_A53@105.ais	1093	19.06	0.1868	3.80E-03	1094	13.06	1.937	3.78E-02	1096	8.007	7.60E-02	1.29E-04	0.9848	18.86	15.62	38.34	9	0.9941	0.9923	1.0085	1.9241	0.0378	0.1845	0.0035	0.00757	0.0003	1.091	19.06	1089	13.06
VA15-2_A53@106.ais	1093	19.06	0.1868	3.80E-03	1094	13.06	1.937	3.78E-02	1096	8.007	7.60E-02	1.29E-04	0.9848	18.86	15.62	38.34	9	0.9941	0.9923	1.0085	1.9241	0.0378	0.1845	0.0035	0.00757	0.0003	1.091	19.06	1089	13.06
VA15-2_A53@107.ais	1093	19.06	0.1868	3.80E-03	1094	13.06	1.937	3.78E-02	1096	8.007	7.60E-02	1.29E-04	0.9848	18.86	15.62	38.34	9	0.9941	0.9923	1.0085	1.9241	0.0378	0.1845	0.0035	0.00757	0.0003	1.091	19.06	1089	13.06
VA15-2_A53@108.ais	1112	22.44	0.1883	4.14E-03	1108	18.64	2.161	5.91E-02	1274	34.6	8.32E-02	1.48E-03	0.9715	18.86	15.62	38.34	9	1.0129	1.071	1.0925	2.1466	0.0580	0.1880	0.0041	0.00828	0.0015	1.110	22.44	1164	18.64
VA15-2_A53@109.ais	1047	30.89	0.1793	5.64E-03	1131	25.34	2.048	7.91E-02	1298	28.06	8.42E-02	1.22E-03	0.9216	18.86	15.62	38.34	9	0.9484	1.0492	1.1999	2.1778	0.0754	0.1790	0.0056	0.00838	0.0012	1.045	30.89	1121	25.34
VA15-2_A53@110.ais	1017	21.69	0.1733	3.95E-03	1049	18.79	1.811	5.91E-02	1089	26.57	7.58E-02	1.01E-03	0.8926	18.86	15.62	38.34	9	0.9322	0.9278	0.9951	1.7989	0.0520	0.1730	0.0040	0.00754	0.0010	1.029	21.69	1045	18.79
VA15-2_A53@111.ais	1110	30.2	0.1879	5.96E-03	1277	38.89	2.518	0.1348	1571	60.64	9.72E-02	3.15E-03	0.9024	18.86	15.62	38.34	9	1.0268	1.2900	1.2766	2.5012	0.1348	0.1876	0.0056	0.00957	0.0032	1.108	30.2	1172	38.89
VA15-2_A53@112.ais	1126	28.56	0.1908	5.96E-03	1277	38.89	2.518	0.1348	1571	60.64	9.72E-02	3.15E-03	0.9024	18.86	15.62	38.34	9	1.0268	1.2900	1.2766	2.5012	0.1348	0.1876	0.0056	0.00957	0.0032	1.108	30.2	1172	38.89
VA15-2_A53@113.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@114.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@115.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@116.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@117.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@118.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@119.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@120.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@121.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@122.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@123.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@124.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@125.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@126.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102	0.0628	0.1771	0.0039	0.00827	0.0012	1.124	28.56	1172	22.49
VA15-2_A53@127.ais	1020	21.12	0.1774	3.87E-03	1189	19.75	2.225	6.28E-02	1271	27.3	8.31E-02	1.16E-03	0.9024	18.86	15.62	38.34	9	0.9420	1.1399	1.2366	2.2102									

Appendix B: LA-ICP-MS Data. Presented in order of analysis

Analysis	U (ppm)	206Pb 204Pb	U/Th	Isotope ratios				Apparent ages (Ma)										Conc (%)	
				206Pb* 207Pb*	± (%)	207Pb* 235U*	± (%)	206Pb* 238U*	± (Ma)	error corr.	206Pb* 238U*	± (Ma)	207Pb* 235U	± (Ma)	206Pb* 207Pb*	± (Ma)	Best age (Ma)		± (Ma)
-N15-1 spot 109	34	4464	4.0	14.1692	± 2.9	1.6171	± 2.9	0.1662	± 2.6	0.91	991.4	± 24.0	976.8	± 17.9	945.2	± 24.0	945.2	± 24.0	104.9
-N15-1 spot 100	62	8463	5.7	13.9482	± 3.0	1.6372	± 3.0	0.1657	± 2.8	0.91	988.4	± 25.2	984.6	± 19.2	977.3	± 26.3	977.3	± 26.3	101.1
-N15-1 spot 97	250	20879	8.7	13.9392	± 2.8	1.6539	± 2.8	0.1673	± 2.7	0.96	997.1	± 25.1	991.0	± 18.0	978.6	± 16.9	978.6	± 16.9	101.9
-N15-1 spot 27	81	23542	6.2	13.9366	± 2.5	1.6857	± 2.5	0.1705	± 2.3	0.91	1014.6	± 21.3	1003.1	± 15.9	978.9	± 20.8	978.9	± 20.8	103.6
-N15-1 spot 60	41	5069	3.2	13.9361	± 3.3	1.6274	± 3.3	0.1646	± 2.9	0.91	982.0	± 26.8	980.8	± 20.5	979.0	± 28.2	979.0	± 28.2	100.3
-N15-1 spot 12	306	30718	11.4	13.9263	± 3.0	1.6584	± 3.0	0.1676	± 2.9	0.96	998.8	± 26.7	992.8	± 19.1	980.4	± 17.6	980.4	± 17.6	101.9
-N15-1 spot 42	19	3387	4.2	13.9026	± 3.0	1.7210	± 3.0	0.1736	± 2.8	0.90	1031.9	± 26.3	1016.4	± 19.5	983.9	± 26.4	983.9	± 26.4	104.9
-N15-1 spot 18	157	33249	8.4	13.9015	± 1.2	1.6576	± 3.0	0.1672	± 2.8	0.92	996.7	± 25.5	992.5	± 19.0	984.1	± 23.6	984.1	± 23.6	101.3
-N15-1 spot 47	52	9680	3.8	13.8799	± 1.3	1.6523	± 2.9	0.1664	± 2.6	0.89	992.3	± 24.1	990.4	± 18.7	987.3	± 27.4	987.3	± 27.4	100.5
-N15-1 spot 24	33	4192	5.7	13.8727	± 1.3	1.6512	± 2.8	0.1662	± 2.5	0.89	991.2	± 22.8	990.0	± 17.6	988.3	± 25.4	988.3	± 25.4	100.3
-N15-1 spot 108	48	5029	6.8	13.8574	± 1.4	1.6744	± 2.9	0.1684	± 2.5	0.86	1003.0	± 22.9	998.8	± 18.2	990.6	± 29.4	990.6	± 29.4	101.3
-N15-1 spot 35	70	13671	6.0	13.8458	± 1.2	1.6905	± 3.6	0.1698	± 3.4	0.94	1011.2	± 32.0	1004.9	± 23.1	992.3	± 24.3	992.3	± 24.3	101.9
-N15-1 spot 31	169	44174	12.5	13.8424	± 0.8	1.7100	± 3.0	0.1718	± 2.9	0.96	1021.7	± 27.0	1012.3	± 19.1	992.8	± 17.0	992.8	± 17.0	102.9
-N15-1 spot 72	146	33346	7.2	13.8221	± 0.9	1.6602	± 3.0	0.1665	± 2.9	0.96	992.8	± 26.4	993.5	± 19.0	995.8	± 17.3	995.8	± 17.3	99.7
-N15-1 spot 70	31	9388	3.0	13.8171	± 1.7	1.6724	± 3.3	0.1677	± 2.8	0.86	999.2	± 26.3	998.1	± 20.9	996.5	± 33.6	996.5	± 33.6	100.3
-N15-1 spot 5	271	36116	8.9	13.8050	± 0.8	1.6842	± 3.2	0.1687	± 3.1	0.97	1005.0	± 29.1	1002.6	± 20.5	998.2	± 15.6	998.2	± 15.6	100.7
-N15-1 spot 44	76	45021	5.9	13.8034	± 1.0	1.6930	± 3.0	0.1696	± 2.9	0.94	1009.7	± 26.8	1005.9	± 19.4	998.5	± 20.3	998.5	± 20.3	101.1
-N15-1 spot 20	32	6231	3.4	13.7922	± 1.3	1.6491	± 3.1	0.1650	± 2.8	0.91	984.7	± 25.5	989.2	± 19.4	1000.1	± 26.2	1000.1	± 26.2	98.5
-N15-1 spot 80	400	69821	11.3	13.7824	± 0.9	1.7059	± 2.6	0.1706	± 2.4	0.93	1015.4	± 22.4	1010.7	± 16.4	1001.6	± 18.8	1001.6	± 18.8	101.4
-N15-1 spot 21	37	10017	3.5	13.7797	± 1.3	1.6673	± 3.8	0.1667	± 3.6	0.94	993.9	± 32.7	996.2	± 24.0	1002.0	± 25.6	1002.0	± 25.6	99.2
-N15-1 spot 26	64	32677	6.0	13.7787	± 1.0	1.7150	± 2.9	0.1715	± 2.8	0.94	1020.1	± 26.1	1014.1	± 18.8	1002.1	± 19.6	1002.1	± 19.6	101.8
-N15-1 spot 88	221	29210	12.4	13.7738	± 0.9	1.6967	± 3.3	0.1696	± 3.2	0.96	1009.8	± 29.9	1007.3	± 21.2	1002.8	± 18.1	1002.8	± 18.1	100.7
-N15-1 spot 19	40	8449	3.2	13.7697	± 1.1	1.7023	± 2.9	0.1701	± 2.7	0.92	1012.6	± 25.1	1009.4	± 18.6	1003.4	± 23.2	1003.4	± 23.2	100.9
-N15-1 spot 91	70	17748	6.2	13.7662	± 1.0	1.6877	± 2.5	0.1686	± 2.3	0.92	1004.3	± 21.1	1003.9	± 15.8	1004.0	± 20.0	1004.0	± 20.0	100.0
-N15-1 spot 2	260	148814	8.9	13.7598	± 1.1	1.6795	± 3.4	0.1677	± 3.2	0.95	999.3	± 29.8	1000.8	± 21.7	1004.9	± 22.1	1004.9	± 22.1	99.4
-N15-1 spot 89	24	37591	4.0	13.7589	± 1.5	1.6589	± 3.2	0.1656	± 2.8	0.88	987.9	± 26.0	992.9	± 20.4	1005.0	± 30.4	1005.0	± 30.4	98.3
-N15-1 spot 36	14	30163	3.5	13.7561	± 1.8	1.6744	± 3.9	0.1671	± 3.5	0.89	996.3	± 32.2	998.9	± 24.9	1005.5	± 36.3	1005.5	± 36.3	99.1
-N15-1 spot 67	45	3151	4.9	13.7512	± 1.9	1.6541	± 3.8	0.1650	± 3.3	0.86	984.7	± 30.2	991.1	± 24.3	1006.2	± 39.4	1006.2	± 39.4	97.9
-N15-1 spot 59	137	204596	4.3	13.7450	± 1.0	1.6880	± 3.0	0.1683	± 2.8	0.94	1003.0	± 26.5	1004.0	± 19.2	1007.1	± 20.2	1007.1	± 20.2	99.6
-N15-1 spot 66	29	35790	3.0	13.7421	± 1.3	1.6713	± 3.4	0.1666	± 3.1	0.92	993.6	± 28.6	997.7	± 21.3	1007.5	± 26.0	1007.5	± 26.0	98.6
-N15-1 spot 77	131	27622	7.7	13.7404	± 1.1	1.7126	± 3.6	0.1707	± 3.4	0.96	1016.2	± 32.1	1013.3	± 22.9	1007.8	± 21.3	1007.8	± 21.3	100.8
-N15-1 spot 23	66	16991	5.6	13.7342	± 1.1	1.7232	± 2.5	0.1717	± 2.2	0.89	1021.6	± 20.7	1017.2	± 15.8	1008.7	± 22.7	1008.7	± 22.7	101.3
-N15-1 spot 87	139	14908	8.4	13.7289	± 1.1	1.6617	± 3.0	0.1655	± 2.8	0.94	987.4	± 25.8	994.0	± 19.1	1009.5	± 21.6	1009.5	± 21.6	97.8
-N15-1 spot 48	45	19235	6.8	13.7114	± 1.4	1.6539	± 3.0	0.1645	± 2.7	0.89	982.0	± 24.7	991.1	± 19.3	1012.0	± 28.0	1012.0	± 28.0	97.0
-N15-1 spot 37	73	25235	6.1	13.7027	± 1.0	1.6954	± 3.0	0.1686	± 2.8	0.94	1004.2	± 26.5	1006.8	± 19.2	1013.3	± 20.0	1013.3	± 20.0	99.1
-N15-1 spot 68	46	4966	5.3	13.6985	± 2.2	1.6869	± 3.4	0.1677	± 2.6	0.77	999.3	± 24.1	1003.6	± 21.7	1013.9	± 44.4	1013.9	± 44.4	98.6
-N15-1 spot 25	83	12232	6.2	13.6936	± 1.1	1.6938	± 2.2	0.1683	± 1.9	0.87	1002.7	± 17.9	1006.2	± 14.1	1014.7	± 22.1	1014.7	± 22.1	98.8
-N15-1 spot 84	71	25873	6.2	13.6790	± 1.3	1.6615	± 3.0	0.1649	± 2.7	0.90	984.0	± 24.5	993.9	± 18.9	1016.8	± 26.6	1016.8	± 26.6	96.8
-N15-1 spot 83	65	29342	5.7	13.6515	± 1.2	1.6820	± 2.6	0.1666	± 2.3	0.89	993.4	± 21.2	1001.7	± 16.4	1020.9	± 23.6	1020.9	± 23.6	97.3
-N15-1 spot 68	32	5462	3.9	13.6512	± 1.9	1.6786	± 3.5	0.1663	± 2.9	0.84	991.5	± 26.7	1000.4	± 22.1	1021.0	± 38.5	1021.0	± 38.5	97.1
-N15-1 spot 29	187	41768	15.7	13.6500	± 1.2	1.6866	± 3.6	0.1670	± 3.4	0.94	995.8	± 31.5	1003.5	± 23.1	1021.1	± 24.4	1021.1	± 24.4	97.5
-N15-1 spot 65	40	14263	5.4	13.6334	± 1.6	1.7037	± 3.4	0.1685	± 3.0	0.89	1004.0	± 27.8	1009.9	± 21.6	1023.6	± 31.6	1023.6	± 31.6	98.1
-N15-1 spot 43	622	62005	17.4	13.6313	± 0.7	1.6889	± 2.8	0.1670	± 2.8	0.97	995.8	± 25.4	1004.4	± 18.1	1023.9	± 14.5	1023.9	± 14.5	97.3
-N15-1 spot 28	48	465178	3.0	13.6265	± 1.1	1.7332	± 3.5	0.1714	± 3.3	0.95	1019.6	± 30.9	1020.9	± 22.2	1024.6	± 22.4	1024.6	± 22.4	99.5
-N15-1 spot 95	48	15929	6.1	13.6230	± 1.2	1.7419	± 3.3	0.1722	± 3.0	0.93	1024.1	± 28.6	1024.2	± 21.0	1025.1	± 24.9	1025.1	± 24.9	99.9

