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Testing the Correlation of Trace Element Characteristics with the Petrology
and Temperature of Eruption of mid-Miocene Rhyolites in Eastern Oregon

by

Brianna Christine Young

A thesis submitted in partial fulfillment of the
requirements for the degree of

Master of Science
in
Geology

Thesis Committee:
Martin J. Streck, Chair
Jeffrey Templeton
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Portland State University
2020

Abstract

The Lake Owyhee Volcanic Field (LOVF) in eastern Oregon experienced several major eruptive events during the mid-Miocene (16.8 to 15.5 Ma), resulting in the emplacement of 3,900 km³ of rhyolitic lava flows and ash-flow tuffs. Eighteen samples from eleven different silicic centers in the LOVF were selected for this study. While all samples of this study are classified as rhyolite, their compositions vary greatly in terms of trace and major elements. Using trace elements, these rhyolite samples are classified as “A-type”, described as resulting from “hot and dry” magmas and associated with hot-spot activity, or as “I-type” or “calc-alkaline”, described as rhyolites from “cool and wet” magmas and associated with subduction zones. Seven samples from four units (Buchanan, Circle Bar, Unity, and Dam rhyolites) are classified as I-type, eight samples from five units (Dinner Creek Tuff, Littlefield, Jump Creek, Mahogany Mountain, and Three Fingers rhyolites) are classified as A-type, and three samples from two units (Cottonwood and Dooley Mountain rhyolites) are classified as “borderline”, plotting between A- and I-type.

Mineral assemblages were determined for each sample. Similarities in these assemblages can be seen among samples from different centers of the same “type” (A- or I-). I-type samples contain plagioclase feldspar with high An, sanidine with high Or, orthopyroxene, apatite, biotite, and/or amphibole. A-type rhyolites, on the other hand, typically contain lower-An plagioclase, low-Or alkali feldspar, Fe-rich clinopyroxene, and/or zircon.

Temperatures were estimated using geothermometers specific to the mineral assemblages that were recorded for each sample. The temperature range for samples that

are classified as A-type is 783 to 984 °C, whereas the I-type rhyolites give a much larger range of 737 to 1043 °C when including every geothermometer used. When excluding geothermometers that yield estimates that are greatly influenced by composition (i.e. high An feldspar will yield anomalously high temperatures), the estimate range for I-type rhyolites is 737 to 900 °C.

The temperatures estimated for the A-type rhyolites in this study are consistent with published A-type rhyolite temperatures, such as those found in the Snake River Plain. The I-type rhyolites are slightly more complicated. When excluding the geothermometers that appear greatly influenced by composition, the I-type rhyolites align with published values, such as calc-alkaline rhyolites found at South Sister in Oregon and Okareka center in New Zealand. The appearance of hydrous minerals, biotite and/or amphibole, in several of these I-type rhyolites correlates with much lower average temperatures than samples that do not contain these phases. Similarly, the I-type samples that contain pyroxene tend to yield much higher average temperatures than other I-type rhyolites.

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Introduction

The middle Miocene (16 to 14 million years ago) saw extensive volcanic activity in eastern Oregon, including lava flows of the main Columbia River Basalt and numerous contemporaneous rhyolite eruptions. The Lake Owyhee Volcanic Field is a region of eastern Oregon characterized by several silicic centers that were active during the mid-Miocene. An increasing number of studies are correlating the Columbia River flood basalts to the arrival and passage of the Yellowstone hot spot beneath eastern Oregon (Coble and Mahood, 2012; Ferns and McClaughry, 2013; Colon, 2015). Rhyolites associated with mafic Columbia River Basalt group magmas range widely in character from typical high-temperature, drier, more reduced A-type rhyolites like those found along the Snake River Plain (Christiansen and McMurry, 2008) to cooler, more oxidized, wetter calc-alkaline I-type rhyolites that are more typical for volcanic arcs. Presently, these characterizations are entirely borne out by geochemical characteristics. This study investigates how observed geochemical characteristics correlate with mineralogical and physical parameters such as temperature derived from geothermometers and relates possible temporal and spatial patterns of rhyolite volcanism to flood basalt volcanism.

This project focuses on multiple silicic units found in and around the Lake Owyhee Volcanic Field (Fig. 1). This includes rhyolites from the following areas or units: Dooley Mountain, Buchanan Dome Complex, Unity, Dinner Creek Tuff, Malheur River, Cottonwood Mountain, Littlefield Rhyolite, Jump Creek, Owyhee Dam, and Three Fingers/Mahogany Mountain. Using geochemical data from previous studies, these rhyolites have been grouped as “A-type” or “I-type” using discrimination techniques that were initially developed for felsic plutonic rocks by Whalen et al. (1987). Additionally, a

“borderline” group was designated for multiple rhyolitic centers that have geochemical signatures of near or between “A-“ and “I-type” fields.

Eighteen samples from eleven different silicic centers were selected for this study. Mineralogy was documented for each sample and compared to other samples within the same unit as well as other samples that were classified as the same “type” using geochemical data. This study also reports the estimated eruption temperatures for these rhyolites based on multiple geothermometers.

Understanding the conditions under which these rhyolites formed will lead to a more comprehensive understanding of the greater Lake Owyhee Volcanic Field. Additionally, it will enhance our understanding of the thermal pulse associated with the CRB magmas below eastern Oregon and its relationship to the movement of the Yellowstone hot spot.

1. Background

1.1 Geologic Setting

Eastern Oregon has experienced a long volcanic history, including several major eruptive events of both basaltic and rhyolitic magmas (e.g., Coble and Mahood, 2012). During the mid-Miocene (16.8 to 15.5 Ma), the eruption of the main Columbia River Basalt units covered more than 200,000 square kilometers of Oregon, Idaho, and Washington State (Barry et al., 2013). Contemporaneously or slightly after these flood basalt eruptions, rhyolitic eruptions began in eastern Oregon, western Idaho, and northwestern Nevada, resulting in the emplacement of 3900 km³ of rhyolitic lava flows and ash-flow tuffs that covered an area of 25,000 km² (Coble and Mahood, 2012; Streck et al., 2015; Webb et al., 2018).

Figure 1. (a) Map of Oregon; study area is contained in the yellow rectangle. (b) Location map for the centers considered in this study with age of onset of rhyolite volcanism. The extent of the Dinner Creek tuff is shown in tan shading (Streck, unpublished data).

Mid-Miocene rhyolite volcanism is preserved in silicic centers belonging to the Lake Owyhee Volcanic Field (LOVF) centered near the town of Vale, the McDermitt volcanic field along the Oregon–Nevada state border, and other rhyolitic centers in their vicinity (Cummings et al., 2000; Ferns and McClaughry, 2013; Ford et al., 2013), many of which have not been studied as much as the contemporaneous lava flows of the Columbia River Basalt Group (CRBG) (Fig. 1). Mid-Miocene centers associated with the Lake Owyhee field and surroundings are Dooley Mountain, which is the northernmost silicic center within the Lake Owyhee Volcanic Field, in Baker County. East of Dooley Mountain are exposures of rhyolites found at the Unity Reservoir (further to be referred to as the Unity rhyolites). South of Unity, rhyolitic lavas and domes are exposed along the Malheur river, referred to as the Malheur rhyolites, which overlie lavas belonging to

the Steens Basalt (Camp et al., 2003). This study focuses on one of these units, the Circle Bar rhyolite. The Cottonwood Mountain and Littlefield rhyolites (now known as lower and upper Littlefield Rhyolite, respectively (Webb et al., 2018), erupted coevally to the formation of the Oregon-Idaho graben (Cummings et al., 2000). The Cottonwood Mountain center is a large area (~500 square kilometers) of silicic lavas (up to 200 meters thick) that can be found north of the Malheur River. The Littlefield Rhyolite covers an area of about 450 square kilometers extending south of the Malheur River. In some locations, the Littlefield Rhyolite can be upwards of 300 meters thick. Stratigraphically immediately below the Littlefield rhyolite is the Dinner Creek Tuff (Webb et al., 2018). Covering a region of approximately 20,000 square kilometers of eastern Oregon, the extensive Dinner Creek Tuff has multiple units and indicate variable welding (Streck et al., 2015). The Dinner Creek Tuff acts as an excellent marker for much of the LOVF. Along the eastern edge of the Oregon-Idaho graben there are two important silicic centers: Three Fingers and Mahogany Mountain calderas. Approximately 5 kilometers of distance separates the calderas. Tuff of Spring Creek is a low silica rhyolite ash-flow tuff that was erupted during the collapse of Three Fingers caldera and the tuff of Leslie Gulch during the collapse of the Mahogany Mountain caldera, around 15.4 Ma. (Cummings et al., 2000; Ferns and McClaughry, 2013); although some workers favor the interpretation of only one larger caldera giving rise to only one ignimbrite (Benson and Mahood, 2016). In the area of the Mahogany Mountain caldera, the Jump Creek rhyolite erupted on the eastern flank of the Oregon-Idaho graben between 11.1-10.6 Ma. This flow covered roughly 100 square kilometers (Cummings et al., 2000). Lastly, along the western edge

of the rhyolite distribution area, there are several rhyolite centers and domes such as Buchanan, Donnelly Butte, rhyolite at Craft Point, and others.

1.2 Geochemistry and Petrology of Rhyolites

Rhyolites from the Lake Owyhee Volcanic Field can be separated into “A-type” and “I-type” based on the methodology for discrimination of granitic rocks by Whalen et al. (1987). Originally, Whalen et al. (1987) show that granitoids could be classified as A-type based on the relative abundance of Nb, Y, Ta, Yb and Rb trace element data (as was already noted by Pearce et al., 1984). A-type rhyolites are also distinguished by using the original classification scheme of Chappell and White (1974) that utilizes alkali content. According to the above sources, typical A-type rhyolites have higher SiO₂, are rich in iron and neodymium, and the sum of concentrations of Zr, Nb, Y, and Ce is above 350 ppm. When compared with I-type rhyolites, A-type display a higher Ba/Sr and lower La/Yb ratios in addition to having higher concentrations of both high field strength elements and rare earth elements, specifically those that are more incompatible. Additionally, A-type rhyolites exhibit a high Fe/Mg ratio compared to I-type rhyolites (Whalen et al., 1987). And lastly, typical phenocrystic phases are Fe-rich pyroxene, fayalite, and anorthoclase or Na-rich sanidines. They are described as originating from “hot and dry” magmas and are typically associated with bimodal provinces or flood basalt provinces (Whalen et al., 1987; Anderson et al., 2008; Christensen et al., 2008). “I-type” (or calc-alkaline) rhyolites are silicic rocks often with lower SiO₂, higher concentrations of magnesium, aluminum, and strontium, and have a sum of Zr, Nb, Y, and Ce concentrations below 350 ppm (Fig. 2). The Fe/Mg ratio will be lower than

rhyolites classified as A-type (Whalen et al., 1987). Typically, these rhyolites are crystal-rich, hydrous minerals are common, and if they contain pyroxene, these are typically augite or orthopyroxenes with lower Fe/Mg ratios. These are described as “cool and wet” magmas, have higher water content, and are often associated with volcanic arcs (Whalen et al., 1987; Anderson et al., 2008; Christensen et al., 2008). When compositions of mid-Miocene rhyolites are plotted using trace elements sensitive for distinguishing A- from I-type, then it can be observed that eastern Oregon rhyolites range widely from I- to A-type (Fig. 3).

Figure 2. FeO versus SiO₂ content for the rhyolites of LOVE. Samples with SiO₂ content greater than 75% are considered “high silica”. As SiO₂ content increases, FeO concentrations tend to decrease. Data from Steiner and Streck, 2013; Marcy, 2013; Streck et al., 2015; Hess, 2014; and Streck, unpublished data.

Figure 3. Nb versus Zr concentrations for the rhyolites of LOVF. Samples that plot within the box can be classified as I-type using discrimination techniques of Whalen et al., 1987. The coordinates of the box are X=250, Y=20. Samples with Zr less than 250 ppm and Nb less than 20 ppm are classified as I-type. Data from Steiner and Streck, 2013; Marcy, 2013; Streck et al., 2015; Hess, 2014; and Streck, unpublished data.

1.3 Ages of Rhyolites

Rhyolites of interest within the Lake Owyhee Volcanic Field have been dated using potassium-argon or argon-argon dating techniques. Buchanan rhyolites give a variable K/Ar age date of 13.9 to 15.1 Ma (Evans and Brown, 1981; Fiebelkorn et al., 1982, respectively). Dooley Mountain has been dated at 14.7 Ma (Evans, 1992). Dinner Creek Tuff has most recently been dated between 15.38 and 16.15 (Streck et al., 2015). Cottonwood has been dated around 14.6 and 15.7 Ma (Hooper et al., 2002). Ages of Littlefield rhyolites have been found to range widely up to around 16.6 Ma (Hooper et al.,

2002, cf. Webb et al., 2018). Mahogany Mountain gives an age of 15.5 Ma (Vander Meulen et al., 1987). Malheur River rhyolites have been described as erupting between 15.7 to 7 Ma based on stratigraphic relationships to surrounding rock units (Camp et al., 2003). Three Fingers displays a similar age to Mahogany Mountain of 15.64 Ma (Marcy, 2013). Lastly, Unity had been dated at 15.45 Ma (Large, 2016). Recent high-precision Ar-Ar dating by Streck et al. indicate that the published ages of older publications mentioned above tend to be more variable and tend to have yielded younger ages, possibly due to Ar loss.

2. Methods

2.1 Sample Selection

This study utilized thin sections made during previous studies. Eighteen thin sections were selected to represent eleven distinct silicic centers (Table 1). Because some centers erupted a range of rhyolites, in other words, differ in their A/I-type classification, several samples from the same center were sometimes investigated.

Table 1. Unit IDs used to represent volcanic units for each sample used in this study.

Unit ID	Volcanic Unit	Sample #
BDC	Buchanan Rhyolite Complex	EJ-12-03
BDC	Buchanan Rhyolite Complex	B010
BDC	Buchanan Rhyolite Complex	B114
CMR	Rhyolite of Cottonwood Mountain	EJ-12-16
CMR	Rhyolite of Bully Creek	EJ-12-17
DAM	Dam Rhyolite	EJ-12-15
DIT	Dinner Creek Tuff	EJ-12-08
DMR	Dooley Mountain Rhyolite	DR2
JCR	Jump Creek Rhyolite	EJ-12-13B
LIT	Littlefield Rhyolite	EJ-12-10
MAH	Old McIntyre Rhyolite	EJ-12-12
MAH	Young McIntyre Rhyolite	EJ-12-14
MAH	Young McIntyre Rhyolite	MS-13-24b
MAH	Spring Creek Tuff	MS-13-29
MAL	Circle Bar Rhyolite (Malheur River)	EJ-12-05B
TFI	Three Fingers Rhyolite	TF-153H
UNI	Rhyolite Lava Flow, North of Unity	CR-U3A
UNI	Tuff, North of Unity	CR-U4B

2.2 Analytical Methods

2.2.1. Thin Section and Petrographic Analyses

Mineral assemblages and petrographic characteristics were determined using plane and crossed polarized transmitted light. A summary of findings can be found in Table 2. Optical microscopy was also to determine the mineral phases present in each thin section and pre-select phenocrysts for analysis on the scanning electron microscope.