Appendix B: LA-ICP-MS Data. Presented in order of analysis

Analysis	U (ppm)	206Pb 204Pb	U/Th	Isotope ratios				Apparent ages (Ma)										Conc (%)
				206Pb* 207Pb*	±	207Pb* 235U*	±	206Pb* 238U	±	206Pb* 238U*	±	207Pb* 235U	±	206Pb* 207Pb*	±	Best age (Ma)	± (Ma)	
-N115-1 spot 61	35	4910	2.9	13.6229	±	1.4	1.7171	3.3	0.1697	3.0	0.90	1010.6	27.8	1014.9	21.1	1025.2	28.7	98.6
-N115-1 spot 102	27	84325	2.9	13.6172	±	1.1	1.7324	2.7	0.1712	2.4	0.91	1018.6	22.8	1020.7	17.2	1026.0	22.8	99.3
-N115-1 spot 58	32	28959	5.0	13.6171	±	1.1	1.6702	2.9	0.1650	2.7	0.93	984.6	24.5	997.2	18.4	1026.0	22.0	96.0
-N115-1 spot 1	98	17662	8.0	13.6106	±	1.1	1.6844	3.0	0.1663	2.8	0.93	991.9	25.6	1002.6	19.1	1027.0	22.1	96.6
-N115-1 spot 93	212	31998	9.3	13.6055	±	1.0	1.7298	2.8	0.1708	2.7	0.94	1016.3	25.2	1019.7	18.3	1027.7	19.3	98.9
-N115-1 spot 57	69	219481	5.8	13.6054	±	1.1	1.7104	3.5	0.1688	3.3	0.95	1005.8	30.4	1012.4	22.1	1027.8	22.6	97.9
-N115-1 spot 8	23	1845909	4.8	13.5931	±	1.2	1.6902	3.4	0.1667	3.1	0.94	993.9	29.0	1004.8	21.4	1029.6	24.0	96.5
-N115-1 spot 32	39	8405	3.3	13.5893	±	1.0	1.6958	3.0	0.1672	2.8	0.94	996.7	25.7	1007.0	19.0	1030.1	21.2	96.8
-N115-1 spot 94	258	51281	8.7	13.5886	±	0.8	1.7314	2.4	0.1707	2.3	0.94	1016.0	21.2	1020.3	15.5	1030.3	16.7	98.6
-N115-1 spot 103	80	34052	4.8	13.5854	±	1.3	1.6494	2.6	0.1626	2.2	0.87	971.1	20.2	989.3	16.2	1030.7	25.6	94.2
-N115-1 spot 54	38	4191	4.2	13.5819	±	1.3	1.6749	3.4	0.1651	3.1	0.92	984.9	28.7	999.1	21.7	1031.2	27.0	95.5
-N115-1 spot 52	69	21977	5.9	13.5799	±	1.0	1.6979	3.2	0.1673	3.0	0.95	997.2	27.6	1007.7	20.2	1031.6	20.5	96.7
-N115-1 spot 7	146	120411	7.7	13.5669	±	1.3	1.6782	3.1	0.1652	2.8	0.90	985.6	25.9	1000.3	20.0	1033.5	27.0	95.4
-N115-1 spot 33	127	37075	9.1	13.5537	±	0.8	1.6849	2.8	0.1657	2.7	0.96	988.4	24.6	1002.8	17.9	1035.5	16.5	95.5
-N115-1 spot 98	34	20421	4.2	13.5525	±	1.3	1.7146	3.1	0.1686	2.8	0.90	1004.4	26.3	1014.0	20.1	1035.6	27.1	97.0
-N115-1 spot 50	41	6154	3.2	13.5520	±	1.6	1.7390	3.3	0.1710	2.9	0.88	1017.6	27.3	1023.1	21.2	1035.7	31.4	98.3
-N115-1 spot 16	34	11082	3.0	13.5343	±	1.5	1.6935	3.1	0.1663	2.7	0.88	991.8	25.0	1006.1	19.8	1038.3	30.2	95.5
-N115-1 spot 10	63	7316	6.0	13.5245	±	1.0	1.7060	3.9	0.1674	3.7	0.97	997.8	34.6	1010.8	24.7	1039.8	19.6	96.0
-N115-1 spot 105	42	34240	3.0	13.5219	±	1.3	1.7166	2.8	0.1684	2.5	0.88	1003.4	23.2	1014.7	18.1	1040.2	26.8	96.5
-N115-1 spot 104	35	5775	2.9	13.5043	±	2.0	1.6948	3.1	0.1661	2.4	0.77	990.4	21.9	1006.6	19.7	1042.8	39.6	95.0
-N115-1 spot 38	68	15698	5.4	13.5022	±	1.0	1.6907	3.6	0.1656	3.5	0.96	988.0	32.0	1005.0	23.3	1043.1	20.7	94.7
-N115-1 spot 86	70	7709	6.0	13.4924	±	1.3	1.6678	3.3	0.1633	3.0	0.91	975.0	27.4	996.4	21.0	1044.6	27.1	93.6
-N115-1 spot 78	33	29002	3.6	13.4854	±	1.4	1.7596	2.8	0.1722	2.4	0.86	1024.1	23.0	1030.7	18.3	1045.7	28.9	97.9
-N115-1 spot 14	25	25586	3.6	13.4760	±	1.6	1.7029	3.4	0.1665	3.0	0.89	992.8	28.0	1009.6	21.9	1047.1	31.9	94.8
-N115-1 spot 110	69	107350	5.1	13.4678	±	1.4	1.7025	2.9	0.1664	2.5	0.87	992.1	22.9	1009.5	18.4	1048.3	28.9	94.6
-N115-1 spot 9	25	9151	3.0	13.4664	±	1.3	1.6884	3.5	0.1650	3.3	0.93	984.3	29.7	1004.1	22.5	1048.5	27.0	93.9
-N115-1 spot 45	20	4368	4.8	13.4621	±	1.8	1.6528	4.8	0.1614	4.4	0.93	964.8	39.5	990.6	30.1	1049.2	36.4	92.0
-N115-1 spot 4	42	19256	4.9	13.4530	±	1.3	1.7548	3.2	0.1713	3.0	0.91	1019.2	27.9	1028.9	21.0	1050.5	26.7	97.0
-N115-1 spot 53	25	15002	4.1	13.4496	±	1.1	1.7435	3.5	0.1701	3.4	0.95	1012.9	31.5	1024.8	22.8	1051.0	22.2	96.4
-N115-1 spot 11	98	72461	6.9	13.4485	±	0.7	1.7148	2.7	0.1673	2.6	0.96	997.4	24.3	1014.1	17.5	1051.2	14.6	94.9
-N115-1 spot 74	30	25272	3.1	13.4432	±	1.4	1.7112	3.0	0.1669	2.6	0.88	995.1	23.9	1012.8	18.9	1052.0	28.5	94.6
-N115-1 spot 17	501	183233	13.8	13.4397	±	0.9	1.7386	3.4	0.1695	3.3	0.97	1009.6	30.4	1023.0	21.7	1052.5	17.3	95.9
-N115-1 spot 63	36	14096	2.9	13.4386	±	1.3	1.6819	3.2	0.1640	3.0	0.92	979.0	26.9	1001.7	20.5	1052.7	25.6	93.0
-N115-1 spot 79	290	614076	8.6	13.4368	±	1.0	1.7294	3.9	0.1686	3.8	0.97	1004.4	35.3	1019.5	25.3	1053.0	20.7	95.4
-N115-1 spot 71	28	62257	2.8	13.4235	±	1.3	1.7240	2.8	0.1679	2.4	0.88	1000.6	22.5	1017.5	17.8	1055.0	26.4	94.8
-N115-1 spot 73	53	19392	6.6	13.4187	±	1.4	1.7472	3.0	0.1701	2.7	0.89	1012.8	25.5	1026.1	19.7	1055.7	27.9	95.9
-N115-1 spot 64	19	16848	4.0	13.4178	±	1.8	1.7102	3.8	0.1665	3.4	0.89	992.8	31.0	1012.3	24.4	1055.8	35.3	94.0
-N115-1 spot 99	49	52527	5.2	13.4154	±	1.4	1.6813	3.1	0.1637	2.8	0.89	977.1	25.1	1001.5	19.9	1056.2	29.0	92.5
-N115-1 spot 49	33	6997	3.1	13.4136	±	1.3	1.6707	3.3	0.1626	3.0	0.92	971.2	27.3	997.4	21.0	1056.5	26.7	91.9
-N115-1 spot 15	28	26447	4.1	13.3931	±	1.4	1.6708	2.6	0.1624	2.1	0.84	969.9	19.4	997.5	16.2	1059.5	27.8	91.5
-N115-1 spot 41	36	14937	4.4	13.3705	±	1.7	1.7612	3.2	0.1709	2.7	0.85	1016.9	25.7	1031.3	20.9	1062.9	34.5	95.7
-N115-1 spot 30	43	11191	5.1	13.3416	±	1.3	1.7335	4.0	0.1678	3.8	0.95	1000.1	34.9	1021.1	25.6	1067.3	25.6	93.7
-N115-1 spot 69	35	8622	4.6	13.3130	±	1.2	1.7603	3.1	0.1700	2.8	0.92	1012.3	26.4	1030.9	19.9	1071.6	24.2	94.5
-N115-1 spot 62	37	10316	4.4	13.2937	±	1.2	1.7035	3.7	0.1643	3.5	0.95	980.7	31.9	1009.8	23.7	1074.5	23.5	91.3
-N115-1 spot 82	24	129444	2.7	13.2904	±	1.5	1.8424	2.6	0.1777	2.1	0.82	1054.2	20.7	1060.7	17.1	1075.0	29.7	98.1
-N115-1 spot 3	31	61292	3.1	13.2189	±	1.6	1.7756	3.1	0.1703	2.6	0.85	1013.8	24.4	1036.6	19.9	1085.8	32.4	93.4

Appendix B: LA-ICP-MS Data. Presented in order of analysis

Analysis	U (ppm)	206Pb 204Pb	U/Th	Isotope ratios				Apparent ages (Ma)								Conc (%)				
				206Pb* 207Pb*	±	207Pb* 235U*	±	206Pb* 238U	±	error corr.	206Pb* 238U*	±	207Pb* 235U	±	206Pb* 207Pb*		±	Best age (Ma)	±	
-NJ15-1 spot 40	35	15638		3.0	13.1810	1.3	1.7573	2.4	0.1681	2.1	0.85	1001.4	19.4	1029.9	15.8	1091.5	25.6	1091.5	25.6	91.7
-NJ15-1 spot 92	29	43304		3.0	13.1781	1.7	1.7232	3.9	0.1648	3.5	0.90	983.2	32.2	1017.2	25.3	1092.0	34.6	1092.0	34.6	90.0
-NJ15-1 spot 46	17	7595		3.3	13.1121	1.6	1.7117	3.3	0.1628	2.9	0.87	972.6	26.1	1012.9	21.2	1102.1	32.1	1102.1	32.1	88.3
-NJ15-1 spot 106	29	93079		3.9	13.1072	1.3	1.7482	3.3	0.1663	3.0	0.92	991.5	27.7	1026.5	21.1	1102.8	25.6	1102.8	25.6	89.9
-NJ15-1 spot 85	38	37789		4.2	13.0070	1.2	1.7648	2.8	0.1666	2.5	0.91	993.1	23.4	1032.6	18.1	1118.1	23.0	1118.1	23.0	88.8

T (C)	SiO2	TiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	moles SiO moles TiO moles Al2 moles Fe2 moles Mg moles Ca moles Na moles K2(S moles	X SiO2	X TiO2	X Al2O3	X Fe2O3								
1250	62.88	1.67	13.65	1.54	0.95	4.01	2.87	3.53	1.05	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.39	0.75	0.02	0.1	0.01
1225	62.88	1.67	13.65	1.55	0.95	4.01	2.87	3.53	1.05	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.39	0.75	0.02	0.1	0.01
1200	62.88	1.67	13.65	1.56	0.95	4.01	2.87	3.53	1.05	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.39	0.75	0.02	0.1	0.01
1175	62.88	1.67	13.65	1.57	0.95	4.01	2.87	3.53	1.05	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.39	0.75	0.02	0.1	0.01
1150	62.88	1.67	13.65	1.58	0.95	4.01	2.87	3.53	1.05	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.39	0.75	0.02	0.1	0.01
1125	62.88	1.67	13.65	1.6	0.95	4.01	2.87	3.53	1.05	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.39	0.75	0.02	0.1	0.01
1100	63.72	1.52	13.78	1.47	0.93	4.04	2.91	3.57	1.06	0.02	0.14	0.01	0.02	0.07	0.05	0.04	1.4	0.76	0.01	0.1	0.01
1075	64.87	1.38	14.05	1.27	0.75	4.08	2.98	3.67	1.08	0.02	0.14	0.01	0.02	0.07	0.05	0.04	1.42	0.76	0.01	0.1	0.01
1050	66.24	1.28	13.97	1.08	0.58	3.99	2.93	3.88	1.1	0.02	0.14	0.01	0.01	0.07	0.05	0.04	1.44	0.77	0.01	0.1	0.01
1025	67.98	1.23	13.42	0.9	0.45	3.79	2.66	4.23	1.13	0.02	0.13	0.01	0.01	0.07	0.04	0.04	1.45	0.78	0.01	0.09	0
1000	69.41	1.2	12.93	0.75	0.35	3.65	2.38	4.55	1.16	0.01	0.13	0	0.01	0.07	0.04	0.05	1.46	0.79	0.01	0.09	0
975	69.88	1.18	12.89	0.61	0.3	3.49	2.09	5.2	1.16	0.01	0.13	0	0.01	0.06	0.03	0.06	1.47	0.79	0.01	0.09	0
950	70.06	1.17	13.04	0.49	0.26	3.25	1.83	5.91	1.17	0.01	0.13	0	0.01	0.06	0.03	0.06	1.47	0.79	0.01	0.09	0
925	70.15	1.01	13.28	0.41	0.21	2.98	1.59	6.53	1.17	0.01	0.13	0	0.01	0.05	0.03	0.07	1.47	0.8	0.01	0.09	0
900	70.13	0.83	13.57	0.37	0.19	2.76	1.52	6.54	1.17	0.01	0.13	0	0	0.05	0.02	0.07	1.46	0.8	0.01	0.09	0
875	70.04	0.68	13.75	0.33	0.16	2.6	1.5	6.46	1.17	0.01	0.13	0	0	0.05	0.02	0.07	1.45	0.8	0.01	0.09	0
850	69.81	0.54	13.88	0.3	0.14	2.49	1.51	6.33	1.16	0.01	0.14	0	0	0.04	0.02	0.07	1.45	0.8	0	0.09	0
825	69.41	0.43	13.99	0.28	0.13	2.43	1.54	6.15	1.16	0.01	0.14	0	0	0.04	0.02	0.07	1.44	0.8	0	0.1	0
800	69	0.32	13.67	0.28	0.11	2.41	1.84	5.79	1.15	0	0.13	0	0	0.04	0.03	0.06	1.43	0.81	0	0.09	0
775	68.37	0.23	12.85	0.29	0.1	2.46	2.52	5.19	1.14	0	0.13	0	0	0.04	0.04	0.06	1.41	0.81	0	0.09	0
750	66.79	0.14	11.91	0.31	0.09	2.67	3.46	4.41	1.11	0	0.12	0	0	0.05	0.06	0.05	1.38	0.8	0	0.08	0

T (C)	SiO2	TiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	moles SiO moles TiO moles Al2 moles Fe2 moles Mg moles Ca moles Na moles K2(S moles				X SiO2	X TiO2	X Al2O3	X Fe2O3					
1250	62.64	1.66	13.6	1.53	0.94	3.99	2.86	3.51	1.04	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.38	0.75	0.02	0.1	0.01
1225	62.64	1.66	13.6	1.54	0.94	3.99	2.86	3.51	1.04	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.38	0.75	0.02	0.1	0.01
1200	62.64	1.66	13.6	1.55	0.94	3.99	2.86	3.51	1.04	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.38	0.75	0.02	0.1	0.01
1175	62.64	1.66	13.6	1.56	0.94	3.99	2.86	3.51	1.04	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.38	0.75	0.02	0.1	0.01
1150	62.64	1.66	13.6	1.58	0.94	3.99	2.86	3.51	1.04	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.38	0.75	0.02	0.1	0.01
1125	62.64	1.66	13.6	1.59	0.94	3.99	2.86	3.51	1.04	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.38	0.75	0.02	0.1	0.01
1100	63.26	1.54	13.7	1.5	0.93	4.03	2.88	3.55	1.05	0.02	0.13	0.01	0.02	0.07	0.05	0.04	1.4	0.75	0.01	0.1	0.01
1075	64.35	1.36	13.89	1.31	0.86	4.1	2.94	3.62	1.07	0.02	0.14	0.01	0.02	0.07	0.05	0.04	1.41	0.76	0.01	0.1	0.01
1050	65.27	1.24	14.12	1.13	0.69	4.16	3.01	3.7	1.09	0.02	0.14	0.01	0.02	0.07	0.05	0.04	1.43	0.76	0.01	0.1	0
1025	66.46	1.16	14	0.96	0.55	4.07	2.95	3.9	1.11	0.01	0.14	0.01	0.01	0.07	0.05	0.04	1.44	0.77	0.01	0.1	0
1000	68.1	1.11	13.51	0.8	0.43	3.78	2.72	4.22	1.13	0.01	0.13	0.01	0.01	0.07	0.04	0.04	1.45	0.78	0.01	0.09	0
975	69.54	1.07	13.07	0.67	0.34	3.5	2.47	4.52	1.16	0.01	0.13	0	0.01	0.06	0.04	0.05	1.46	0.79	0.01	0.09	0
950	70.42	1.04	12.85	0.55	0.28	3.26	2.23	4.93	1.17	0.01	0.13	0	0.01	0.06	0.04	0.05	1.47	0.8	0.01	0.09	0
925	70.56	0.92	12.95	0.46	0.23	3.04	2.02	5.55	1.17	0.01	0.13	0	0.01	0.05	0.03	0.06	1.47	0.8	0.01	0.09	0
900	70.52	0.8	13.19	0.39	0.2	2.77	1.81	6.11	1.17	0.01	0.13	0	0	0.05	0.03	0.06	1.46	0.8	0.01	0.09	0
875	70.35	0.67	13.46	0.34	0.16	2.57	1.68	6.39	1.17	0.01	0.13	0	0	0.05	0.03	0.07	1.46	0.8	0.01	0.09	0
850	70.1	0.54	13.64	0.31	0.14	2.47	1.66	6.28	1.17	0.01	0.13	0	0	0.04	0.03	0.07	1.45	0.8	0	0.09	0
825	69.68	0.43	13.78	0.28	0.13	2.4	1.68	6.12	1.16	0.01	0.14	0	0	0.04	0.03	0.06	1.44	0.81	0	0.09	0
800	69.15	0.33	13.71	0.27	0.11	2.39	1.84	5.84	1.15	0	0.13	0	0	0.04	0.03	0.06	1.43	0.81	0	0.09	0
775	68.56	0.23	12.89	0.28	0.1	2.43	2.53	5.24	1.14	0	0.13	0	0	0.04	0.04	0.06	1.41	0.81	0	0.09	0
750	67.08	0.15	11.95	0.31	0.09	2.62	3.47	4.47	1.12	0	0.12	0	0	0.05	0.06	0.05	1.39	0.8	0	0.08	0