2.2.2. Scanning Electron Microscopy

Polished thin sections were carbon-coated and analyzed using the Zeiss Sigma VP FEG SEM in the Center for Electron Microscopy and Nanofabrication (CEMN) located at Portland State University. Backscattered electron and energy-dispersive X-ray spectroscopy (EDS) modes on the SEM were used to measure elemental concentrations to confirm mineral assemblages and to determine their composition. The following parameters were used to during analysis:

- High accelerating voltage: 15 kV
- Large aperture: 60 um (in high current mode)
- Analytical working distance: 8.5 mm

Between 3-5 point analyses within single phenocrysts were averaged as a measure of the composition of a phenocryst.

2.3 Geothermometry

Based on the observed mineralogy of the samples selected, appropriate geothermometers were applied. In several cases, more than one geothermometer was applied to better constrain temperatures. Most geothermometers require a pressure component. For this study, a pressure of 0.1 GPa (1 kbar) was used to represent a shallow magma body, as 1 kbar equates to roughly 3.5 km of overlying rock. When pressure is changed to a higher value (i.e. 1 GPa or 10 kbar), the estimated temperature increases by about 30 to 40°C, depending on the geothermometer. Some geothermometers (i.e. the Two-Pyroxene) use the composition of the mineral phases compared to the bulk composition or another mineral phase to estimate pressure and calculate the eruption temperature. Likewise, no values of H₂O needed to be entered for any geothermometers; either the geothermometer would estimate water content itself, or the component was not necessary to estimate temperature. Below is a list of geothermometers that were applied to the rhyolites. This list does not include the two-oxide geothermometer because a companion study (Orr, 2019) applies this geothermometer to the same set of rhyolites.

- **Plagioclase or Alkali Feldspar – Liquid** - This geothermometer is based on the equilibrium between the feldspar and liquid (i.e. glass) components (Putirka, 2008). This is calculated by using the cation fractions of a liquid component and mole fractions of albite and anorthite in plagioclase (Eq. 1) or of albite in alkali feldspar (Eq. 2). For this study, the bulk composition of the rhyolite was used as the liquid component.

Equation 1. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of plagioclase feldspar and bulk rhyolite geochemistry. This is equation 24a from Putirka (2008).

$$\begin{aligned} \frac{10^4}{T(K)} = & 6.4706 + 0.3128 \ln \left(\frac{X_{An}^{pl}}{X_{CaO}^{liq} (X_{AlO_{1.5}}^{liq})^2 (X_{SiO_2}^{liq})^2} \right) - 8.103 (X_{SiO_2}^{liq}) \\ & + 4.872 (X_{KO_{0.5}}^{liq}) + 1.5346 (X_{Ab}^{pl})^2 + 8.661 (X_{SiO_2}^{liq})^2 \\ & - 3.341 \times 10^{-2} (P(\text{kbar})) + 0.18047 (H_2O^{liq}) \end{aligned} \quad (24a)$$

Equation 2. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of alkali feldspar and bulk rhyolite geochemistry. This is equation 24b from Putirka (2008).

$$\begin{aligned} \frac{10^4}{T(K)} = & 17.3 - 1.03 \ln \left(\frac{X_{Ab}^{afs}}{X_{NaO_{0.5}}^{liq} X_{AlO_{1.5}}^{liq} (X_{SiO_2}^{liq})^3} \right) - 200 (X_{CaO}^{liq}) \\ & - 2.42 (X_{NaO_{0.5}}^{liq}) - 29.8 (X_{KO_{0.5}}^{liq}) + 13500 (X_{CaO}^{liq} - 0.0037)^2 \\ & - 550 (X_{KO_{0.5}}^{liq} - 0.056) (X_{NaO_{0.5}}^{liq} - 0.089) - 0.078 P(\text{kbar}) \end{aligned} \quad (24b)$$

- **Two – Feldspar₋** This geothermometer considers the partitioning of albite component between plagioclase and alkali feldspar. Cation fractions of Si and Ca are used in conjunction with mole fractions of albite and anorthite in both plagioclase and alkali feldspar (Eq. 3) (Putirka, 2008)

Equation 3. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of plagioclase feldspar and alkali feldspar. This is equation 27b from Putirka (2008).

$$T(^{\circ}\text{C}) = \frac{-442 - 3.72P(\text{kbar})}{-0.11 + 0.1 \ln \left(\frac{X_{Ab}^{afs}}{X_{Ab}^{pl}} \right) - 3.27 (X_{An}^{afs}) + 0.098 \ln (X_{An}^{afs}) + 0.52 (X_{An}^{pl} X_{Ab}^{pl})} \quad (27b)$$

- **Orthopyroxene – Liquid** – This geothermometer considers the equilibrium between orthopyroxene and liquid components. Temperature is determined by using cation fractions in orthopyroxene and the liquid as well as the mole fraction of enstatite and ferrosilite (Eq. 4) (Putirka, 2008).

Equation 4. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of orthopyroxene and bulk rhyolite geochemistry. This is equation 28a from Putirka (2008).

$$\begin{aligned} \frac{10^4}{T(^{\circ}\text{C})} = & 4.07 - 0.329[P(\text{GPa})] + 0.12[\text{H}_2\text{O}^{liq}] \\ & + 0.567 \ln \left[\frac{X_{\text{Fm}_2\text{Si}_2\text{O}_6}^{opx}}{(X_{\text{SiO}_2}^{liq})^2 (X_{\text{FeO}}^{liq} + X_{\text{MnO}}^{liq} + X_{\text{MgO}}^{liq})^2} \right] \\ & - 3.06[X_{\text{MgO}}^{liq}] - 6.17[X_{\text{K}_{0.5}}^{liq}] + 1.89[Mg\#^{liq}] + 2.57[X_{\text{Fe}}^{opx}] \end{aligned} \quad (28a)$$

- **Clinopyroxene-Liquid** – In this geothermometer, only clinopyroxene is considered. Temperature is calculated using cation fractions of various elements (Ti, Fe, Al, Cr, Na, K) and activity of enstatite in clinopyroxene (Fig. 5) (Putirka, 2008).

Equation 5. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of clinopyroxene and bulk rhyolite geochemistry. This is equation 33 from Putirka (2008).

$$\begin{aligned} \frac{10^4}{T(\text{K})} = & 7.53 - 0.14 \ln \left(\frac{X_{\text{Jd}}^{cpx} X_{\text{CaO}}^{liq} X_{\text{Fm}}^{liq}}{X_{\text{DiHd}}^{cpx} X_{\text{Na}}^{liq} X_{\text{Al}}^{liq}} \right) + 0.07(\text{H}_2\text{O}^{liq}) - 14.9(X_{\text{CaO}}^{liq} X_{\text{SiO}_2}^{liq}) \\ & - 0.08 \ln(X_{\text{TiO}_2}^{liq}) - 3.62(X_{\text{Na}_{0.5}}^{liq} + X_{\text{K}_{0.5}}^{liq}) - 1.1(Mg\#^{liq}) \\ & - 0.18 \ln(X_{\text{EnFs}}^{cpx}) - 0.027P(\text{kbar}) \end{aligned} \quad (33)$$

- **Two – Pyroxene** – This geothermometer utilizes the partitioning of Al between the clinopyroxene and liquid as well as Jadeite-Diopside + Hedenbergite exchange as a means of calculating temperature. This thermometer considers cation fractions within each phase as well as mole fractions of enstatite, ferrosilite, or diopside (Eq. 6) (Putirka, 2008).

Equation 6. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of clinopyroxene and orthopyroxene. This is equation 37 from Putirka (2008).

$$\frac{10^4}{T(^{\circ}\text{C})} = 13.4 - 3.4 \ln \left(\frac{X_{\text{EnFs}}^{\text{cpx}}}{X_{\text{EnFs}}^{\text{opx}}} \right) + 5.59 \ln \left(X_{\text{Mg}}^{\text{cpx}} \right) - 8.8 \left(Mg^{\# \text{cpx}} \right) \quad (37)$$

$$+ 23.85 \left(X_{\text{Mn}}^{\text{opx}} \right) + 6.48 \left(X_{\text{FmAl}_2\text{SiO}_6}^{\text{opx}} \right) - 2.38 \left(X_{\text{Di}}^{\text{cpx}} \right) - 0.044 P(\text{kbar})$$

- **Olivine – Liquid** – This geothermometer uses the partitioning of Mg between olivine and the liquid components (Eq. 7) (Putirka, 2008).

Equation 7. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of olivine and bulk rhyolite geochemistry. This is equation 21 from Putirka (2008).

$$\ln D_{\text{Mg}}^{\text{ol/liq}} = -2.158 + 55.09 \frac{P(\text{GPa})}{T(^{\circ}\text{C})} - 6.213 \times 10^{-2} \left[\text{H}_2\text{O}^{\text{liq}} \right] + \frac{4430}{T(^{\circ}\text{C})}$$

$$+ 5.115 \times 10^{-2} \left[\text{Na}_2\text{O}^{\text{liq}} + \text{K}_2\text{O}^{\text{liq}} \right] \quad (21)$$

- **Hornblende – Plagioclase Feldspar** – Temperature is calculated using the cation fractions of various elements (Al, Fe, Mg, Ca) and the mole fractions of albite and anorthite in plagioclase feldspar (Eq. 8) (Holland and Blundy, 1994).

Equation 8. Equation used to estimate the temperature of LOVF rhyolites using measured element concentrations in phenocrysts of amphibole and plagioclase feldspar. This is equation 17 from Holland and Blundy (1994).

$$T_{(ed-ri)} = \frac{\Delta H_B^0 + Y_{ab-an} + Y_{(ed-ri)}}{\Delta S_B^0 - R \ln K_{ideal}^{ed-ri}} \quad (17)$$

- **Zircon and Apatite Saturation** – Zircon and apatite saturation thermometry refers to the proportion of zircon and/or apatite that has crystallized at specific temperatures to calculate temperature (Eq. 9) (Watson and Harrison, 1983).

Equation 9. Equation used to estimate the temperature of LOVF rhyolites using bulk rhyolite geochemistry and confirmation of zircon phenocrysts. This is equation 2 from Watson and Harrison (1983).

$$\ln D_{Zr}^{zircon/melt} = \{-3.80 - [0.85(M - 1)]\} + 12900/T \quad (2)$$

3. Results

3.1 Geochemistry of Rhyolites

For each unit considered in this study, geochemical data were compiled from previous studies to compare samples of a single silicic center as well as to compare to other mid-Miocene centers of silicic volcanism of the LOVF. This compilation also demonstrates how each sample of this study, which was used for a petrographic analysis and geothermometry, relates to other samples of the same center and thus indicates how representative it is of the entire center.

Focus was given to assign a sample whether it is compositionally an “A-type” rhyolite or and “I-type”, also designated here as “calc-alkaline” type. This was done to investigate correlation of mineralogy and temperature with geochemical characteristics as A-type rhyolites are considered hotter, drier, and more reduced magmas while calc-alkaline (or I-type) rhyolites are wetter, cooler, and more oxidized (Bachmann and Bergantz, 2009; Streck, 2014). Whalen et al. (1987) present several “tests” based on trace element concentrations to determine if a sample is “A-type” or “I-type”. Zr, Nb, Ce, Y, and 10000Ga/Al concentrations appear to be diagnostic and determine if a sample has A- or I-type affinities. Samples that have Zr concentrations higher than 250 ppm, Nb that is above 20 ppm, 10000Ga/Al higher than 2.6, and trace element (Zr+Ce+Y+Nb) concentrations of greater than 350 ppm are all considered signs of being an A-type rhyolite. If the samples fall below these values, they are considered I-type (i.e. calc-alkaline). In addition, A-type rhyolites tend to have higher FeO* concentrations at a given silica content, despite that there is a general negative correlation between silica and iron oxide that, in turn, is mostly caused by processes of fractional crystallization (Fig. 2).

3.1.1. Buchanan Rhyolite Complex

Compositional data for the Buchanan rhyolite complex were taken from Hess (2014) and from Large (2016). Buchanan rhyolites indicate a wide range of silica and iron oxide content (69-84% and 0.6 to 4.1% respectively) (Fig. 42). SiO₂ values greater than 77.4 wt.% are considered to be induced during secondary processes and are not considered magmatic values (Hildreth, 1981). As such, there are five Buchanan rhyolites that record silica contents greater than 77.4% and one sample used in this study (EJ-12-03) indicates secondary processes (78.81%). The samples considered for this study have varying degrees of silica and iron oxide. One representative of the Buchanan complex, B114, has the lowest silica (69%) and one of the highest percentages of iron (4.1%) compared to the rest of the collected samples. The other two samples used as representatives for this center have silica and iron contents that fall in line with the majority of Buchanan rhyolites (77-78% SiO₂ and 0.8-1.04% FeO*).

Zr concentrations range between 121 and 360 ppm (Fig. 4). Similarly, Nb concentrations range between 9.3 and 19.54 ppm. As a result, Buchanan samples range from being I- type to mildly A-type rhyolites with the majority of samples plotting as I-type. Two of the Buchanan samples considered for this study, B010 and B114, fall within the I-type range; one of these rhyolites has the lowest concentration of Zr of the entire sample set. The second Buchanan rhyolite falls in the middle range for both Zr and Nb. The third sample that is used as a representative (EJ-12-03) plots as an A-type rhyolite; this sample had the highest SiO₂ and lowest FeO of the three.

Figure 4. Diagram illustrating Nb versus Zr concentration in rhyolites from the Buchanan Rhyolite Complex. Samples used in this study as representatives for the center are denoted in red. Samples that plot within the box (where $x=250$ and $y=20$) are denoted as “I-type” whereas those that fall outside of the box are “A-type”.

Using $10000\text{Ga}/\text{Al}$ and the sum of trace elements, Buchanan samples plot as A- and I-type (Fig. 43) similarly to using the Zr against SiO_2 as discriminator (Fig. 44).