	X MgO	X CaO	X Na2O	X K2O	moles Si	moles Ti	moles Al	moles Fe	moles Mg	moles Ca	moles Na	moles K	S moles α	X Si	X Ti	X Al	X Fe	X Mg	X Ca	X Na	X K	M
	0.02	0.05	0.03	0.03	0.75	0.02	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.02	0.05	0.03	0.03	0.75	0.02	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.02	0.05	0.03	0.03	0.75	0.02	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.02	0.05	0.03	0.03	0.75	0.02	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.02	0.05	0.03	0.03	0.75	0.02	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.02	0.05	0.03	0.03	0.75	0.02	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.02	0.05	0.03	0.03	0.75	0.01	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.02	0.05	0.03	0.03	0.76	0.01	0.19	0.01	0.02	0.05	0.07	0.05	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.01	0.05	0.03	0.03	0.76	0.01	0.19	0.01	0.01	0.05	0.07	0.06	1.16	0.65	0.01	0.17	0.01	0.01	0.04	0.06	0.05	1.79
	0.01	0.05	0.03	0.03	0.77	0.01	0.19	0.01	0.01	0.05	0.07	0.06	1.16	0.66	0.01	0.16	0.01	0.01	0.04	0.06	0.05	1.78
	0.01	0.05	0.03	0.03	0.78	0.01	0.18	0.01	0.01	0.05	0.06	0.06	1.16	0.68	0.01	0.16	0.01	0.01	0.04	0.05	0.05	1.74
	0.01	0.04	0.03	0.03	0.79	0.01	0.18	0.01	0.01	0.04	0.05	0.07	1.15	0.69	0.01	0.15	0	0.01	0.04	0.05	0.06	1.7
	0	0.04	0.02	0.04	0.8	0.01	0.17	0	0	0.04	0.05	0.07	1.15	0.7	0.01	0.15	0	0	0.03	0.04	0.06	1.67
	0	0.04	0.02	0.04	0.8	0.01	0.17	0	0	0.04	0.04	0.08	1.15	0.7	0.01	0.15	0	0	0.03	0.04	0.07	1.65
	0	0.03	0.02	0.04	0.8	0.01	0.18	0	0	0.03	0.04	0.09	1.15	0.69	0.01	0.15	0	0	0.03	0.03	0.08	1.6
	0	0.03	0.02	0.05	0.8	0.01	0.18	0	0	0.03	0.04	0.09	1.16	0.69	0	0.16	0	0	0.03	0.03	0.08	1.54
	0	0.03	0.02	0.05	0.8	0	0.18	0	0	0.03	0.04	0.09	1.16	0.69	0	0.16	0	0	0.03	0.03	0.08	1.48
	0	0.03	0.02	0.05	0.81	0	0.19	0	0	0.03	0.04	0.09	1.16	0.69	0	0.16	0	0	0.03	0.03	0.08	1.44
	0	0.03	0.02	0.04	0.81	0	0.19	0	0	0.03	0.04	0.09	1.16	0.69	0	0.16	0	0	0.03	0.04	0.07	1.44
	0	0.03	0.03	0.04	0.81	0	0.18	0	0	0.03	0.06	0.08	1.16	0.7	0	0.15	0	0	0.03	0.05	0.07	1.59
	0	0.03	0.04	0.03	0.8	0	0.17	0	0	0.03	0.08	0.07	1.16	0.69	0	0.15	0	0	0.03	0.07	0.06	1.85

T (C)	SiO2	TiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	moles SiO2 moles TiO2 moles Al2O3 moles Fe2O3 moles MgO moles CaO moles Na2O moles K2O 5 moles										X SiO2	X TiO2	X Al2O3	X Fe2O3	X MgO	X CaO	X Na2O
1375	5925	2.23	14.74	1.57	1.7	5.63	2.92	3.34	0.99	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.39	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1350	5933	2.23	14.75	1.57	1.7	5.57	2.93	3.34	0.99	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.39	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1325	5941	2.24	14.78	1.58	1.71	5.5	2.93	3.35	0.99	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.39	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1300	5948	2.24	14.79	1.58	1.71	5.44	2.93	3.35	0.99	0.03	0.15	0.01	0.04	0.1	0.05	0.04	1.4	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1275	5954	2.24	14.81	1.58	1.71	5.39	2.94	3.36	0.99	0.03	0.15	0.01	0.04	0.1	0.05	0.04	1.4	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1250	596	2.24	14.82	1.59	1.71	5.35	2.94	3.36	0.99	0.03	0.15	0.01	0.04	0.1	0.05	0.04	1.4	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1225	5964	2.24	14.83	1.6	1.71	5.32	2.94	3.36	0.99	0.03	0.15	0.01	0.04	0.09	0.05	0.04	1.4	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1200	5967	2.25	14.84	1.61	1.71	5.29	2.94	3.36	0.99	0.03	0.15	0.01	0.04	0.09	0.05	0.04	1.4	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1175	5969	2.25	14.85	1.62	1.71	5.27	2.94	3.37	0.99	0.03	0.15	0.01	0.04	0.09	0.05	0.04	1.4	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1150	5975	2.26	14.89	1.62	1.65	5.26	2.96	3.38	0.99	0.03	0.15	0.01	0.04	0.09	0.05	0.04	1.4	0.71	0.02	0.1	0.01	0.03	0.07	0.03	
1125	6012	2.32	15.13	1.57	1.28	5.23	3.02	3.49	1	0.03	0.15	0.01	0.03	0.09	0.05	0.04	1.4	0.72	0.02	0.11	0.01	0.02	0.07	0.03	
1100	6298	2.3	14.36	1.28	0.93	4.91	2.72	4.13	1.05	0.03	0.14	0.01	0.02	0.09	0.04	0.04	1.42	0.74	0.02	0.1	0.01	0.02	0.06	0.03	
1075	652	2.31	13.74	1.04	0.7	4.69	2.36	4.67	1.09	0.03	0.13	0.01	0.02	0.08	0.04	0.05	1.44	0.75	0.02	0.09	0	0.01	0.06	0.03	
1050	6693	2.34	13.24	0.84	0.54	4.51	2.01	5.12	1.11	0.03	0.13	0.01	0.01	0.08	0.03	0.05	1.46	0.76	0.02	0.09	0	0.01	0.06	0.02	
1025	6856	2.04	12.85	0.71	0.38	4.27	1.7	5.55	1.14	0.03	0.13	0	0.01	0.08	0.03	0.06	1.47	0.78	0.02	0.09	0	0.01	0.05	0.02	
1000	6879	1.84	13.35	0.56	0.3	3.87	1.31	6.58	1.14	0.02	0.13	0	0.01	0.07	0.02	0.07	1.47	0.78	0.02	0.09	0	0	0.05	0.01	
975	6862	1.59	13.97	0.47	0.25	3.64	1.03	7.03	1.14	0.02	0.14	0	0.01	0.06	0.02	0.07	1.46	0.78	0.01	0.09	0	0	0.04	0.01	
950	6863	1.32	14.37	0.41	0.22	3.44	0.91	7.05	1.14	0.02	0.14	0	0.01	0.06	0.01	0.07	1.46	0.78	0.01	0.1	0	0	0.04	0.01	
925	6906	1.08	14.56	0.37	0.2	3.07	0.93	6.99	1.15	0.01	0.14	0	0	0.05	0.02	0.07	1.46	0.79	0.01	0.1	0	0	0.04	0.01	
900	6926	0.88	14.68	0.34	0.18	2.81	0.96	6.89	1.15	0.01	0.14	0	0	0.05	0.02	0.07	1.45	0.79	0.01	0.1	0	0	0.03	0.01	
875	6928	0.71	14.72	0.31	0.16	2.65	1.00	6.74	1.15	0.01	0.14	0	0	0.05	0.02	0.07	1.45	0.8	0.01	0.1	0	0	0.03	0.01	
850	6918	0.57	14.76	0.29	0.14	2.53	1.06	6.58	1.15	0.01	0.14	0	0	0.05	0.02	0.07	1.44	0.8	0	0.1	0	0	0.03	0.01	
825	6912	0.44	14.39	0.27	0.12	2.45	1.32	6.27	1.15	0.01	0.14	0	0	0.04	0.02	0.07	1.43	0.8	0	0.1	0	0	0.03	0.01	
800	6897	0.32	13.66	0.28	0.11	2.42	1.84	5.78	1.15	0	0.13	0	0	0.04	0.03	0.06	1.42	0.81	0	0.09	0	0	0.03	0.02	
775	6832	0.23	12.92	0.28	0.10	2.46	2.47	5.21	1.14	0	0.13	0	0	0.04	0.04	0.06	1.41	0.81	0	0.09	0	0	0.03	0.03	
750	6663	0.15	12.26	0.28	0.10	2.68	3.21	4.51	1.11	0	0.12	0	0	0.05	0.05	0.05	1.38	0.8	0	0.09	0	0	0.03	0.04	

T (C)	SiO2	TiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	moles SiO2 moles TiO2 moles Al2O3 moles Fe2O3 moles MgO moles CaO moles Na2O moles K2O 5 moles										X SiO2	X TiO2	X Al2O3	X Fe2O3	X MgO	X CaO	X Na2O	X K2O
1375	5872	2.21	14.6	1.55	1.69	5.58	2.9	3.31	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1350	5872	2.21	14.6	1.55	1.69	5.58	2.9	3.31	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1325	5872	2.21	14.6	1.56	1.69	5.58	2.9	3.31	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1300	5872	2.21	14.6	1.56	1.69	5.58	2.9	3.31	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1275	5872	2.21	14.6	1.57	1.69	5.58	2.9	3.31	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1250	5878	2.21	14.62	1.57	1.69	5.53	2.9	3.31	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1225	5883	2.21	14.63	1.58	1.69	5.49	2.9	3.32	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1200	5886	2.22	14.64	1.59	1.69	5.46	2.9	3.32	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1175	5889	2.22	14.65	1.6	1.69	5.44	2.91	3.32	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1150	589	2.22	14.65	1.61	1.69	5.43	2.91	3.32	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1125	5891	2.22	14.65	1.63	1.69	5.42	2.91	3.32	0.98	0.03	0.14	0.01	0.04	0.1	0.05	0.04	1.38	0.71	0.02	0.1	0.01	0.03	0.07	0.03		
1100	5993	2.07	14.98	1.45	1.4	5.48	2.99	3.43	1	0.03	0.15	0.01	0.03	0.1	0.05	0.04	1.4	0.71	0.02	0.11	0.01	0.02	0.07	0.03		
1075	6107	1.92	15.36	1.25	1.12	5.48	3.1	3.54	1.02	0.02	0.15	0.01	0.03	0.1	0.05	0.04	1.41	0.72	0.02	0.11	0.01	0.02	0.06	0.04		
1050	6286	1.81	15.03	1.04	0.88	5.12	3.02	3.9	1.05	0.02	0.15	0.01	0.02	0.09	0.05	0.04	1.43	0.73	0.02	0.1	0	0.02	0.06	0.03		
1025	6475	1.74	14.62	0.85	0.7	4.6	2.83	4.32	1.08	0.02	0.14	0.01	0.02	0.08	0.05	0.05	1.44	0.75	0.02	0.1	0	0.01	0.06	0.03		
1000	6637	1.48	14.28	0.73	0.54	4.13	2.62	4.72	1.1	0.02	0.14	0	0.01	0.07	0.04	0.05	1.45	0.76	0.01	0.1	0	0.01	0.05	0.03		
975	6771	1.27	14	0.62	0.42	3.73	2.39	5.09	1.13	0.02	0.14	0	0.01	0.07	0.04	0.05	1.45	0.78	0.01	0.09	0	0.01	0.05	0.03		
950	6883	1.1	13.78	0.53	0.33	3.39	2.14	5.42	1.15	0.01	0.14	0	0.01	0.06	0.03	0.06	1.46	0.79	0.01	0.09	0	0.01	0.04	0.02		
925	6975	0.95	13.6	0.45	0.25	3.09	1.89	5.72	1.16	0.01	0.13	0	0.01	0.06	0.03	0.06	1.46	0.79	0.01	0.09	0	0	0.04	0.02		
900	7035	0.82	13.55	0.38	0.2	2.83	1.66	6.05	1.17	0.01	0.13	0	0	0.05	0.03	0.06	1.46	0.8	0.01	0.09	0	0	0.03	0.02		
875	7015	0.7	13.88	0.32	0.16	2.57	1.46	6.57	1.17	0.01	0.14	0	0	0.05	0.02	0.07	1.46	0.8	0.01	0.09	0	0	0.03	0.02		
850	6993	0.57	14.07	0.29	0.14	2.46	1.44	6.45	1.16	0.01	0.14	0	0	0.04	0.02	0.07	1.45	0.8	0	0.1	0	0	0.03	0.02		
825	6955	0.45	14.23	0.27	0.13	2.4	1.45	6.3	1.16	0.01	0.14	0	0	0.04	0.02	0.07	1.44	0.8	0	0.1	0	0	0.03	0.02		
800	6928	0.33	13.74	0.27	0.11	2.37	1.84	5.89	1.15	0	0.13	0	0	0.04	0.03	0.06	1.43	0.81	0	0.09	0	0	0.03	0.02		
775	6873	0.23	12.94	0.28	0.1	2.4	2.52	5.3	1.14	0	0.13	0	0	0.04	0.04	0.06	1.42	0.81	0	0.09	0	0	0.03	0.03		
750	6725	0.16	12.39	0.27	0.1	2.58	3.21	4.66	1.12	0	0.12	0	0	0.05	0.05	0.05	1.39	0.8	0	0.09	0	0	0.03	0.04		

[illegible]

T (C)	SiO2	TiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	moles SiO2 moles	TiO2 moles	Al2O3 moles	Fe2O3 moles	MgO moles	CaO moles	Na2O moles	K2O moles	X SiO2	X TiO2	X Al2O3	X Fe2O3
1150	67.99	0.76	13.92	0.87	0.7	2.76	3.21	5.63	1.13	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.46	0.77	0.01	0.09
1125	67.99	0.76	13.92	0.88	0.7	2.76	3.21	5.63	1.13	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.46	0.77	0.01	0.09
1100	67.99	0.76	13.92	0.88	0.7	2.76	3.21	5.63	1.13	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.46	0.77	0.01	0.09
1075	67.99	0.76	13.92	0.9	0.7	2.76	3.21	5.63	1.13	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.46	0.77	0.01	0.09
1050	68.47	0.8	13.69	0.88	0.51	2.7	3.08	5.84	1.14	0.01	0.13	0.01	0.01	0.05	0.05	0.06	1.46	0.78	0.01	0.09
1025	69.52	0.91	13.11	0.81	0.34	2.6	2.74	6.19	1.16	0.01	0.13	0.01	0.01	0.05	0.04	0.07	1.47	0.79	0.01	0.09
1000	70.6	1.03	12.48	0.73	0.24	2.67	2.4	6.26	1.18	0.01	0.12	0	0.01	0.05	0.04	0.07	1.47	0.8	0.01	0.08
975	71.24	1.06	12.17	0.59	0.23	2.93	2.18	6.28	1.19	0.01	0.12	0	0.01	0.05	0.04	0.07	1.48	0.8	0.01	0.08
950	70.93	1.06	12.37	0.5	0.23	2.93	2.08	6.31	1.18	0.01	0.12	0	0.01	0.05	0.03	0.07	1.48	0.8	0.01	0.08
925	70.62	1.01	12.5	0.43	0.22	2.93	2.03	6.28	1.18	0.01	0.12	0	0.01	0.05	0.03	0.07	1.47	0.8	0.01	0.08
900	70.76	0.76	12.58	0.4	0.19	2.71	2.08	6.17	1.18	0.01	0.12	0	0	0.05	0.03	0.07	1.47	0.8	0.01	0.08
875	70.72	0.61	12.58	0.37	0.17	2.56	2.16	6.02	1.18	0.01	0.12	0	0	0.05	0.03	0.06	1.46	0.81	0.01	0.08
850	70.52	0.49	12.55	0.34	0.15	2.45	2.26	5.84	1.17	0.01	0.12	0	0	0.04	0.04	0.06	1.45	0.81	0	0.08
825	70.12	0.38	12.5	0.32	0.13	2.39	2.4	5.61	1.17	0	0.12	0	0	0.04	0.04	0.06	1.44	0.81	0	0.09
800	69.44	0.29	12.42	0.31	0.12	2.39	2.58	5.33	1.16	0	0.12	0	0	0.04	0.04	0.06	1.43	0.81	0	0.09
775	68.31	0.21	12.31	0.31	0.1	2.48	2.84	4.95	1.14	0	0.12	0	0	0.04	0.05	0.05	1.41	0.81	0	0.09
750	66.35	0.14	11.86	0.32	0.09	2.73	3.43	4.32	1.1	0	0.12	0	0	0.05	0.06	0.05	1.38	0.8	0	0.08