Using these last two parameters, samples are fairly split 50-50 in the I- and A-type ranges. In summary, the representatives for this study consist of two Buchanan samples that plot as I-type (B010 and B114) and one sample that plots as A-type, consistently in all plots.

3.1.2. Malheur River Rhyolite

The range of SiO₂ for the Malheur rhyolites is fairly narrow with the exception of one sample. The majority of the rhyolites have SiO₂ concentrations between 74.5 and 77%; however, one sample plots below 72% SiO₂ (Fig. 45). This single sample also has a significantly higher amount of FeO* (4.5%) compared to rest of the rhyolites (between 0.93 and 1.47%). The rhyolite selected to represent this group, EJ-12-05b, has moderate silica values (75.34%), but has slightly elevated FeO* compared to the other Malheur rhyolites with similar SiO₂ (1.40%).

Using the Zr and Nb parameters, the majority of Malheur samples are classified as I-type with the exception of two outliers that plot as A-type (Fig. 47). The Malheur rhyolite representative has Zr and Nb concentrations indicating I-type (117 ppm and 13.5 ppm, respectively). This representative falls in a small cluster of Malheur rhyolites with respect to Zr and SiO₂ (Fig. 48).

When considering 10000Ga/Al and the sum of trace elements, the majority of Malheur rhyolite samples plot as I-type, however there are three samples that are classified as A-type (Fig. 46). Two of these A-type samples are also designated as A-type using Zr and Nb concentrations. The Malheur sample used in this study falls directly in the middle of the concentrations for the cluster of I-type Malheur rhyolites with a 10000Ga/Al of 2.12 and a sum of trace elements of 200 ppm. The cluster has a range of 10000Ga/Al between 1.98 and 2.3 and a trace element sum range that falls between 146 and 347 ppm. In summary, the Malheur River rhyolites are mostly I-type,

including the sample used for this study. Two samples consistently can be classified as A-type and one sample appears to be borderline A-/I- type.

3.1.3. Unity Rhyolite

The Unity rhyolites have a broad range in SiO₂ (72.07 to 76.57%), but a small range in FeO* (0.53 to 1.90%) (Fig. 49). Two samples used to represent the Unity rhyolites. One of the samples used in this study, U4B, has the lowest SiO₂ and a higher FeO* compared to the rest of the sample set. The second representative for this group, U3A, has average SiO₂ and FeO* concentrations compared to the other Unity rhyolites.

When using Zr and Nb to determine A- or I-type, the Unity samples fall in the I-type range with the exception of one rhyolite that is just on the border between A- and I-type (20.5 ppm Nb) (Fig. 51). There are three small clusters of Unity rhyolites. Two groups are lower in Zr concentration (120 to 130 ppm) than the third cluster (170 ppm). The lower Zr samples separate into two groups based on Nb and SiO₂ concentrations. One group has Nb near 17.5 ppm whereas the other group is closer to 13 ppm. Similarly, one group has lower SiO₂ (around 72.0 to 72.5%) whereas the other group has higher values (76.0 to 76.5%) (Fig. 52). The third group is a sample set of three rhyolites with the highest Zr concentration of the Unity rhyolites, clustering near 170 ppm Zr and 14.5 ppm Nb.

Lastly, the trace element sum and 10000Ga/Al diagram classifies all Unity samples as I-type (Fig. 50). One sample is on the borderline of 10000Ga/Al (at 2.57), but technically falls within the bounds of I-type. Within the I-type field, the Unity samples

are spread apart. One of the Unity representatives, U4B, has the lowest 10000Ga/Al value and one of the lowest trace element sums (1.95 and 191.3 ppm, respectively) along with the lowest Nb, the lowest SiO₂, and one of the highest FeO* concentrations. The other sample used for this study, U3A, has a moderate value of 10000Ga/Al and trace element sum: 2.39 and 228.5 ppm. In summary, the Unity rhyolites can be classified as I-type, with some samples on the borderline between A- and I-type.

3.1.4. Cottonwood/Littlefield Rhyolite Complex

The Cottonwood and Littlefield samples have a narrow range of SiO₂ concentrations (~71 to 73.4%) (Fig. 53). The Cottonwood samples mostly plot between 72.4 to 73.4% and record FeO* concentrations within a narrow range (2.72 to 3.78%). When compared to the Littlefield samples, the Cottonwood center displays lower FeO* and higher SiO₂. Despite this, the range of SiO₂ in Littlefield is also very narrow: 71.08 to 72.35%. There is a cluster of Littlefield samples around 4% FeO* and between 72 and 72.5% SiO₂. The Bully Creek sample used as a representative in this study (EJ-12-17) plots within this Littlefield cluster. The Cottonwood representative (EJ-12-16) has a SiO₂ value that is slightly higher (73.04%) than the Bully Creek representative, making it more similar to the other Cottonwood samples. Lastly, the rhyolite used as the upper Littlefield Rhyolite representative (EJ-12-10) has the highest FeO* (5.79%) and lowest SiO₂ (71.08%) of the entire Cottonwood/lower Littlefield suite.

When using Nb against Zr to determine type, all samples of both Littlefield and Cottonwood fall in the A-type field (Fig. 54). There are two distinct groups of Littlefield

samples. One cluster comprised of five Littlefield rhyolites and the entirety of Cottonwood samples plots near 300 ppm Zr, but records concentrations below 20 ppm Nb. The Cottonwood and Bully Creek representatives both plot within this group. The other group of Littlefield samples plots around 550 ppm Zr and between 35 to 40 ppm Nb. The Littlefield representative falls within this cluster.

Using the $10000\text{Ga}/\text{Al}$ and trace element sum tests to determine type, the Littlefield and Cottonwood samples are classified solely as A-type (Fig. 5). Two distinct groups can be noted. The Cottonwood samples (including the Cottonwood and Bully Creek representatives and lower Littlefield samples) plot alongside about half of the Littlefield samples between 2.5 and 3 $10000\text{Ga}/\text{Al}$ and have trace element sums between 400 to 500 ppm. The Littlefield representative falls alongside the other half of the Littlefield group near trace element concentrations of 800 ppm and $10000\text{Ga}/\text{Al}$ between 3.5 and 4. To summarize, the Cottonwood and Littlefield rhyolite complex can be classified as A-type, indicating two distinct groups of rhyolites separated by concentrations of trace elements.

Figure 5. Diagram illustrating the sum of trace elements (Zr+Nb+Y+Ce) versus 10000Ga/Al in rhyolites from the Cottonwood/Littlefield Rhyolite Complex. Samples used in this study as representatives for the Cottonwood center are in dark red. The representative selected for Littlefield is in pink. All other lower Littlefield samples are dark blue, upper Littlefield samples are dark blue open diamonds, and the rhyolites of Cottonwood are noted in light blue. All samples plot outside of the I-type field, given by the coordinates $x=2.6$, $y=350$. As a result, all samples are classified as A-type.

3.1.5. Dinner Creek Tuff

The Dinner Creek Tuff rhyolites are compositionally variable depending on which unit it is (Streck et al., 2015). Silica concentrations range between ~71 to almost 78%. FeO* concentrations fall between ~0.75 to 4.2% (Fig. 59). For the sample selected as a representative of Dinner Creek Tuff (EJ-12-08), the average composition of Unit 1 of the Dinner Creek Tuff was used. As a result, the representative plots with SiO₂ that is similar to other Dinner Creek tuff samples (76%), with moderate FeO* contents (2.07%).