T (C)	SiO2	TiO2	Al2O3	Fe2O3	MgO	CaO	Na2O	K2O	moles SiO2 moles	TiO2 moles	Al2O3 moles	Fe2O3 moles	MgO moles	CaO moles	Na2O moles	K2O moles	X SiO2	X TiO2	X Al2O3	X Fe2O3
1150	67.56	0.76	13.83	0.86	0.7	2.74	3.19	5.6	1.12	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.45	0.77	0.01	0.09
1125	67.56	0.76	13.83	0.87	0.7	2.74	3.19	5.6	1.12	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.45	0.77	0.01	0.09
1100	67.56	0.76	13.83	0.88	0.7	2.74	3.19	5.6	1.12	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.45	0.77	0.01	0.09
1075	67.56	0.76	13.83	0.89	0.7	2.74	3.19	5.6	1.12	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.45	0.77	0.01	0.09
1050	67.56	0.76	13.83	0.9	0.7	2.74	3.19	5.6	1.12	0.01	0.14	0.01	0.02	0.05	0.05	0.06	1.45	0.77	0.01	0.09
1025	67.77	0.77	13.97	0.85	0.5	2.76	3.23	5.67	1.13	0.01	0.14	0.01	0.01	0.05	0.05	0.06	1.45	0.78	0.01	0.09
1000	68.5	0.82	13.66	0.79	0.35	2.6	3.06	5.96	1.14	0.01	0.13	0	0.01	0.05	0.05	0.06	1.46	0.78	0.01	0.09
975	69.81	0.79	13.14	0.63	0.29	2.51	2.77	6.29	1.16	0.01	0.13	0	0.01	0.04	0.04	0.07	1.47	0.79	0.01	0.09
950	70.9	0.8	12.59	0.54	0.23	2.53	2.52	6.33	1.18	0.01	0.12	0	0.01	0.05	0.04	0.07	1.48	0.8	0.01	0.08
925	71.78	0.8	12.23	0.46	0.2	2.45	2.36	6.16	1.19	0.01	0.12	0	0	0.04	0.04	0.07	1.48	0.81	0.01	0.08
900	71.57	0.74	12.35	0.4	0.19	2.39	2.34	6.11	1.19	0.01	0.12	0	0	0.04	0.04	0.06	1.47	0.81	0.01	0.08
875	71.32	0.62	12.4	0.37	0.17	2.37	2.36	6	1.19	0.01	0.12	0	0	0.04	0.04	0.06	1.47	0.81	0.01	0.08
850	70.95	0.49	12.41	0.34	0.15	2.38	2.42	5.85	1.18	0.01	0.12	0	0	0.04	0.04	0.06	1.46	0.81	0	0.08
825	70.53	0.39	12.42	0.32	0.13	2.34	2.52	5.66	1.17	0	0.12	0	0	0.04	0.04	0.06	1.45	0.81	0	0.08
800	69.89	0.3	12.41	0.3	0.11	2.33	2.67	5.41	1.16	0	0.12	0	0	0.04	0.04	0.06	1.44	0.81	0	0.08
775	68.86	0.22	12.38	0.29	0.1	2.4	2.88	5.08	1.15	0	0.12	0	0	0.04	0.05	0.05	1.42	0.81	0	0.09
750	67.18	0.15	11.96	0.31	0.09	2.6	3.48	4.49	1.12	0	0.12	0	0	0.05	0.06	0.05	1.39	0.8	0	0.08

X MgO	X CaO	X Na2O	X K2O	moles Si	moles Ti	moles Al	moles Fe	moles Mg	moles Ca	moles Na	moles K	S moles cal	X si	X ti	X al	X fe	X mg	X ca	X na	X k	M
0.01	0.03	0.04	0.04	0.77	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.04	0.04	0.77	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.04	0.04	0.77	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.03	0.04	0.78	0.01	0.18	0.01	0.01	0.03	0.07	0.08	1.17	0.67	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.03	0.04	0.79	0.01	0.18	0.01	0.01	0.03	0.06	0.09	1.17	0.68	0.01	0.15	0.01	0	0.03	0.05	0.08	1.8
0	0.03	0.03	0.05	0.8	0.01	0.17	0.01	0	0.03	0.05	0.09	1.16	0.69	0.01	0.14	0.01	0	0.03	0.05	0.08	1.81
0	0.04	0.02	0.05	0.8	0.01	0.16	0	0	0.04	0.05	0.09	1.15	0.69	0.01	0.14	0	0	0.03	0.04	0.08	1.86
0	0.04	0.02	0.05	0.8	0.01	0.16	0	0	0.04	0.05	0.09	1.15	0.69	0.01	0.14	0	0	0.03	0.04	0.08	1.81
0	0.04	0.02	0.05	0.8	0.01	0.17	0	0	0.04	0.04	0.09	1.15	0.69	0.01	0.14	0	0	0.03	0.04	0.08	1.78
0	0.03	0.02	0.04	0.8	0.01	0.17	0	0	0.03	0.05	0.09	1.15	0.7	0.01	0.15	0	0	0.03	0.04	0.08	1.71
0	0.03	0.02	0.04	0.81	0.01	0.17	0	0	0.03	0.05	0.09	1.15	0.7	0	0.15	0	0	0.03	0.04	0.08	1.67
0	0.03	0.03	0.04	0.81	0	0.17	0	0	0.03	0.05	0.09	1.15	0.7	0	0.15	0	0	0.03	0.05	0.07	1.65
0	0.03	0.03	0.04	0.81	0	0.17	0	0	0.03	0.06	0.08	1.16	0.7	0	0.15	0	0	0.03	0.05	0.07	1.65
0	0.03	0.03	0.04	0.81	0	0.17	0	0	0.03	0.07	0.07	1.16	0.7	0	0.15	0	0	0.03	0.06	0.06	1.69
0	0.04	0.04	0.03	0.8	0	0.17	0	0	0.04	0.08	0.07	1.16	0.69	0	0.15	0	0	0.03	0.07	0.06	1.86

X MgO	X CaO	X Na2O	X K2O	moles Si	moles Ti	moles Al	moles Fe	moles Mg	moles Ca	moles Na	moles K	S moles cal	X si	X ti	X al	X fe	X mg	X ca	X na	X k	M
0.01	0.03	0.04	0.04	0.77	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.04	0.04	0.77	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.04	0.04	0.77	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.04	0.04	0.77	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.04	0.04	0.78	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.17	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.79
0.01	0.03	0.04	0.04	0.78	0.01	0.19	0.01	0.01	0.03	0.07	0.08	1.18	0.66	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.78
0.01	0.03	0.03	0.04	0.78	0.01	0.18	0.01	0.01	0.03	0.07	0.09	1.17	0.67	0.01	0.16	0.01	0.01	0.03	0.06	0.07	1.78
0	0.03	0.03	0.05	0.79	0.01	0.18	0.01	0	0.03	0.06	0.09	1.17	0.68	0.01	0.15	0	0	0.03	0.05	0.08	1.79
0	0.03	0.03	0.05	0.8	0.01	0.17	0	0	0.03	0.06	0.09	1.16	0.69	0.01	0.14	0	0	0.03	0.05	0.08	1.79
0	0.03	0.03	0.04	0.81	0.01	0.16	0	0	0.03	0.05	0.09	1.15	0.7	0.01	0.14	0	0	0.03	0.04	0.08	1.75
0	0.03	0.03	0.04	0.81	0.01	0.16	0	0	0.03	0.05	0.09	1.15	0.7	0.01	0.14	0	0	0.03	0.04	0.08	1.71
0	0.03	0.03	0.04	0.81	0.01	0.17	0	0	0.03	0.05	0.09	1.15	0.7	0	0.14	0	0	0.02	0.05	0.08	1.69
0	0.03	0.03	0.04	0.81	0	0.17	0	0	0.03	0.05	0.09	1.15	0.7	0	0.14	0	0	0.03	0.05	0.07	1.68
0	0.03	0.03	0.04	0.81	0	0.17	0	0	0.03	0.06	0.08	1.16	0.7	0	0.15	0	0	0.02	0.05	0.07	1.66
0	0.03	0.03	0.04	0.81	0	0.17	0	0	0.03	0.06	0.08	1.16	0.7	0	0.15	0	0	0.02	0.05	0.07	1.66
0	0.03	0.03	0.04	0.81	0	0.17	0	0	0.03	0.07	0.08	1.16	0.7	0	0.15	0	0	0.03	0.06	0.07	1.69
0	0.03	0.04	0.03	0.8	0	0.17	0	0	0.03	0.08	0.07	1.16	0.69	0	0.15	0	0	0.03	0.07	0.06	1.85

Appendix D: SHRIIMP-RG Trace Element Data. Presented in order of analysis.

Spot Name	Date/Time	Hours	Total 46	ctb/sec	Total 196	ctb/sec	48/46	% err	48/49	% err	56/46	% err	59/46	% err	63/46	% err	139/46	% err	146/46	% err	147/46	% err
MADDER-1.1	2017-02-09	0	42807		1.50E+05	0.02754	4.36	14.85	4.73	0.03185	1.6	1.705	0.46	0.0000146	45	0.01732	2.62	0.000383	11	0.000825	7.53	
MADDER-2.1	2017-02-09	0.25	42300		1.40E+05	0.02818	4.4	13.79	4.51	0.02981	1.66	1.734	0.46	0.00002069	38	0.01936	2.48	0.000482	9.91	0.000888	7.31	
MADDER-2.2	2017-02-09	0.383	42391		1.40E+05	0.02841	4.62	15.31	4.71	0.03001	1.65	1.71	0.46	0.00000295	100	0.01777	2.56	0.000537	7.42	0.000167	13	
MADDER-2.3	2017-02-09	0.5	41176		1.40E+05	0.02961	4.23	13	4.33	0.02947	1.69	1.737	0.46	0	100	0.01882	2.56	0.00053	7.58	0.000162	14	
MADDER-2.4	2017-02-09	0.617	40431		1.40E+05	0.02888	4.9	16.73	4.99	0.02776	1.76	1.759	0.47	0.00000928	58	0.02023	2.5	0.000484	8	0.00135	4.8	
MADDER-3.2	2017-02-10	22.08	34815		121387	0.0275	4.93	13.88	5.05	0.02905	1.85	1.329	0.54	0	100	0.01813	2.84	0.00047	8.75	0.001448	4.99	
MADDER-3.3	2017-02-10	22.22	33292		118329	0.0277	5.38	15.92	5.49	0.02962	1.88	1.164	0.57	0.00000375	100	0.01732	2.97	0.00043	9.36	0.001509	5	
MADDER-4.1	2017-02-10	22.33	34375		120542	0.0278	5.11	14.86	5.22	0.02585	1.97	1.65	0.51	0.00001212	55	0.01802	2.87	0.00055	8.14	0.001516	4.91	
MADDER-4.2	2017-02-10	22.45	34501		120411	0.0269	4.67	12.09	4.8	0.02776	1.9	1.685	0.51	0	100	0.01712	2.93	0.000403	9.49	0.001365	5.17	
MADDER-4.3	2017-02-10	22.68	33167		118536	0.0284	4.86	13.43	4.97	0.03332	1.39	1.666	0.51	0.00001789	45	0.01826	2.83	0.000461	8.82	0.001444	4.99	
MADDER-3.1	2017-02-10	0.75	42155		1.40E+05	0.02698	5.04	14.27	5.15	0.02556	2.02	1.76	0.51	0.00000377	100	0.01887	2.85	0.000519	8.53	0.001662	4.78	
NIJ5-1-1.1	2017-02-09	2.25	39983		7.50E+04	0.0922	4.57	14.16	4.67	0.02515	1.81	1.673	0.46	0.0000089	58	0.01753	2.62	0.000306	9.84	0.001328	4.74	
NIJ5-1-1.2	2017-02-09	2.117	39345		7.20E+04	0.12633	2.16	13.6	2.49	0.03757	1.53	2.06	0.45	0.00002084	39	0.04416	1.72	0.000521	7.75	0.001459	4.64	
NIJ5-1-2.2	2017-02-09	2.367	39449		6.90E+04	0.13502	2.07	13.41	2.09	0.02319	1.93	6.073	0.39	0.00015685	14	0.05841	1.69	0.000817	6.25	0.002014	3.99	
NIJ5-1-2.2	2017-02-09	2.483	39425		8.70E+04	0.0176	5.76	13.78	5.91	0.17143	0.79	1.296	0.51	0.00000951	58	0.02877	2.13	0.000235	12	0.000554	8.7	
NIJ5-1-3.2	2017-02-09	2.6	38105		8.60E+04	0.06543	4.39	13.18	3.05	0.01454	2.48	4.747	0.41	3.30E-06	100	0.04621	1.72	0.00179	4.29	0.004755	2.65	
NIJ5-1-3.2	2017-02-09	2.717	39508		9.50E+04	0.0305	4.34	13.53	4.44	0.03413	1.61	1.082	0.53	8.50E-06	58	0.03154	2.03	0.000278	11	0.000471	8.2	
NIJ5-1-4.1	2017-02-09	2.833	38770		71035	0.1841	4.11	13.51	1.82	0.01489	2.43	1.702	0.48	1.60E-05	45	0.02761	2.19	0.000642	7.1	0.001354	4.89	
NIJ5-1-4.2	2017-02-09	2.95	39351		88558	0.04414	3.64	13.65	3.72	0.06828	1.26	2.032	0.43	3.20E-06	100	0.0693	1.51	0.000971	5.73	0.003351	3.69	
NIJ5-1-1.2	2017-02-09	3.083	38779		91545	0.14372	2.07	13.84	2.09	0.03409	1.63	1.405	0.49	3.20E-06	100	0.01482	2.97	0.000498	8.05	0.001322	4.95	
NIJ5-1-1.1	2017-02-09	3.2	38047		81879	0.28827	1.48	13.94	1.48	0.01005	2.94	2.056	0.46	2.90E-05	33	0.0138	3.38	0.00118	5.23	0.002343	3.8	
NIJ5-1-1.1	2017-02-09	3.317	38850		91211	0.08492	2.62	13.35	2.67	0.02752	1.18	2.286	0.45	6.40E-06	71	0.02533	2.28	0.000911	5.96	0.003146	3.89	
NIJ5-1-2.2	2017-02-09	3.433	37802		87114	0.12363	2.28	14.21	2.31	0.04634	1.43	1.64	0.49	1.30E-05	50	0.01499	2.59	0.000975	7.01	0.002101	5.26	
NIJ5-1-3.1	2017-02-09	3.35	39040		82044	0.14742	1.83	13.15	1.84	0.06843	1.06	4.321	0.41	5.10E-05	25	0.01466	2.98	0.003157	3.2	0.006889	2.17	
NIJ5-1-3.2	2017-02-09	3.667	37653		84272	0.06851	2.66	13.82	2.71	0.05874	1.28	11.52	0.34	1.00E-05	58	0.01148	3.42	0.000325	10	0.000819	6.38	
NIJ5-1-4.1	2017-02-09	3.783	38460		78135	0.30441	1.45	13.83	1.44	0.05548	1.3	1.729	0.48	4.80E-05	27	0.01141	3.39	0.0009	6.02	0.0019	4.15	
NIJ5-1-4.2	2017-02-09	3.9	38591		86994	0.11849	2.27	13.75	2.3	0.03736	1.56	1.405	0.5	0	100	0.01953	3.07	0.00035	9.63	0.001029	5.62	
NIJ5-2-1.1	2017-02-09	4.017	39319		93517	0.0745	2.88	14.31	2.93	0.02744	0.73	5.146	0.45	0.00003179	32	0.06632	4.5	0.000575	7.44	0.001914	4.09	
NIJ5-2-1.2	2017-02-09	4.15	38568		100818	0.12593	2.21	13.82	2.24	0.01512	2.41	2.104	0.46	0.00002593	35	0.02343	2.38	0.000634	7.16	0.001512	4.64	
NIJ5-2-2.2	2017-02-09	4.383	38270		87999	0.11108	2.34	13.58	2.37	0.05666	1.21	1.506	0.45	0.00217207	3.89	0.01823	2.7	0.001252	5.12	0.001325	4.98	
NIJ5-2-3.1	2017-02-09	4.5	38876		94742	0.11848	2.26	13.81	2.3	0.01693	1.28	2.425	0.45	0.00000965	58	0.02034	2.54	0.000772	6.46	0.00209	3.94	
NIJ5-2-3.2	2017-02-09	4.617	38139		91697	0.07399	2.86	13.64	2.92	0.05607	1.21	1.385	0.51	0	100	0.0138	3.1	0.00298	10	0.000714	6.79	
NIJ5-2-4.1	2017-02-09	4.733	37802		89594	0.09988	2.45	13.1	2.49	0.04442	1.23	1.712	0.49	0.00000992	58	0.01872	2.68	0.0005	8.14	0.001437	4.81	
NIJ5-2-4.2	2017-02-09	4.85	38272		85021	0.11299	2.29	13.92	2.32	0.00946	3.1	3.025	0.44	0.00000327	100	0.01208	3.31	0.000334	9.9	0.000849	6.21	
NIJ5-1-5.1	2017-02-09	5.15	37129		67884	0.11402	4.13	14.93	4.22	0.05266	1.33	2.086	0.46	0.00001683	45	0.03263	2.06	0.001182	5.35	0.002761	3.51	
NIJ5-1-5.2	2017-02-09	5.267	38443		88461	0.03825	2.19	13.57	2.72	0.01051	2.87	2.038	0.46	0.00001698	14	0.04486	1.74	0.000676	6.95	0.001359	4.9	
NIJ5-1-6.1	2017-02-09	5.383	39119		81140	0.07796	2.67	12.77	2.72	0.01051	2.87	2.038	0.46	0.00002556	35	0.03842	1.86	0.000668	6.93	0.00125	5.07	
NIJ5-1-6.2	2017-02-09	5.537	37811		101225	0.02138	5.42	14.17	5.55	0.0652	1.22	1.379	0.51	0	100	0.0493	1.68	0.000213	12	0.000544	7.81	
NIJ5-1-7.1	2017-02-09	5.633	39859		76310	0.13497	2.07	13.42	2.1	0.01599	2.31	1.918	0.46	0.00001882	41	0.0366	1.88	0.00061	7.18	0.001429	4.7	
NIJ5-1-7.2	2017-02-09	5.75	38754		86383	0.03844	3.86	13.23	3.95	0.05446	1.31	1.686	0.48	0.00000645	71	0.04456	1.74	0.000326	9.95	0.001061	5.53	
NIJ5-1-8.1	2017-02-09	5.867	38789		77173	0.14871	2	13.34	2.02	0.04894	1.37	2.276	0.45	0.00002864	34	0.04633	1.71	0.000795	6.38	0.001801	4.25	
NIJ5-1-8.2	2017-02-09	5.98	40570		95982	0.0183	5.28	12.37	5.43	0.02801	0.66	1.134	0.52	0.00001232	50	0.02431	2.28	9.24E-05	18	0.000377	9.05	
NIJ5-1-9.1	2017-02-09	8.23	37034		63940	0.1378	1.9	14.02	2.2	0.01232	2.73	4.021	0.42	0.00005525	25	0.03999	1.87	0.004751	2.69	0.0006407	2.32	
NIJ5-1-10.1	2017-02-09	8.35	36833		64468	0.1754	1.9	13.52	1.92	0.00891	3.21	4.454	0.42	0.00002262	39	0.04301	1.81	0.005196	2.58	0.008402	2.04	
NIJ5-1-11.1	2017-02-09	8.47	38455		69392	0.164	1.93	13.6	1.95	0.01077	2.86	4.727	0.41	0.0000195	41	0.0445	1.75	0.003203	3.21	0.006222	2.31	
NIJ5-1-12.1	2017-02-09	8.6	37394		67022	0.1568	1.97	13.24	1.99	0.01417	2.53	5.424	0.41	0.00008171	20	0.05642	1.58	0.005638	2.46	0.008833	1.98	
NIJ5-1-13.1	2017-02-09	8.73	36188		68131	0.1072	2.41	13.24	2.45	0.04185	1.53	1.972	0.42	0.00043753	8.89	0.05263	1.66	0.002636	3.64	0.005575	4.55	
NIJ5-1-14.1	2017-02-09	8.85	38264		69263	0.1886	0.66	0.08101	2.41	0.08158	2.82	1.84	0.48	0.0000196	41	0.03371	2	0.001347	4.94	0.003084	3.27	
NIJ5-1-15.1	2017-02-09	9.07	39023		79592	0.0862	0.71	0.004352	2.62	0.0227	1.97	2.079	0.46	0.00000961	58	0.04241	1.77	0.000687	6.84	0.001445	4.72	
NIJ5-2-5.1	2017-02-09	9.18	38749		94026	0.0686	0.77	0.00458	3	0.06	0.0265	1.56	1.44	0	100	0.000157	45	0.0000157	6.99	0.001355	4.89	
NIJ5-2-5.1	2017-02-09	9.32	39808		95406	0.078	2.72	13.58	2.77	0.03645	1.84	2.446	0.51	0.0000157	45	0.01406	3.01	0.000244	11	0.00059	7.31	
NIJ5-2-6.1	2017-02-09	9.43	38659		85390	0.1435	2.06	13.17	2.18	0.0158	2.36	0.936	0.56	0.00001292	50	0.01077	3.48	0.000212	12	0.000517	7.91	
NIJ5-2-6.2	2017-02-09	9.55	38659		85390	0.1435	2.06	13.17	2.18	0.0158	2.36	0.936	0.56	0.00001292	50							

Appendix D: SHRIIMP-RG Trace Element Data. Presented in order of analysis.

Spot Name	Date/Time	Hours	min:sec	min:sec	196	48/46	49/46	48/49	56/46	59/46	% err	49/46	53/46	46/46	% err	46/46	46/46	46/46	46/46	% err	46/46	46/46	% err	46/46	46/46	% err
VA15-1-5.1	2017-02-0	10.15	36998	77/158	0.285	0.5	0.02145	1.51	13.48	1.5	0.01606	2.4	1.5	0.51	0.50001689	4.5	0.01213	3.36	0.00935	6.02	0.001956	4.17				
VA15-1-5.2	2017-02-0	10.28	38888	83/112	0.1704	0.56	0.012523	1.88	13.6	1.9	0.03755	1.55	1.39	0.5	0.50003214	3.2	0.01137	3.38	0.00582	7.44	0.0014	4.8				
VA15-1-5.3	2017-02-0	10.4	34763	71/402	0.2915	0.52	0.019873	1.6	14.67	1.59	0.07692	1.18	3.259	0.45	0.60002797	36	0.01534	3.09	0.003942	3.04	0.007363	2.24				
VA15-1-6.2	2017-02-0	10.52	36845	80/420	0.1215	0.64	0.008824	2.29	13.77	2.32	0.01589	0.84	5.707	0.51	0.60006679	71	0.01298	3.25	0.000712	6.91	0.001383	4.97				
VA15-1-7.1	2017-02-0	10.65	37675	78884	0.0998	0.68	0.007288	2.49	13.7	2.53	0.03046	0.57	2.35	0.46	0.60002323	38	0.01989	2.61	0.000889	6.12	0.002308	3.81				
VA15-1-7.2	2017-02-0	10.77	38341	88246	0.0979	0.68	0.007511	2.43	13.04	2.47	0.01417	1.5	1.548	0.49	0.60001613	45	0.02488	2.32	0.000757	6.57	0.001646	4.46				
VA15-1-8.1	2017-02-0	10.88	38073	78110	0.3093	0.49	0.025963	1.43	13.47	1.42	0.03772	1.57	1.253	0.52	0.80000328	100	0.00992	3.66	0.000719	6.77	0.001798	4.29				
VA15-1-8.2	2017-02-0	11	38925	80701	0.291	0.49	0.020536	1.49	14.17	1.48	0.01474	2.44	1.909	0.47	0.80002248	38	0.01153	3.36	0.000938	5.86	0.00238	3.69				
VA15-2-9.1	2017-02-0	11.12	38169	76527	0.1636	0.58	0.011878	1.95	13.77	1.97	0.02712	1.83	2.07	0.46	0.90002947	33	0.0156	2.92	0.000859	6.19	0.002089	3.98				
VA15-2-9.2	2017-02-0	11.25	37511	75615	0.0863	0.72	0.06731	1.37	12.82	2.64	0.01289	2.65	1.082	0.55	0.90000333	100	0.0139	3.12	0.00023	12	0.00626	7.3				
VA15-2-10.1	2017-02-0	11.37	37989	75631	0.2628	0.51	0.025042	1.26	10.49	1.37	1.13442	2.39	3.974	0.48	0.90008555	20	0.0505	1.65	0.0087	1.98	0.016823	1.44				
VA15-2-11.1	2017-02-0	11.48	36921	77201	0.1127	0.66	0.008394	2.35	13.43	2.38	0.01612	2.39	3.974	0.47	0.90000339	100	0.01718	2.83	0.003409	3.17	0.00629	2.35				
VA15-2-12.1	2017-02-0	11.6	38375	94049	0.0826	0.79	0.00526	2.91	12.49	2.97	0.01376	2.55	2.065	0.47	0.0	100	0.01924	2.63	0.000715	6.79	0.001869	4.21				
VA15-2-13.1	2017-02-0	11.72	38375	94049	0.0826	0.72	0.006589	2.59	12.54	2.64	0.00319	1.73	3.908	0.57	0.0001564	15	0.01324	3.16	0.000308	10	0.00068	6.93				
VA15-2-14.1	2017-02-0	11.83	37576	79857	0.1859	0.56	0.012562	1.91	14.8	1.93	0.04324	0.39	2.012	0.47	0.00015154	41	0.01568	2.94	0.000878	6.17	0.001896	4.2				
VA15-2-15.1	2017-02-0	11.97	37422	92953	0.0969	0.69	0.026944	2.56	13.96	2.6	0.08301	2.17	1.84	0.59	0.0007794	21	0.01474	3.03	0.00278	11	0.000735	6.75				
VA15-1-9.1	2017-02-0	12.08	35860	69886	0.2935	0.51	0.023273	1.49	13.12	1.48	0.02028	1.17	3.145	0.45	0.90002091	41	0.0138	3.2	0.002138	4.06	0.004344	2.86				
VA15-1-10.1	2017-02-0	12.22	31208	76591	0.591	0.48	0.006514	1.72	14.59	1.18	0.01103	3.14	2.053	0.51	0.90000801	71	0.01497	3.1	0.001114	6.01	0.002181	4.3				
VA15-1-11.1	2017-02-0	12.33	37199	84955	0.2055	0.55	0.010529	1.74	13.29	1.75	0.01083	2.9	2.664	0.46	0.90000336	100	0.01612	2.91	0.00327	5.73	0.002412	3.75				
VA15-1-12.1	2017-02-0	12.45	39074	84657	0.1893	0.54	0.014245	1.77	13.29	1.78	0.79921	0.4	0.943	0.56	0.9000064	71	0.01139	3.37	0.00391	9.05	0.000714	6.7				
VA15-1-13.1	2017-02-0	12.57	37850	80955	0.2247	0.53	0.017108	1.56	13.13	1.65	0.01104	2.85	2.027	0.47	0.90003303	32	0.01132	3.18	0.00328	5.98	0.002071	4.01				
NU15-1-17.1	2017-02-0	12.7	38109	77122	0.0604	0.82	0.04928	3.24	14.28	3.3	0.0283	1.79	2.08	0.47	0.90002296	38	0.04658	1.72	0.00387	7.49	0.001464	4.81				
NU15-1-18.1	2017-02-0	12.82	37279	66598	0.1461	0.6	0.010722	2.07	13.63	2.1	0.01894	2.2	2.381	0.46	0.90002012	41	0.03519	1.99	0.001036	5.7	0.002284	3.85				
NU15-1-20.1	2017-02-0	12.93	38256	72506	0.1494	0.59	0.010658	2.04	13.76	2.06	0.02897	1.77	1.834	0.48	0.90000327	100	0.03965	1.85	0.00679	6.95	0.001477	4.72				
NU15-1-20.2	2017-02-0	13.05	37974	75393	0.0998	0.68	0.007116	2.51	14.03	2.55	0.0395	1.53	1.807	0.48	0	100	0.04278	1.79	0.00428	8.78	0.001426	4.82				
NU15-1-21.1	2017-02-0	13.17	37404	74313	0.0683	0.79	0.00511	2.98	13.37	3.03	0.02244	2.03	2.046	0.47	0.90001003	58	0.04782	1.71	0.00418	8.95	0.001457	4.8				
NU15-1-21.2	2017-02-0	13.28	38271	76596	0.0904	0.7	0.006733	2.57	13.43	2.61	0.02017	2.11	2.031	0.47	0.90001306	50	0.04388	1.76	0.00621	7.26	0.00159	4.55				
NU15-1-22.1	2017-02-0	13.42	38096	75722	0.076	0.75	0.005521	2.84	13.77	2.89	0.01269	2.65	1.525	0.5	0	100	0.03959	1.94	0.00357	9.59	0.000809	6.38				
NU15-1-23.1	2017-02-0	13.53	36103	74044	0.0808	0.75	0.006266	2.74	12.9	2.79	0.01702	2.36	2.061	0.48	0.90000692	71	0.04556	1.82	0.00559	8.03	0.001548	4.74				
VA15-1-14.1	2017-02-0	13.65	36926	74838	0.1074	0.67	0.007914	2.42	13.58	2.45	0.19976	0.77	4.208	0.42	0.90002708	35	0.01784	2.78	0.00401	2.93	0.007198	2.2				
VA15-1-15.1	2017-02-0	13.77	37537	76820	0.1739	0.57	0.012836	1.9	13.55	1.91	0.06313	1.24	5.048	0.41	0.9000148	15	0.02424	2.37	0.00461	2.02	0.012483	1.67				
VA15-1-16.1	2017-02-0	13.9	36955	78363	0.2712	0.51	0.020813	1.52	13.03	1.51	0.01333	2.63	2.021	0.47	0.90001691	45	0.01333	3.21	0.001049	5.69	0.00215	3.98				
VA15-2-16.1	2017-02-0	14.02	36809	86369	0.1206	0.65	0.009684	2.19	12.45	2.23	0.02523	1.93	1.206	0.53	0.90000679	71	0.01213	3.37	0.00283	11	0.000973	5.92				
VA15-2-16.2	2017-02-0	14.13	37622	87626	0.0599	0.83	0.004294	3.25	13.94	3.31	0.02585	1.9	1.37	0.51	0.90000335	100	0.01466	3.05	0.00242	12	0.000973	5.88				
VA15-2-17.1	2017-02-0	14.25	37229	84497	0.1106	0.66	0.008105	2.38	13.64	2.41	0.04198	1.51	1.45	0.51	0.90004029	29	0.01309	3.22	0.000433	8.82	0.000985	5.85				
VA15-2-18.1	2017-02-0	14.38	37739	82657	0.1059	0.67	0.007898	2.39	13.41	2.43	0.03175	1.71	1.714	0.49	0.900001325	50	0.01531	2.96	0.000714	6.82	0.001587	4.58				
VA15-2-18.2	2017-02-0	14.5	37478	84484	0.1115	0.66	0.008683	2.29	12.84	2.33	0.06549	1.22	1.721	0.49	0.90000334	100	0.01538	2.97	0.000541	7.86	0.001261	5.16				
VA15-2-19.1	2017-02-0	14.62	37641	92472	0.083	0.73	0.006004	2.74	13.82	2.79	0.01996	2.14	1.077	0.55	0.90000332	100	0.0135	3.16	0.00021	13	0.000598	7.46				
VA15-2-19.2	2017-02-0	14.73	37287	96792	0.1016	0.71	0.006606	2.63	13.69	2.67	0.08082	1.11	1.168	0.54	0.900003725	30	0.01598	2.92	0.00032	10	0.000607	7.44				
VA15-2-20.1	2017-02-0	14.85	37932	100808	0.1314	0.68	0.007615	2.43	13.34	2.67	0.01407	2.53	1.235	0.52	0	100	0.0159	2.9	0.000245	12	0.000797	6.44				
VA15-2-21.1	2017-02-0	14.97	36797	98669	0.1314	0.63	0.009171	2.25	14.32	2.28	0.02591	1.91	2.062	0.47	0.90000334	100	0.01794	2.78	0.000672	7.12	0.001749	4.42				
VA15-2-22.1	2017-02-0	15.1	36881	71085	0.0778	0.76	0.006058	2.76	12.85	2.81	0.03919	1.56	3.752	0.43	0.900003389	32	0.02082	2.58	0.003696	3.05	0.006075	2.39				
VA15-2-23.1	2017-02-0	15.22	36984	97311	0.0981	0.69	0.007773	2.44	12.61	2.48	0.06283	1.25	1.153	0.54	0	100	0.01603	2.93	0.00027	11	0.000713	6.89				
VA15-2-25.1	2017-02-0	15.33	37288	86382	0.1085	0.67	0.007797	2.42	13.92	2.46	0.04455	1.46	1.342	0.44	0.90000335	35	0.01727	2.83	0.000399	9.18	0.001084	5.57				
VA15-2-26.1	2017-02-0	15.45	36715	77959	0.1149	0.66	0.008115	2.39	14.16	2.43	0.02965	1.79	3.123	0.44	0.900002724	35	0.01229	2.83	0.001177	5.39	0.00297	3.41				
VA15-2-27.1	2017-02-0	15.57	37799	86161	0.0876	0.71	0.0064	2.65	13.69	2.7	0.06321	1.24	1.213	0.53	0.90000331	100	0.01729	2.71								

Appendix D: SHRIMP-RG Trace Element Data. Presented in order of analysis.