Using the Nb vs Zr parameters, every sample in the Dinner Creek group is classified as A-type (Fig. 61). A positive trend with regard to Nb and Zr can be noted; as Zr concentration increases, Nb also increases. This positive trend is also noted when considering Zr against SiO₂; as SiO₂ increases, Zr concentration also increases,. The representative has fairly high Zr concentration (429 ppm) and with moderate Nb concentration (23.98 ppm).

When considering the 10000Ga/Al and trace element sum tests, all Dinner Creek samples again plot solely as A-type (Fig. 60). The samples appear more dispersed rather than clustered using these parameters. The range for 10000Ga/Al is between 2.9 to almost 3.3 whereas the trace element sum spans roughly 466 to 670 ppm. The Dinner Creek Tuff representative is on the high end of the 10000Ga/Al range compared to the rest of the group (3.26) and also displays one of the highest trace element sum (638 ppm). In summary, the Dinner Creek tuff plots exclusively as A-type and the average composition of Unit 1 of Dinner Creek Tuff plots on the high end of SiO₂, Zr, Nb, 10000Ga/Al, and trace element sums compared to the other units of Dinner Creek Tuff.

3.1.6. Dooley Mountain Rhyolite

The Dooley Mountain center records a moderate range of SiO₂ (~73.9 to 77.65%) and a considerable span for FeO* (0.62 to 2.86%) (Fig. 6). The majority of Dooley Mountain rhyolites are over 76% SiO₂ and below 1.5% FeO*. For this study, the representative sample, DR2, has the lowest SiO₂ concentration (73.9%) and fairly high FeO* (2.08%) compared to the majority of rhyolites in this sample set.

Figure 6. Diagram illustrating FeO* versus SiO₂ concentration in rhyolites from Dooley Mountain. Samples used in this study as representatives for the center are noted in red. The sample used for this study, DR2, has the lowest SiO₂ of all other collected samples from Dooley Mountain.

The rhyolites of Dooley Mountain are split between A- and I-type when using the parameter of Zr and Nb concentrations (Fig. 57). The representative for this study is classified as A-type and lies within a cluster of rhyolites recording higher concentrations of Zr compared to the rest of the group (363 ppm). The concentration of Nb in this sample (14.1 ppm) lies directly in the middle range for the A-type cluster.

Using the parameters of trace element sums against 10000Ga/Al shows about half of the Dooley Mountain samples falling in both A- and I-type (Fig. 56). The Dooley sample used in this study plots as A-type using this discrimination technique, however it plots near the lower end of A-type with regard to 10000Ga/Al (2.68). Additionally, this

sample falls in the middle of the range for the majority of A-type Dooley rhyolites when considering the sum of trace elements (490 ppm). In summary, the Dooley Mountain rhyolites record trace element concentrations that split samples between A- and I-type rhyolites. The sample used in this study consistently plots as A-type using these parameters.

3.1.7. Three Fingers/Mahogany Mountain Caldera Complex

This large center displays a very wide range of both SiO₂ and FeO* contents. Overall, the Three Fingers-Mahogany Mountain complex records SiO₂ values between 72.6 and 82.0%, with a very high outlier around 86.6% (Fig. 63). These very high SiO₂ contents (>77.4%) indicate secondary processes are at play and are not considered magmatic SiO₂ values. With regard to FeO*, the samples range between 0.28 and 4.72%. Within the Dam rhyolite, an extension of the Mahogany complex, the range is very narrow: from 72.6 to 72.8% SiO₂ and 1.9 to 2% FeO* and the representative (EJ-12-15) is the sample with higher SiO₂, lower FeO*. The Jump Creek rhyolite (EJ-12-13b) plots at 73.52% SiO₂ and 1.81% FeO*, near the Dam rhyolites. The range for Three Fingers rhyolite is also fairly narrow. These samples range between 76.63 to 78.43% SiO₂ and 0.88 to 2.11% FeO*. The sample selected as a representative of Three Fingers rhyolite (TF-153H) lies right in the middle of these ranges (77.20% SiO₂ and 1.95% FeO*). The Mahogany suite, on the other hand, has a large range in both silica and iron oxide. These samples span from 72.61 to 86.58% SiO₂ and 0.28 to 4.72% FeO*. Four samples were selected to represent the Mahogany Mountain caldera rhyolites: two representing Young

McIntyre (EJ-12-14 and MS-13-24b), one sample representing Old McIntyre (EJ-12-12), and a fourth sample that represents the intra-caldera tuff of Spring Creek (MS-13-29). The tuff of Spring Creek sample has very high FeO* compared to the rest of the group (4.72%) and lies on the lower end of the range of SiO₂ (72.9%). The sample of Old McIntyre plots within a small cluster of Mahogany Mountain rhyolites near 74% SiO₂ and 4.15% FeO*. The two representatives of Young McIntyre plot near each other around 76.35 to 77.14% SiO₂ and 1.59 to 1.4% FeO*. These two samples fall near a cluster of Three Fingers rhyolites, which are slightly lower in FeO* compared to the rest of the Mahogany Mountain rhyolites with similar SiO₂.

The Three Fingers, Mahogany Mountain, and Jump Creek rhyolites can be classified as A-type using Zr and Nb as discriminator (Fig. 7). The Dam rhyolite, however, plots as I-type. The Dam representative plots very close to the other Dam rhyolite. The Mahogany Mountain samples range widely in their trace element contents with 297 to 831 ppm of Zr, 29.6 to 62.1 ppm of Nb. The Mahogany Mountain rhyolite representatives are fairly spread out as well. The two Young McIntyre samples plot close to each other (297 and 311 ppm Zr, 36.3 and 36.8 ppm Nb) whereas the other representatives have twice the concentration of Zr. The Old McIntyre sample plots at the high end of the representative group at 727 ppm Zr and 44.9 ppm Nb. The Spring Creek sample plots between Young McIntyre rhyolites and Old McIntyre rhyolite around 582 ppm Zr and 37.7 ppm Nb. The Three Fingers samples are slightly more condensed, with concentrations between 477 to 725 ppm Zr and 28.8 to 48.9 ppm Nb. The Three Fingers complex representative plots right in the center of the range of Three Fingers rhyolites at

672 ppm Zr and 47.2 ppm Nb. Lastly, the Jump Creek rhyolite plots amongst a large cluster of both Mahogany and Three Fingers samples (575 ppm Zr and 44.1 ppm Nb).

Figure 7. Diagram illustrating Nb versus Zr concentration in rhyolites from the Mahogany Mountain/Three Fingers Rhyolite Complex. The lightest blue diamonds denote the Three Fingers rhyolites, moderately blue are the Mahogany Mountain rhyolite, and the darkest blue are the Dam rhyolite. Samples used in this study as representatives for the complex are noted in different shades of red: pink is Three Fingers, red closed squares are Mahogany Mountain, red open square is Jump Creek, and dark red is Dam. Samples that plot within the box (where $x=250$ and $y=20$) are denoted as “I-type” whereas those that fall outside of the box are “A-type”. Only the Dam rhyolite plots as I-type for this complex.

When comparing $10000\text{Ga}/\text{Al}$ and trace element sums, the majority of Three Fingers and Mahogany rhyolites are classified as A-type (Fig. 64). Dam rhyolite is again the exception, plotting as I-type due to low $10000\text{Ga}/\text{Al}$ and sums of trace elements. Mahogany Mountain caldera rhyolite samples have a wide range. A small cluster of samples has a range of 3.5 to 3.9 $10000\text{Ga}/\text{Al}$ and 848 to 1014 ppm trace element sum.