Spot Name	Date/Time	Hours	Total 46	Total 46 1/s/Sec	Total 196	Total 196 1/s/Sec	48/46	% Err	49/46	% Err	48/49	% Err	56/46	% Err	59/46	% Err	49/46	% Err	49/46	% Err	46/46	% Err	47/46	% Err
VA15-1-17.1	2017-02-10	15.93	36348	75467	75467	75467	0.1382	0.62	0.010718	2.1	12.89	2.13	0.00866	3.28	2.994	0.45	0.00001719	0.45	0.01495	3.06	0.001846	4.33	0.003701	3.07
VA15-1-18.1	2017-02-10	16.05	36577	72751	72751	72751	0.2883	0.51	0.021216	1.51	13.59	1.51	0.004833	1.42	3.097	0.44	0.000001367	0.44	0.01222	3.36	0.001766	4.41	0.004265	2.85
VA15-1-19.1	2017-02-10	16.18	37676	84421	84421	84421	0.1031	0.67	0.007029	2.49	14.14	2.53	0.01252	2.68	1.583	0.49	0.00002332	0.49	0.001413	3.09	0.00073	6.75	0.001835	4.27
VA15-1-20.1	2017-02-10	16.3	36892	73907	73907	73907	0.0521	0.89	0.004131	3.33	12.6	3.4	0.00793	1.21	3.65	0.43	0.00001016	0.43	0.016	2.93	0.002697	3.56	0.00547	2.52
VA15-1-21.1	2017-02-10	16.42	35933	79590	79590	79590	0.0814	0.75	0.006185	2.76	13.17	2.82	0.02173	2.1	2.269	0.47	0.00003131	0.47	0.001367	3.3	0.001165	5.48	0.002592	3.68
VA15-1-22.1	2017-02-10	16.47	37166	74404	74404	74404	0.3274	0.49	0.02428	1.38	13.48	1.4	0.33783	0.63	2.412	0.46	0.00002018	0.46	0.00936	3.81	0.001166	5.38	0.002946	3.4
VA15-1-23.1	2017-02-10	16.63	35589	73529	73529	73529	0.3508	0.49	0.02428	1.38	13.25	1.37	0.81723	0.51	1.613	0.51	0.00004293	0.51	0.00107	3.75	0.001038	5.83	0.001772	4.47
VA15-1-24.1	2017-02-10	16.78	35804	73441	73441	73441	0.2989	0.51	0.022095	1.5	13.53	1.49	0.2434	0.71	2.1	0.48	0.00002793	0.48	0.01358	3.23	0.001148	5.53	0.0023	3.91
VA15-1-24.2	2017-02-10	16.9	36285	83944	83944	83944	0.1723	0.58	0.012688	1.94	13.58	1.95	0.01148	2.85	1.514	0.51	0.00002067	0.51	0.01439	3.12	0.000701	7.02	0.001742	4.46
VA15-1-24.1	2017-02-10	17.02	34093	72078	72078	72078	0.2868	0.52	0.021037	1.57	13.63	3.09	0.02338	2.08	1.456	0.53	0.00001017	0.53	0.00995	3.95	0.000827	6.67	0.001589	4.82
VA15-1-25.1	2017-02-10	17.15	36877	72620	72620	72620	0.0701	0.79	0.004994	3.03	14.03	3.09	0.01897	2.21	2.137	0.47	0.00001017	0.47	0.00001017	58	0.03887	7.46	0.001397	4.94
VA15-1-26.1	2017-02-10	17.27	35497	66492	66492	66492	0.0718	0.69	0.005699	2.95	13.07	3	0.04928	1.43	3.551	0.44	0.00001761	0.44	0.00001761	1.9	0.00661	7.46	0.001397	4.94
VA15-1-27.1	2017-02-10	17.38	34592	64492	64492	64492	0.1109	0.69	0.008089	2.47	13.07	2.51	0.01284	2.7	3.842	0.43	0.000012848	0.43	0.000012848	17	0.04906	5.51	0.001314	3.37
VA15-1-28.1	2017-02-10	17.62	37122	65357	65357	65357	0.2327	0.53	0.017208	1.67	13.69	1.67	0.01284	2.7	3.842	0.43	0.00002407	0.43	0.00002407	38	0.04525	5.09	0.003836	3.09
VA15-1-29.1	2017-02-10	17.75	35209	61901	61901	61901	0.2752	0.63	0.009788	2.17	12.84	2.2	0.01034	2.97	4.712	0.42	0.0000101	0.42	0.0000101	58	0.044	3.21	0.006806	2.25
VA15-1-30.1	2017-02-10	17.87	36164	61564	61564	61564	0.2553	0.52	0.019306	1.61	14.26	1.61	0.01984	2.22	2.485	0.47	0.00001775	0.47	0.00001775	45	0.03882	1.95	0.001115	3.76
VA15-1-31.1	2017-02-10	17.98	34658	94616	94616	94616	0.018	0.47	0.001162	6.45	15.5	6.6	0.0657	1.27	0.711	0.64	0.00002765	0.64	0.00002765	35	0.03907	4.15	0.004654	2.75
VA15-1-31.1	2017-02-10	18.1	35235	73209	73209	73209	0.3071	0.51	0.071842	1.52	14.06	1.51	0.01542	2.5	1.369	0.54	0.000033892	0.54	0.000033892	30	0.01027	2.34	0.000105	1.4
VA15-1-32.1	2017-02-10	18.12	35338	79890	79890	79890	0.2956	0.53	0.017132	1.66	13.25	1.66	0.00661	3.72	1.749	0.49	0.000003138	0.49	0.000003138	71	0.01342	3.6	0.001832	2.89
VA15-1-33.1	2017-02-10	18.35	35318	79760	79760	79760	0.0931	0.72	0.006418	2.73	14.35	2.77	0.36661	0.42	1.463	0.52	0.000003138	0.52	0.000003138	34	0.01342	3.2	0.000759	4.16
VA15-2-29.1	2017-02-10	18.47	36542	86977	86977	86977	0.0842	0.75	0.006341	2.73	13.01	2.78	1.53936	0.44	3.211	0.44	0.000042569	0.44	0.000042569	8.97	0.03534	4.89	0.002395	3.8
VA15-2-30.1	2017-02-10	18.58	36311	84919	84919	84919	0.0527	0.89	0.004054	3.39	12.99	3.46	0.07955	1.14	3.969	0.44	0.000003344	0.44	0.000003344	100	0.01821	2.78	0.000881	3.67
VA15-2-31.1	2017-02-10	18.7	36272	82591	82591	82591	0.1211	0.65	0.006087	2.31	13.65	2.34	0.02433	1.98	0.908	0.58	0.000003345	0.58	0.000003345	100	0.01539	3	0.00392	12
VA15-2-31.2	2017-02-10	18.83	36555	90634	90634	90634	0.086	0.75	0.006646	2.65	12.94	2.69	0.07679	1.15	1.615	0.5	0.000003342	0.5	0.000003342	22	0.01463	3.08	0.000396	6.16
VA15-2-32.1	2017-02-10	18.95	36474	86390	86390	86390	0.0811	0.75	0.005786	2.83	14.01	2.88	0.61519	0.53	1.28	0.53	0.000006854	0.53	0.000006854	50	0.01302	3.34	0.000355	6.15
VA15-2-33.2	2017-02-10	19.07	34813	79109	79109	79109	0.1087	0.69	0.008128	2.46	13.37	2.49	0.02342	2.06	1.127	0.56	0.00001436	0.56	0.00001436	71	0.01267	3.34	0.000327	10
VA15-2-33.1	2017-02-10	19.18	35274	79948	79948	79948	0.1272	0.64	0.009533	2.24	13.35	2.27	0.0471	2.55	1.243	0.54	0.0000007	0.54	0.0000007	58	0.01728	2.86	0.000412	9.18
VA15-2-34.1	2017-02-10	19.3	36048	83814	83814	83814	0.0929	0.72	0.006727	2.65	13.81	2.69	0.08819	1.09	1.506	0.51	0.0000104	0.51	0.0000104	45	0.01547	3.03	0.000632	7.46
VA15-1-29.1	2017-02-10	19.42	35630	83928	83928	83928	0.1343	0.52	0.009852	2.21	13.63	2.24	0.03055	1.79	1.304	0.53	0.00001754	0.53	0.00001754	45	0.01066	3.67	0.000729	6.98
VA15-1-30.1	2017-02-10	19.55	35338	74247	74247	74247	0.2817	0.52	0.020636	1.56	13.65	1.55	0.07704	2.38	1.571	0.51	0.00002122	0.51	0.00002122	41	0.01066	3.67	0.000729	6.98
VA15-1-31.1	2017-02-10	19.67	34968	74812	74812	74812	0.0835	0.76	0.006244	2.79	13.37	2.84	0.00751	3.58	2.775	0.46	0.000003357	0.46	0.000003357	100	0.01325	3.31	0.001466	4.95
VA15-1-31.2	2017-02-10	19.78	36025	76807	76807	76807	0.249	0.53	0.018401	1.63	13.53	1.63	0.084131	0.51	1.883	0.49	0.00002082	0.49	0.00002082	41	0.01308	3.28	0.000987	5.94
VA15-1-32.1	2017-02-10	19.9	34674	83699	83699	83699	0.1226	0.66	0.009599	2.23	12.31	2.26	0.04131	0.51	1.821	0.45	0.00002884	0.45	0.00002884	35	0.01504	3.08	0.000862	6.48
VA15-1-33.1	2017-02-10	20.02	35491	75293	75293	75293	0.1354	0.63	0.010168	2.18	13.76	2.21	0.01565	2.89	1.808	0.49	0.000003352	0.49	0.000003352	100	0.012	3.45	0.001007	5.93
VA15-1-34.1	2017-02-10	20.15	35760	75495	75495	75495	0.6246	0.64	0.045068	1.08	13.76	1.04	1.103182	0.39	3.111	0.45	0.000006603	0.45	0.000006603	23	0.01444	3.14	0.002125	4.07
VA15-1-35.1	2017-02-10	20.27	36069	72763	72763	72763	0.1256	0.64	0.009078	2.29	13.84	2.32	0.02843	1.84	0.809	0.61	0.00002079	0.61	0.00002079	41	0.01037	3.68	0.000498	8.34
VA15-1-36.1	2017-02-10	20.4	35632	73938	73938	73938	0.1937	0.57	0.014029	1.86	13.81	1.87	0.06629	1.25	3.926	0.43	0.00002456	0.43	0.00002456	38	0.01517	3.06	0.002978	3.45
VA15-1-37.1	2017-02-10	20.52	36042	79685	79685	79685	0.1627	0.59	0.012112	1.99	13.43	2.01	1.55703	0.45	1.375	0.52	0.0000104	0.52	0.0000104	58	0.01045	3.66	0.000274	11
VA15-2-35.1	2017-02-10	20.63	34538	80018	80018	80018	0.0975	0.72	0.007417	2.58	13.15	2.62	0.06614	1.27	1.061	0.57	0.00000724	0.57	0.00000724	71	0.01329	3.32	0.000306	6.24
VA15-2-36.1	2017-02-10	20.75	34845	74937	74937	74937	0.2176	0.56	0.016013	1.77	13.59	1.78	0.12317	0.96	2.095	0.48	0.0000574	0.48	0.0000574	25	0.01296	2.36	0.007321	2.23
VA15-2-37.1	2017-02-10	20.88	35344	69174	69174	69174	0.0872	0.74	0.005904	2.85	14.76	2.9	0.03027	1.8	4.125	0.43	0.00010217	0.43	0.00010217	19	0.02608	2.36	0.007321	2.23
VA15-2-38.1	2017-02-10	21	35421	71527	71527	71527	0.0755	0.78	0.005351	2.99	14.1	3.04	0.01941	2.23	2.716	0.46	0.00001059	0.46	0.00001059	58	0.0159	3	0.002294	3.94
VA15-2-39.1	2017-02-10	21.12	37146	81826	81826	81826	0.0852	0.73	0.007033	2.51	11.66	2.56	0.02617	1.89	3.523	0.43	0	0.43	0	100	0.01884	2.7	0.001189	5.33
VA15-1-32.1	2017-02-10	21.23	35230	59751	59751	59751	0.2772	0.52	0.021063	1.55	13.16	1.54	0.00779	3.51	4.44	0.43	0.00006308	0.43	0.00006308	24	0.04354	1.84	0.006412	2.38
VA15-1-33.1	2017-02-10	21.35	34276	70811	70811	70811	0.0289	1.19</																

	133/46	155/46	173/46	182/46	230/46	248/46	%R	181	169	%R	28	57	556.3	0.024	9.68	0.99	1.42	0.3	11.42	42.36	45.95	135.8	Q1					
0.000784	7.73	0.002946	6.31	0.022	2.33	0.03667	1.82	0.03321	1.91	3.439	0.43	0.6253	0.46	0.6604	0.46	0.6604	0.57	3.9	4.06	5.3	565.7	45.18	141.7					
0.000972	6.98	0.003336	5.96	0.0217	2.36	0.03605	1.84	0.03464	1.88	3.274	0.44	0.6604	0.46	0.6604	0.46	0.6604	0.57	3.9	4.06	5.3	565.7	45.18	141.7					
0.000898	5.74	0.002857	4.56	0.02183	2.35	0.03724	1.81	0.03384	1.9	3.378	0.43	0.6626	0.46	0.6626	0.46	0.6626	0.57	3.93	3.69	5.2	557.8	46.97	138.4					
0.001046	5.4	0.002759	4.7	0.02101	2.43	0.03745	1.89	0.0343	1.89	3.484	0.44	0.6444	0.46	0.6444	0.46	0.6444	0.58	4.1	4.53	5.2	566.6	46.92	143.4					
0.00089	5.91	0.002995	4.56	0.02108	2.54	0.03713	1.86	0.03516	1.91	3.484	0.44	0.6429	0.47	0.6429	0.47	0.6429	0.59	4	3.43	4.9	573.7	46.92	143.8					
0.000973	6.09	0.003056	4.86	0.02277	2.54	0.03717	1.86	0.03516	2.01	3.487	0.44	0.60889	0.51	0.60889	0.51	0.60889	0.59	4	3.43	4.9	573.7	46.92	143.8					
0.000878	7.14	0.003446	4.68	0.02268	2.6	0.03851	1.91	0.03556	2.09	3.554	0.48	0.60479	0.52	0.60479	0.52	0.60479	0.65	3.8	3.93	5.2	580	43.85	132.9					
0.000885	6.42	0.002869	5.05	0.02072	2.68	0.03857	1.98	0.03187	2.17	3.507	0.48	0.59885	0.52	0.59885	0.52	0.59885	0.65	3.84	3.72	4.6	538	43.85	145.4					
0.000813	6.69	0.003189	5.24	0.02163	2.62	0.03809	1.99	0.03292	2.13	3.499	0.48	0.59469	0.52	0.59469	0.52	0.59469	0.65	3.84	3.72	4.6	538	43.85	145.4					
0.000978	6.06	0.003189	4.75	0.0217	2.6	0.03632	1.92	0.03174	2.16	3.499	0.48	0.58607	0.52	0.58607	0.52	0.58607	0.65	3.73	4.05	4.9	550	47.73	134.6					
0.000913	6.44	0.00333	4.77	0.02154	2.67	0.03743	2.04	0.03362	2.15	3.574	0.48	0.6244	0.52	0.6244	0.52	0.6244	0.66	3.94	3.96	4.5	574	45.51	128.8					
0.000919	5.69	0.00333	4.64	0.01934	2.5	0.03608	1.85	0.03185	1.96	3.426	0.43	0.6282	0.46	0.6282	0.46	0.6282	0.59	3.73	3.79	4.5	545.6	45.51	130.3					
0.002428	3.61	0.002774	4.38	0.02867	2.12	0.05064	1.61	0.04113	1.78	1.88	0.51	0.0119	2.32	0.0201	2.52	12.76	14.12	6.7	672	0.935	24.69	1.35	63.46	168.2				
0.003457	3.05	0.004695	3.7	0.03525	1.93	0.05767	1.53	0.04422	1.73	1.828	0.52	0.0099	2.56	0.0206	2.51	17.48	18.47	13.2	34.7	1.34	18.2	67.87	72.27	180.9				
0.015687	1.46	0.044872	2.08	0.0949	1.2	0.13581	1.02	0.09577	1.2	1.74	0.52	0.0102	2.5	0.031	2.04	18.69	20.02	4.1	1981	0.26	32.66	17.5	57.66	170.19	391.7			
0.00068	6.84	0.004993	8	0.0126	3.19	0.03392	1.97	0.04079	1.8	2.204	0.49	0.0163	0.82	0.0665	1.43	244	25.4	30.4	2.6	30.4	42.3	0.016	16.99	42.51	165.8			
0.000624	2.21	0.00578	2.64	0.0725	1.4	0.11042	1.15	0.0832	1.31	1.988	0.51	0.0137	2.22	0.033	2.03	9.05	9.87	2.6	1548	0.005	25.84	4.66	8.18	37.14	340.3			
0.000839	6.22	0.001012	7.91	0.0157	3.33	0.03824	2.15	0.0328	1.31	2.405	0.48	0.024	1.66	0.023	2.37	4.22	4.48	6.1	353	0.016	17.64	0.72	0.81	32.3	39.3	116.6		
0.000592	3.54	0.003246	4.47	0.02416	2.34	0.03981	1.84	0.03444	1.97	1.822	0.52	0.00442	3.84	0.00779	4.08	25.48	27.09	2.6	555	0.027	15.44	1.66	2.33	1.01	12.58	46.52	48.88	140.9
0.000739	3.93	0.003269	4.12	0.02736	1.88	0.03783	1.32	0.07453	1.35	2.25	0.49	0.05751	1.16	0.02319	1.47	6.11	6.43	10.3	989	0.005	33.16	2.52	4.04	0.81	14.62	71.94	98.66	304.8
0.000671	6.94	0.004622	4.88	0.0223	2.43	0.03919	1.85	0.03421	2.16	2.361	0.49	0.00986	2.18	0.0245	2.32	19.89	20.65	6	488	0.005	8.29	1.29	2.27	0.36	10.55	42.94	48.11	115.2
0.0002154	3.88	0.004125	3.74	0.0347	2.02	0.04691	1.69	0.03429	1.97	2.102	0.5	0.00196	5.73	0.00876	3.85	39.89	41.12	18	671	0.048	6.36	3.06	3.86	0.84	17.92	62.53	58.79	140.3
0.000583	7.46	0.004125	3.97	0.03471	1.96	0.05462	1.58	0.04147	1.8	2.348	0.49	0.04608	1.23	0.0894	1.14	11.75	12.64	4.9	746	0.011	14.16	2.36	3.69	0.33	15.99	68.84	68.45	169.6
0.000595	7.46	0.00428	4.87	0.02364	2.39	0.04004	1.85	0.02914	2.16	2.304	0.5	0.00168	2.02	0.0329	1.87	17.11	17.3	8.2	535	0.022	8.38	1.75	2.07	0.23	10.86	45.51	50.63	115.2
0.0004901	2.75	0.0119	2.35	0.07327	1.38	0.09883	1.19	0.0591	1.51	2.102	0.5	0.00303	3.59	0.0255	2.27	24.18	26.41	15.3	1409	0.085	8.2	8.18	12.03	1.07	46.14	139.36	123.85	241.7
0.0005942	7.83	0.003142	6.37	0.01476	3.02	0.02696	2.25	0.0229	2.44	2.032	0.5	0.01362	2.24	0.0208	2.55	12.19	12.67	10.4	376	0.017	6.42	0.84	1.41	0.21	5.98	28.42	53.78	95.6
0.0005942	4.15	0.003474	4.34	0.02624	2.26	0.04048	1.83	0.02653	2.24	2.032	0.51	0.00176	6.08	0.00716	4.28	42.13	45.76	9.8	564	0.076	6.38	2.33	3.27	0.74	13.47	50.52	50.73	108.5
0.000515	7.94	0.002621	5.36	0.01964	2.59	0.03525	1.95	0.02882	2.15	2.447	0.49	0.00916	2.68	0.00219	2.46	16.4	17.13	6.6	458	0	7.79	0.91	1.77	0.2	8.77	37.82	44.18	117.9
0.000477	8.17	0.004974	3.61	0.0633	1.46	0.13665	1.03	0.11053	1.13	2.378	0.48	0.065	1.05	0.07857	1.32	10.31	10.35	36.8	1678	0.053	3.53	1.49	3.29	0.19	19.09	121.89	171.25	452.1
0.000738	6.64	0.003572	4.28	0.02755	2.2	0.05316	1.6	0.03988	1.84	2.614	0.48	0.02654	1.6	0.07198	1.39	17.43	18.12	2.7	686	0.043	13.1	1.64	2.6	0.29	13.85	53.05	66.62	163.1
0.000885	6.09	0.002381	5.25	0.02994	2.52	0.03724	1.91	0.03318	2.02	2.599	0.49	0.01373	2.21	0.03104	2.08	15.37	16.27	11.7	491	0.607	10.19	3.25	2.28	0.34	9.23	40.31	46.66	135.7
0.001036	5.58	0.003866	4.09	0.03343	1.99	0.0559	1.56	0.04272	1.77	2.437	0.48	0.0196	1.93	0.03941	1.51	16.4	17.05	3	791	0.016	11.37	2	3.6	0.4	14.99	64.37	70.05	174.7
0.000777	6.51	0.001675	6.27	0.01793	2.73	0.03744	1.91	0.03243	2.04	2.404	0.49	0.01831	1.85	0.03381	2	10.24	14.99	11.4	558	0.016	10.47	1.3	2.47	0.17	8.83	45.22	54.26	138
0.00044	8.68	0.00278	5.4	0.02348	2.7	0.04143	1.99	0.03374	2.01	2.221	0.49	0.02581	1.64	0.02729	1.4	13.67	14.99	11.4	558	0.016	10.47	1.3	2.47	0.17	8.83	45.22	54.26	138
0.000715	6.77	0.001979	5.76	0.01826	2.7	0.04143	1.99	0.03374	2.01	2.221	0.49	0.02581	1.64	0.02729	1.4	13.67	14.99	11.4	558	0.016	10.47	1.3	2.47	0.17	8.83	45.22	54.26	138
0.000508	2.5	0.006479	3.24	0.04513	1.77	0.06965	1.44	0.05096	1.67	1.828	0.53	0.00524	3.6	0.01205	3.36	15.78	17.48	1.7	987	0.028	18.24	3.06	4.75	2.14	25.12	86.91	87.28	208.4
0.001395	4.84	0.00258	5.03	0.02885	2.23	0.0534	1.6	0.04806	1.68	2.301	0.49	0.03183	1.47	0.03894	1.86	5.29	5.09	9.3	680	0.382	25.08	1.75	2.34	0.54	10	51.71	66.92	196.6
0.001748	4.29	0.002897	4.71	0.0285	2.15	0.05497	1.57	0.04594	1.71	2.074	0.5	0.01989	1.83	0.02858	2.14	10.79	12.14	1.9	665	0.042	21.48	1.73	2.15	0.68	11.23	54.88	68.89	187.9
0.000816	6.38	0.001146	7.6	0.01439	3.05	0.03725	1.92	0.04231	1.8	2.677	0.48	0.08714	0.94	0.07904	1.34	2.96	3	11.6	450	0	27.56	0.55	0.94	0.32	4.44	27.71	46.67	173
0.002412	3.62	0.003023	4.57	0.02582	2.23	0.04387	1.63	0.03585	1.9	1.914	0.51	0.00796	2.83	0.04419	2.99	18.68	19.99	2.8	626	0.031	20.47	1.58	2.46	0.94	11.72	49.71	62.19	146.6
0.001197	5.2	0.001835	5.94	0.01921	2.62	0.04387	1.75	0.0453	1.73	2.229	0.49	0.04881	1.2	0.04915	1.66	5.32	5.78	9.7	550	0.011	24.92	0.85	1.83	0.47	7.11	37	54.97	185.3
0.000527	7.65	0.000767	8.97	0.01271	3.13	0.02982	2.06	0.03516	1.76	1.99	0.51	0.01221	2.33	0.02296	2.4	20.58	22.17	8.7	742	0.048	25.91	2.06	3.1	1.1	14.69	62.63	69.76	177.7
0.001025	1.79	0.010031	2.62	0.06127	1.53	0.09484	1.25	0.06157	1.53	1.727	0.54	0.00621	3.32	0.01825	1.08	2.53	2.94	45.8	370	0.02	13.59	0.24	0.65	0.2	2.97	24.47	37.37	143.8
0.011238	1.63	0.012076	2.4	0.07257	1.42	0.09677	1.24	0.06623	1.48	1.75	0.54	0.00582	3.43	0.01915	2.69	24.28	25.8	1.6	1453	0.038	24.05	13.47	11.02	4				

[illegible]

Appendix D: SHIRMP-RG Trace Element Data. Presented in order of analysis.

	133/46	135/46	137/46	182/46	138/46	139/46	232/46	248/46	%err	181	119	88	Y	8	C2	PN	US	n3	PS	Ac	J3	Q4							
	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err	%err							
	3.32	0.00315	3.14	0.0482	1.73	0.06734	1.48	0.04355	1.82	2.076	0.52	0.00347	4.47	0.01723	2.85	19.13	21.31	1.5	976	0.029	8.36	4.78	6.37	1.22	27.45	92.81	84.38	178.1	
	0.00463	1.74	0.007781	2.99	0.04795	1.73	0.06603	1.49	0.04222	1.84	1.989	0.52	0.00211	3.72	0.01015	3.63	39.9	42.18	8.6	1010	0.023	6.83	4.58	7.34	1.8	30.17	92.33	82.74	172.7
	0.000877	6.16	0.002802	4.88	0.02467	2.35	0.03761	1.91	0.02765	2.22	2.241	0.5	0.00483	5.7	0.01274	3.25	14.26	14.49	2.2	516	0.039	7.9	1.89	3.16	0.34	10.86	47.5	47.13	113.1
	0.0048	2.68	0.009371	2.71	0.05872	1.56	0.07754	1.37	0.05087	1.97	2.203	0.52	0.00422	4.02	0.02086	2.58	7.21	8.21	12.1	1190	0.017	8.95	6.99	9.41	1.87	36.34	113.06	97.17	208.1
	0.001109	5.61	0.004646	3.89	0.03422	2.05	0.05264	1.67	0.03735	1.67	2.203	0.52	0.00493	3.78	0.01345	3.24	11.27	12.3	3.9	740	0.052	7.64	3.02	4.46	0.43	18.01	65.9	65.96	152.8
	0.003704	3.04	0.006271	3.3	0.03646	1.96	0.05462	1.61	0.0375	1.93	2.002	0.52	0.00167	6.36	0.00695	4.41	45.31	48.27	59.9	787	0.034	5.23	3.02	5.07	1.44	24.31	70.21	68.45	153.4
	0.002217	4	0.00359	4.46	0.02494	2.4	0.0382	1.95	0.0261	2.35	2.066	0.53	0.00146	6.94	0.00631	4.73	48.54	52.63	145	526	0.071	5.63	2.69	3.05	0.86	13.8	48.03	47.87	106.7
	0.002655	3.62	0.004252	4.07	0.03131	2.43	0.04795	1.75	0.03414	2.06	2.079	0.52	0.00218	5.67	0.00988	3.78	41.36	43.93	45.1	685	0.046	7.59	2.98	3.96	1.05	16.49	60.29	60.09	139.6
	0.001719	7.89	0.002855	4.93	0.02398	2.43	0.037	1.97	0.02574	2.34	2.113	0.53	0.00583	3.46	0.01521	3.03	23.84	25.23	2	494	0.034	8.05	1.82	3	0.22	11.07	46.17	46.36	105.3
	0.002068	4.07	0.003121	4.86	0.02343	2.59	0.03463	1.63	0.04605	1.75	1.969	0.53	0.001269	2.34	0.02386	2.46	9.94	10.93	8.7	697	0.017	5.31	2.14	2.73	0.67	12.1	43.18	43.39	95.9
	0.004913	2.7	0.006127	3.41	0.05215	1.69	0.08578	1.34	0.06344	1.54	1.873	0.54	0.01145	2.51	0.02386	2.62	32.8	34.41	2.3	1253	0.04	25.3	10.12	10.84	3.67	36.95	118.54	116.63	253.9
	0.005464	2.6	0.006376	3.39	0.04613	1.81	0.07102	1.48	0.05346	1.69	1.864	0.55	0.00927	2.82	0.0212	2.64	15.34	16.08	6.8	1002	0.213	27.43	3.64	6.6	2.12	24.72	88.82	88.99	218.7
	0.009971	1.89	0.009529	2.71	0.06156	1.54	0.09307	1.27	0.06208	1.53	1.73	0.54	0.00707	3.11	0.02371	2.41	17.29	19.46	11.8	1537	0.017	24.6	8.59	11.71	4.31	47.15	141.92	132.9	305.6
	0.005105	2.66	0.005333	3.67	0.03696	1.62	0.05774	1.61	0.04278	1.86	1.708	0.55	0.00638	3.38	0.01768	2.86	38.09	38.38	3.5	811	0.029	21.7	2.89	4.37	1.98	20.68	71.17	72.36	175
	0.008859	2.01	0.008626	2.86	0.05549	1.62	0.07574	1.39	0.05557	1.62	2.272	0.55	0.00389	4.33	0.01329	3.25	35.33	37.02	1.2	1112	0.046	16.97	5.24	8.01	3.44	33.45	106.84	96.46	227.3
	0.004001	9.5	0.00474	12	0.0067	4.66	0.02036	2.7	0.02361	2.5	2.737	0.53	0.00919	1.15	0.03854	4.67	42.5	43.43	2.7	414	0.095	6.19	4.75	7.44	1.44	27.56	90.1	82.42	96.6
	0.009378	3.11	0.007109	3.18	0.04679	1.78	0.05577	1.51	0.04235	1.87	2.072	0.53	0.00919	1.15	0.03854	4.67	42.5	43.43	2.7	414	0.095	6.19	4.75	7.44	1.44	27.56	90.1	82.42	96.6
	0.009023	6.08	0.004633	4.34	0.0366	2.29	0.04984	1.86	0.03931	2.19	2.148	0.51	0.00967	4.32	0.01358	3.19	31.76	34.43	1.2	570	0.011	7.5	1.97	3.4	0.36	14.09	51.21	51.18	118.4
	0.002739	6.98	0.003862	4.97	0.03232	2.49	0.03853	1.95	0.03997	2.16	2.246	0.52	0.00247	1.81	0.02742	1.49	12.76	13.76	419.9	477	0.052	12.55	1.83	2.83	0.38	11.11	44.9	48.29	126.7
	0.000994	6	0.005168	3.62	0.04649	1.76	0.07798	1.38	0.03799	1.58	2.38	0.5	0.06209	1.11	0.02845	0.89	11.24	12.41	273.1	1047	0.079	19.76	3.72	4.12	0.37	20.43	89.51	97.72	237.2
	0.000425	9.01	0.001049	8.11	0.01264	3.32	0.02235	1.35	0.06995	1.55	2.539	0.51	0.04013	1.36	0.01139	1.13	7.29	8.06	14.1	1099	0.006	10.18	2.28	4.45	0.31	21.21	92.51	103.2	249.3
	0.001166	5.43	0.003002	4.79	0.02467	2.38	0.03954	1.19	0.02396	2.17	2.488	0.5	0.02139	1.83	0.0242	1.66	16.75	17.64	4.3	296	0.006	6.15	0.61	1.05	0.17	4.07	24.33	28	82.9
	0.000685	7.08	0.001386	7.04	0.01684	2.88	0.03481	2.02	0.02463	2.08	2.36	0.5	0.01564	2.13	0.03186	2.11	11.22	11.5	109.2	418	0.114	8.61	2.38	3.25	0.45	11.64	47.5	49.55	122.5
	0.000621	7.61	0.001963	6.06	0.0152	3.1	0.02961	2.23	0.02528	2.41	2.272	0.52	0.01492	2.23	0.02377	2.23	15.04	16.16	4.2	368	0.024	7.09	0.85	1.64	0.24	7.61	29.28	37.11	103.4
	0.000583	9.18	0.00136	6.36	0.01703	2.89	0.03158	2.14	0.02716	2.3	2.278	0.51	0.01103	2.55	0.02295	2.5	17.61	18.95	2.6	405	0.017	9.66	1.07	1.56	0.16	6.54	35.22	48.77	139.6
	0.000442	9.18	0.001688	6.42	0.01829	2.78	0.03892	1.92	0.04414	2.05	2.381	0.51	0.05141	1.22	0.01024	1.18	12.85	13.37	15.6	491	0.017	9.66	1.07	1.56	0.16	6.54	35.22	48.77	139.6
	0.000554	7.97	0.002206	5.65	0.02038	2.65	0.03288	2.1	0.02436	2.43	2.356	0.51	0.00908	2.81	0.02093	2.62	18.58	19.59	5.4	425	0.029	8.65	1.64	2.21	0.22	8.55	39.24	41.2	99.6
	0.001592	4.73	0.003121	4.78	0.02485	2.42	0.03775	1.97	0.02528	2.4	2.101	0.53	0.00204	5.9	0.00668	4.62	38.99	41.03	3	512	0.035	5.92	1.89	3.01	0.62	12.1	47.85	47.3	103.4
	0.002552	3.76	0.005823	3.52	0.04367	1.85	0.06307	1.55	0.04144	1.9	2.139	0.52	0.0033	4.67	0.01295	3.34	11.56	12.41	1.3	905	0.006	7.41	3.8	6.12	0.99	22.58	84.09	79.03	169.5
	0.001777	4.44	0.004434	3.97	0.02983	2.19	0.04837	1.73	0.03193	2.12	2.132	0.52	0.00248	5.3	0.01009	3.73	34.46	36.58	1.5	614	0.035	7.31	2.56	3.62	0.69	17.19	57.44	60.62	130.6
	0.001777	6.82	0.004156	4.79	0.02596	2.39	0.04198	1.89	0.0324	2.14	2.414	0.51	0.00914	2.83	0.02562	2.4	16.97	19.8	149.3	594	0.048	8.61	2.23	2.96	0.3	12.24	49.98	52.6	132.5
	0.001578	4.74	0.003882	4.28	0.02962	2.21	0.04058	1.9	0.03024	2.19	2.121	0.52	0.00285	4.98	0.01014	3.7	18.74	20.21	2.8	590	0.006	6.71	2.61	3.58	0.61	15.05	57.03	50.85	123.7
	0.003352	3.25	0.007775	3.02	0.0482	1.74	0.06923	1.47	0.04746	1.76	2.111	0.52	0.00365	4.39	0.01577	3	86.44	90.27	1397.5	1015	0.11	8.05	5.51	7.51	1.3	30.15	92.82	86.76	194.1
	0.00007	7.05	0.001925	6.01	0.01957	2.69	0.03165	2.13	0.02708	1.76	2.111	0.52	0.00365	4.39	0.01577	3	86.44	90.27	1397.5	1015	0.11	8.05	5.51	7.51	1.3	30.15	92.82	86.76	194.1
	0.005603	2.53	0.010684	2.59	0.06596	1.51	0.08854	1.51	0.05218	1.68	2.075	0.52	0.00348	4.51	0.01753	3.34	17.39	18.05	5	264	0.035	5.8	1.29	2.36	0.27	7.47	37.68	39.67	110.8
	0.000778	6.69	0.002366	5.43	0.0179	2.81	0.03528	2.02	0.03121	2.14	2.211	0.51	0.01057	2.59	0.01619	2.89	22.52	24.08	276.3	448	0.017	5.84	0.71	1.54	0.3	9.17	34.48	44.21	127.6
	0.00067	7.36	0.001962	6.09	0.01731	2.92	0.03139	2.18	0.02796	2.31	2.317	0.52	0.01332	2.36	0.02771	2.32	13.5	14.75	11.7	346	0.012	7.43	0.79	1.48	0.26	7.61	33.34	39.34	114.4
	0.001213	5.45	0.003846	4.34	0.03007	1.32	0.11449	1.17	0.0342	2.08	2.151	0.53	0.01133	2.54	0.03941	1.95	30.12	31.84	21.9	683	0.095	7.25	2.17	3.07	0.47	14.91	57.9	60.87	139.9
	0.003739	2.09	0.015195	2.19	0.08811	1.32	0.11449	1.17	0.0342	2.08	2.151	0.53	0.01133	2.54	0.03941	1.95	30.12	31.84	21.9	683	0.095	7.25	2.17	3.07	0.47	14.91	57.9	60.87	139.9
	0.001103	5.54	0.00626	3.21	0.05087	1.67	0.08283	1.33	0.05751	1.57	2.203	0.51	0.03315	2.9	0.03766	1.97	10.45	10.64	3.4	886	0.018	8.89	5.95	6.25	1.26	23.96	97.96	103.8	178.6
	0.001438	1.62	0.012416	2.42	0.07561	1.42	0.09787	1.26	0.06694	1.93	2.066	0.56	0.00531	3.67	0.01														