Two of the Mahogany samples (Spring Creek and Old McIntyre) border this small cluster. The two Young McIntyre samples used in this study have values of 10000Ga/Al that are similar to the other two Mahogany representatives, but have much lower sums of trace elements: 547 to 562 ppm. When considering the Three Fingers samples, it can be noted that the rhyolites are somewhat spread, with a couple of samples clustered around 4.21 to 4.29 and 976 to 1074 ppm. The sample selected to represent Three Fingers rhyolite falls in the middle of this small cluster. There are three other Three Fingers samples that plot slightly apart from this cluster, but overall the group plots relatively close to one another. The Jump Creek sample plots apart from the rest of the Three Fingers/Mahogany suite. While this sample has a trace element concentration sum that falls in the midst of the rest of the Mahogany/Three Fingers samples, the 10000Ga/Al value is much lower at 2.97. To summarize, the Three Fingers, Mahogany Mountain, and Jump Creek rhyolites can consistently be classified as A-type whereas the Dam rhyolite is classified as I-type based on multiple parameters.

3.2 Petrography of Rhyolites

The rhyolites of the Lake Owyhee Volcanic Field vary widely in texture, percentage of phenocrysts, and mineral phase assemblages (Table 2). Texturally, most samples are porphyritic. Phenocryst content of samples of this study ranges from phenocryst poor (3%) to moderately porphyritic (25%). There are also numerous rhyolites that are aphyric, but these were disregarded since this study focuses on mineral assemblages and mineral composition of phenocrysts. Many samples are glassy,

although the perlitic texture present in some samples indicates post-emplacement hydration has occurred.

The most abundant mineral phase of each sample is feldspar consisting of plagioclase, alkali-feldspar, and, in a few cases, both. Other observed mineral phases include quartz, clinopyroxene, orthopyroxene, biotite, amphibole, fayalite, Fe-Ti oxides, zircon, and apatite. Fe-Ti oxides were found in every sample. Amphibole was only found in the sample of Circle Bar rhyolite and one Unity rhyolite sample (U4B). Biotite was found in one Buchanan sample (B010), Circle Bar rhyolite, and both Unity samples. The two samples that have two feldspars, both sanidine and plagioclase include the Circle Bar rhyolite and U3A of the Unity rhyolites and both also have biotite. Similarly, fayalite was also only observed in one sample and this was the rhyolite of the upper Littlefield; in addition, this sample contained Fe-rich clinopyroxene.

Table 2. Mineral phases and phenocryst abundance of rhyolites of this study. Abbreviations for each center can be found in Table 1.

	Volcanic Center	Sample #	Total Phenocryst Abundance (%)	Mineral Phases
I-Type	BDC	EJ-12-03	20	Sanidine Quartz Zircon Fe-Ti Oxide
	BDC	B010	15	Plagioclase Biotite Quartz Apatite Fe-Ti Oxide
	BDC	B114	15	Plagioclase Orthopyroxene Clinopyroxene Quartz Apatite Fe-Ti Oxide
	MAL	EJ-12-05B	3	Plagioclase Sanidine Amphibole Biotite Quartz Apatite Fe-Ti Oxide
	DAM	EJ-12-15	5	Plagioclase Orthopyroxene
	UNI	CR-U3a	3	Plagioclase Sanidine Biotite Fe-Ti Oxide
	UNI	CR-U4b	5	Plagioclase Amphibole Biotite Quartz Zircon Apatite Fe-Ti Oxide
Borderline	CMR	EJ-12-16	10	Plagioclase Clinopyroxene Apatite Fe-Ti Oxide

	Volcanic Center	Sample #	Total Phenocryst Abundance (%)	Mineral Phases
Borderline	CMR	EJ-12-17	10	Plagioclase Clinopyroxene Apatite Fe-Ti Oxide
	DMR	DR2	10	Plagioclase Clinopyroxene Zircon Fe-Ti Oxide
A-Type	DIT	EJ-12-08	3	Plagioclase Zircon Apatite Fe-Ti Oxide
	LIT	EJ-12-10	7	Plagioclase Fayalite Clinopyroxene Quartz Fe-Ti Oxide
	JCR	EJ-12-13B	20	Plagioclase Zircon Apatite Fe-Ti Oxide
	MAH	EJ-12-12	5	Sanidine Clinopyroxene Zircon Fe-Ti Oxide
	MAH	EJ-12-14	25	Sanidine Clinopyroxene Quartz Zircon Fe-Ti Oxide
	MAH	MS-13-24b	20	Sanidine Clinopyroxene Quartz Zircon Fe-Ti Oxide
	MAH	MS-13-29	5	Sanidine Clinopyroxene Fe-Ti Oxide
	TFI	TF-153H	5	Sanidine Clinopyroxene Quartz Zircon Fe-Ti Oxide

3.2.1. *Feldspar*

Using elemental concentrations measured on the SEM, the feldspar composition of each rhyolite was plotted on a ternary diagram. Of the eighteen samples, eleven samples had plagioclase as the single feldspar, five samples had alkali-feldspar as single feldspar, and only two samples have two feldspars, plagioclase and sanidine (Fig. 8). This includes the Circle Bar rhyolite, which contains labradorite and sanidine, and one of the Unity samples (U3a) which contains oligoclase and sanidine. Among samples that contain a single plagioclase, samples of Buchanan and Dam rhyolite contain labradorite, Buchanan, Bully Creek, Cottonwood, and Dooley Mountain rhyolites contain andesine, Littlefield contains oligoclase, and Unity and Dam rhyolites straddle the border between andesine and oligoclase. Plagioclase in samples with a single feldspar are wide ranging in composition (Or_{0-14} , An_{9-63} , Ab_{36-80}) with a Buchanan sample at the highest end of An and Dinner Creek Tuff at the highest Ab. The total An range of plagioclase phenocrysts of a single sample is in the order of 1 to 17 An units, however the majority of samples have a narrow range of less than ~2 to 5 An units. Significant outliers are rare. Samples that contain single alkali feldspar are the rhyolites of Young McIntyre, Three Fingers, and one of the Buchanan samples (B114), which contain sanidine. And then there are samples where single feldspar plot as ternary feldspar, anorthoclase. The unit with ternary feldspar is the Old McIntyre rhyolite. The Dinner Creek and Spring Creek samples lie along the border between oligoclase and anorthoclase. Alkali feldspar in samples containing a single feldspar has the range Or_{9-50} , An_{0-22} , Ab_{47-70} where the Spring Creek Tuff alkali feldspars contain the lowest Or and the Buchanan sample has the highest Or value.

Figure 8. Feldspar ternary diagram for all samples of this study. Average feldspar compositions were plotted. Samples classified as I-type (blue) plot on the most extreme An and Or ends whereas A-type (red) tend to plot as ternary feldspars. Only two samples (Circle Bar of Malheur and U3a of Unity) contain both plagioclase and alkali feldspars. Purple color is used for samples that straddle the A-/I-type boundary.

On the other hand, all of the rhyolites with ternary feldspar were characterized as A-type. All of the samples that contain two feldspars were classified as I-type rhyolites. Rhyolites with plagioclase as the single feldspar with lower An content were mildly A- or I-type rhyolites. Only samples with the highest An content and/or highest Or content had strong I-type character.