Appendix D: SHRIMP-RG Trace Element Data. Presented in order of analysis.

SHRIMP	U	Th	U/Th	PN/PS	PN/PA	PN/MS	MS/Sm	U/PA	U/Ce	Eu*/Eu*	Temp	ε _{Pb}	1197/1187	La	Ce	Pr	PN	MS	Nd	PS	Ac	Pa	Th	U	Th	
17355	3973	463.7	0.12	11.89	11.5	13.68	1.43	6.82	29.25	410.3	0.23	693	5.7	14.8	15.79	2.17	15.79	2.17	5.41	57.4	172.2	287.2	843.7			
16525	4195	514.2	0.12	10.95	10.35	11.33	1.22	7.17	29.61	382.9	0.26	694	5.3	13.8	15.78	2.74	15.78	2.74	6.71	65	169.9	282.4	880			
17049	4019	506.7	0.13	12.49	7.95	99.4	0.21	34.42	29.04	406.1	0.6	694	5.3	15.3	16.15	3.05	16.15	3.05	6.2	55.67	170.9	291.7	859.5			
17260	4094	516.5	0.13	13.4	7.79	104.4	0.2	37.77	28.56	389.1	0.72	698	5.2	13	17.17	3	17.17	3	7.22	53.76	164.4	293.3	890.5			
17078	4085	496.3	0.12	12.38	9.25	114.6	1.85	4.87	28.4	361.1	0.2	696	4.9	16.7	16.65	2.75	16.65	2.75	15.7	16.84	178.3	287.4	825.6			
17597	3868	475.8	0.12	11.22	9.72	109	2.04	4.07	29.1	381.6	0.21	692	5.2	13.9	16.53	2.67	16.53	2.67	6.72	59.54	178.3	287.4	825.6			
17938	3842	484	0.13	10.88	12	130.6	2.33	3.73	26.42	396.8	0.15	692	5.3	15.9	16.59	2.44	16.59	2.44	17.55	5.1	177.5	301.6	903.3			
17698	3804	469	0.12	11.72	7.81	91.5	1.83	3.86	29.18	377.5	0.19	693	4.6	14.9	16.44	3.12	16.44	3.12	17.55	5.1	177.5	301.6	903.3			
17614	3778	481.2	0.13	13.11	9.84	129	2.25	4.08	28.06	394.6	0.2	690	4.9	12.1	15.62	2.28	15.62	2.28	16.78	6.75	162.4	169.3	298.3	836.2		
17659	3723	451	0.12	10.5	10.34	108.6	2.08	4.1	28.68	364.7	0.21	691	9.5	13.4	16.66	2.62	16.66	2.62	16.78	6.75	162.4	169.3	298.3	836.2		
18037	3967	490	0.12	10.64	9.6	102.2	2.13	3.69	28.85	376	0.18	695	4.5	14.3	16.06	17.21	15.99	17.4	15.44	6.34	54.05	151.3	282.6	854.1		
17289	3991	469.8	0.12	12.11	13.54	164	2.88	4.29	30.64	407.2	0.22	690	4.5	14.2	16.62	15.99	17.4	15.44	6.34	54.05	151.3	282.6	854.1			
9490	76	18.2	0.24	13.23	9.41	124.5	1.86	9.84	0.45	3.1	0.51	806	6.7	13	10.46	40.28	2.96	16.96	16.76	63.89	224.4	396.6	1044.8			
9225	63	18.7	0.3	9.94	8.6	85.5	1.64	7.54	0.35	2.4	0.52	840	7.1	13.6	11.13	42.63	4.63	23.42	23.86	91.48	275.9	451.7	1123.4			
11721	739	60.2	0.08	43.31	6.33	274.3	1.19	2.2	0.17	2	0.57	847	4.1	13.4	10.96	53.28	38.3	122.71	108.27	289.77	742.9	1063.7	2432.8			
8780	65	28	0.43	6.93	3.29	22.4	1.04	1.8	0.43	1.1	0.57	847	4.1	13.4	10.96	53.28	38.3	122.71	108.27	289.77	742.9	1063.7	2432.8			
11031	87	29.9	0.34	20.69	5.45	161.9	1.13	2.16	0.26	3.4	0.47	771	2.6	13.2	13.2	42.15	10.19	55.29	47.79	186.63	565.5	864.8	2113.4			
12138	153	20.8	0.14	20.69	5.45	161.9	1.13	2.16	0.26	3.4	0.47	771	2.6	13.2	13.2	42.15	10.19	55.29	47.79	186.63	565.5	864.8	2113.4			
9247	28	7	0.25	11.19	7.57	84.7	1.4	6.63	0.2	1.8	0.57	884	2.6	13.5	10.13	25.19	3.64	15.74	17.89	19.73	90.6	221.2	724			
11358	324	56.3	0.17	20.86	5.91	121.2	1.61	8.2	1.09	10.1	0.32	773	10.3	13.7	13.7	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11914	63	22.2	0.35	11.01	8.19	90	1.76	3.64	0.59	2	0.31	854	6	13.8	13.8	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
10650	12	7.9	0.63	7.83	5.96	45.8	1.26	3.65	0.09	2	0.15	833	11.7	13.6	13.6	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11849	293	98.6	0.34	10.68	6.78	71.9	1.56	3.83	1.73	12.7	0.09	797	4.9	13.4	13.4	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11650	107	35.3	0.33	10.28	6.21	68.2	1.48	4.05	0.13	12.7	0.15	837	8.2	14.2	14.2	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
16607	32	23.1	0.72	5.24	5.64	29.5	1.47	0.68	0.13	3.9	0.22	877	15.3	13.2	13.2	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
12256	87	18.8	0.22	15.66	7.11	111.3	1.67	4.35	0.32	13.5	0.22	801	10.4	13.8	13.8	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
10253	11	6.5	0.58	8.06	5.77	46.5	1.4	1.35	0.1	1.8	0.34	948	9.8	13.8	13.8	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11338	58	19.8	0.34	13.68	9.67	130	1.95	4.4	0.49	7.5	0.15	833	6.6	13.7	13.7	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
12004	413	71.1	0.17	23.68	12.8	303.1	2.21	1.07	0.91	116.9	0.07	784	36.8	14.3	14.3	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
13193	169	65.1	0.39	11.78	8.43	99.3	1.58	5.03	1.03	12.9	0.15	839	2.7	13.8	13.8	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11605	87	28.1	0.32	14.77	8.84	41.8	0.7	4.47	0.64	8.6	0.23	826	11.7	13.6	13.6	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
12300	125	53.8	0.43	11.66	7.49	87.4	1.8	3.16	0.71	11	0.17	833	3	13.8	13.8	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
12134	116	30.6	0.26	20.42	8.4	171.6	1.59	6.28	0.88	15.1	0.33	783	11.7	13.6	13.6	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11962	164	66	0.4	15.62	6.82	106.5	1.91	4.23	1.19	15.7	0.11	813	11.4	13.1	13.1	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
12121	71	23.7	0.33	16.59	8.87	147.1	1.69	4.62	0.56	10.6	0.25	827	1.9	13.4	13.4	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
9228	33	10.9	0.33	8.3	8.2	68	1.55	3.84	0.16	1.8	0.6	828	1.7	13	13	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11614	202	35.2	0.17	19.65	5.71	112.2	1.34	10.73	1.03	8.1	0.34	720	9.3	14.9	14.9	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
10468	126	25.9	0.2	16.73	6.49	108.5	1.24	9.99	0.67	5.9	0.47	788	1.9	12.8	12.8	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
13511	554	71.5	0.13	38.94	8.05	313.4	1.69	29.47	3.2	20.1	0.47	771	11.6	14.2	14.2	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
9662	51	12.8	0.25	12.51	7.42	92.8	1.56	8.33	0.34	2.5	0.53	847	2.8	13.4	13.4	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11250	310	44.5	0.14	26.04	8.42	219.2	2.16	13.65	1.67	12.4	0.39	771	9.7	13.2	13.2	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
10041	78	20.8	0.27	12.1	7.13	86.3	1.5	8.36	0.44	3	0.5	858	8.7	13.3	13.3	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
11940	1149	107.2	0.09	48.36	12.41	600.2	2.7	20.97	7.99	84.6	0.45	659	45.8	12.4	12.4	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
8714	39	16.5	0.42	6.47	3.16	20.5	0.9	2.03	0.16	1.8	0.63	850	2.2	14	14	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
8834	37	17.3	0.47	5.79	3.48	20.1	1.07	1.66	0.14	1.5	0.61	878	1.6	13.5	13.5	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
9107	45	18.2	0.41	6.49	5.56	36.1	1.29	2.32	0.15	1.8	0.6	870	1.9	13.6	13.6	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
9046	56	24.7	0.44	7.11	3.17	22.5	1.04	2.08	0.17	1.8	0.64	865	2.5	13.2	13.2	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
9756	48	10.2	0.21	11.87	10	118.7	1.87	6.07	0.27	2.7	0.47	829	2.1	13.1	13.1	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
9502	69	26.3	0.38	7.91	6.38	50.5	1.4	3.27	0.2	2.3	0.59	822	7.4	13.2	13.2	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
9136	29	9.6	0.34	8.15	6.31	51.4	1.52	3.55	0.16	1.5	0.6	887	2	13.3	13.3	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
10294	136	30.8	0.23	12.75	8.12	103.6	1.4	9.54	0.74	5.7	0.36	799	4	13.6	13.6	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
12273	210	77.1	0.37	14.72	7.17	105.5	1.36	4.06	1.16	22.4	0.28	778	4.7	14.1	14.1	54.09	5.5	27.33	14.35	73.45	289.1	311.8	874.9			
12096	231	61.7	0.27																							

Appendix D: SHIMP-RG Trace Element Data. Presented in order of analysis.																																																									
H	He	Li	Be	B	C	N	O	F	Ne	Ar	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Ni	Cu	Zn	Ga	Ge	As	Se	Br	Kr	Rb	Sr	Zr	Nb	Mo	Tc	Pt	Au	Hg																					
10625	10787	10866	11056	11067	11161	11286	11326	11366	11426	11466	11506	11546	11586	11626	11666	11706	11746	11786	11826	11866	11906	11946	11986	12026	12066	12106	12146	12186	12226	12266	12306	12346	12386	12426	12466																						
11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45																							
5	0.44	7.35	6.15	4.52	1.39	2.02	0.1	1.7	0.43	939	2.8	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2																						
Temp	939	2.8	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2																						
Eu/Eu*	0.3	0.32	0.37	0.42	0.47	0.52	0.57	0.62	0.67	0.72	0.77	0.82	0.87	0.92	0.97	1.02	1.07	1.12	1.17	1.22	1.27	1.32	1.37	1.42	1.47	1.52	1.57	1.62	1.67	1.72	1.77	1.82	1.87	1.92	1.97																						
U/Th	0.1	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18	0.19	0.20	0.21	0.22	0.23	0.24	0.25	0.26	0.27	0.28	0.29	0.30	0.31	0.32	0.33	0.34	0.35	0.36	0.37	0.38	0.39	0.40	0.41	0.42	0.43	0.44																						
Sm/Nd	1.39	2.02	0.1	1.7	0.43	939	2.8	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2																					
La/Ba	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2																				
Ce/Ca	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2																		
Pr/Sm	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2																
Nd/Sm	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2														
La/Th	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2														
Ar/Ar	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2													
Fe	939	2.8	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2											
Ar	2.8	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2									
Ca	939	2.8	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2								
Sc	2.8	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2									
Ti	13.5	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2							
V	0.118	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2								
Cr	11.07	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2									
Mn	5.3	22.74	17.75	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2							
Fe	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2								
Ni	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2						
Cu	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2				
Zn	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2		
Ga	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2
Ge	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	
As	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9	218.2	412.2	74.9															

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