3.2.2. Pyroxene

Pyroxene phenocrysts were found in eleven of the eighteen samples. Of these eleven samples, nine samples have clinopyroxene as a single pyroxene, one has

orthopyroxene as a single pyroxene, and one sample contains both clinopyroxene and orthopyroxene (Fig. 9). The sample with both types of pyroxene is one of the Buchanan rhyolite complex representatives, B114, which contained enstatite and augite. The sample with a single orthopyroxene, the Dam rhyolite, plotted as enstatite.

Figure 9. Pyroxene ternary diagram for all LOVF samples that contain at least one pyroxene phase. Average pyroxene compositions were plotted. Samples classified as I-type (blue) tend to have higher En and lower Fs concentrations, whereas A-type rhyolites (red) have lower En and higher Fs. Only one sample contains both clinopyroxene and orthopyroxene (B114 of Buchanan). Similarly, one sample (Cottonwood) contains two types of clinopyroxene.

Of the samples that contain a single clinopyroxene, four contain only ferrohedenbergite, two plot as ferroaugite, and one has only intermediate pigeonite. There is one sample, the Cottonwood rhyolite, which contains two types of pyroxene: augite and intermediate pigeonite. Pyroxenes that fall within the ferrohedenbergite field have compositions that range from Wo_{42-43} , En_{0-9} , Fs_{49-56} . Pyroxene of the two rhyolites that lie in the ferroaugite field have very similar compositions of about Wo_{42} , En_{15} , Fs_{43} .

The third group of rhyolites containing clinopyroxene is in the augite field and has higher En and lower Fs components. These two rhyolites have compositions of Wo_{42-43} , En_{36-39} , Fs_{18-21} . The two samples that contain pigeonite, Cottonwood and Bully Creek rhyolites, have compositions of Wo_{10} , En_{37} , Fs_{53} . Lastly, pyroxene of the two samples in which only orthopyroxene was found have compositions ranging from Wo_{2-3} , En_{59-69} , Fs_{29-38} .

3.2.3. Biotite

Biotite was found in the following four samples: B114 of the Buchanan rhyolites, the Circle Bar rhyolite, and the two Unity samples (U3a and U4b) (Fig. 10). Two of the samples (B114 and U4b) that contain biotite have plagioclase as single feldspar whereas the other two contain both sanidine and plagioclase. B114 has an average composition of An_{57} thus plotting in the labradorite field. Plagioclase of U4b is oligoclase with an average composition of An_{26} . In the Circle Bar sample and U3a of the Unity rhyolites, biotite is found alongside two types of feldspar, plagioclase and sanidine. The plagioclase composition of these two rhyolites plot similarly to B114 and U4b, respectively, with plagioclase of An_{53} for Circle Bar and of An_{17} for U3a plotting near the other Unity sample U4b.

Figure 10. Diagram of Mg # of biotite phenocrysts against Mg # of the whole rock.

3.2.4. Amphibole

Amphibole was found in two samples, the Circle Bar sample and in one of the Unity rhyolites (U4b) alongside the other hydrous mineral phase, biotite (Fig. 11). The Circle Bar rhyolite also contains two feldspar phases.

Figure 11. Diagram of Mg # for amphibole phenocrysts against Mg # of the whole rock.

3.2.5. Fayalite

The only sample in which fayalite was observed is the Littlefield rhyolite. This sample also contains plagioclase with an average composition of An₂₄ (oligoclase) and ferrohedenbergite clinopyroxene.

3.3 Within Center Variations

3.3.1. Buchanan Rhyolite Complex

There are three Buchanan samples in this study and there are distinct mineralogical differences between them. The phenocryst content is similar between the three samples and falls in the range of 15-20%. Two Buchanan samples contain plagioclase as the single feldspar and the third sample contains a single alkali feldspar. B010 contains plagioclase with andesine composition ($\text{Or}_{3-7}, \text{An}_{35-49}, \text{Ab}_{48-61}$) (Fig. 67), whereas B114 contains labradorite ($\text{Or}_{0-2}, \text{An}_{50-63}, \text{Ab}_{36-48}$) (Fig. 68). EJ-12-03 has alkali feldspar that plots as sanidine ($\text{Or}_{47-50}, \text{An}_{0-2}, \text{Ab}_{47-51}$) (Fig. 66). Zircon was found in the sample that contains sanidine, but was not found in the other two Buchanan rhyolites. Pyroxene was not found in B010 or EJ-12-03, but B114 contained both enstatite ($\text{Wo}_{2-4}, \text{En}_{52-66}, \text{Fs}_{31-45}$) and augite ($\text{Wo}_{41-43}, \text{En}_{36-42}, \text{Fs}_{16-22}$) (Fig. 12). Similarly, only one sample (B010) has biotite. Apatite was seen in only two Buchanan samples (B010 and B114), but oxides were found in all three samples

In thin section, devitrification textures are seen in B010 and EJ-12-03, including spherulites forming in the groundmass of EJ-12-03 (Figs. 24, 25). Feldspars throughout each sample often have twins and some display zoning. Sieved feldspars are seen in B114, often having rims surrounding the sieved portion of the feldspar (Fig. 26). Biotite phenocrysts in B010 are surrounded with dark red rims.

Figure 12. Pyroxene ternary diagram of sample B114 from Buchanan displaying all measured phenocrysts. Average compositions are shown by black plus symbol. This sample contained two types of pyroxene: augite and enstatite.

3.3.2. Unity Rhyolite

The phenocryst content of the two Unity samples is similar at 3% (U3a) and 5% (U4b). U4b contains a single feldspar composition of oligoclase (Or₄₋₆, An₂₃₋₃₀, Ab₆₆₋₇₂) (Fig. 71) whereas U3a contains both oligoclase (Or₅₋₉, An₁₁₋₂₀, Ab₇₄₋₈₀) and sanidine (Or₅₃₋₆₄, An₀₋₃, Ab₃₄₋₄₆) (Fig. 13). In both of these samples, the feldspars are mostly twinned and some show zoning. In U4b, however, both feldspar and mafic silicates display sieved textures. Additionally, both samples contain biotite and Fe-Ti oxide. In addition to a higher phenocryst percentage, U4b contains a higher variety of mineral phases than U3a, including amphibole, quartz, zircon, and apatite. U4b, along with the Circle Bar

rhyolite, is one of only two samples that contain both amphibole and biotite; these two rhyolites also contain the largest variety of mineral phases present compared to all other LOVF rhyolites of this study.

Figure 13. Feldspar ternary diagram displaying all measured feldspar phenocrysts for sample U3a of the Unity rhyolites. This sample contains two types of feldspar: plagioclase (oligoclase) and sanidine. Average compositions are shown by black plus symbol.

Both Unity samples contain a groundmass that is glassy, however, U4b has a hydrated perlitic groundmass whereas U3a has a glassy groundmass that shows some devitrification and flow features (Figs. 29, 30). The phenocrysts, specifically feldspar, in U4b are often very large.

3.3.3. Cottonwood/Littlefield Rhyolite

Cottonwood and Bully Creek rhyolites have similar phenocryst contents at ~10%. Pyroxene, plagioclase, Fe-Ti oxide, and apatite were found in both of these samples. These two rhyolites contain a single feldspar composition of andesine (Or₄₋₅, An₃₇₋₄₅, Ab₅₂₋₅₈) (Figs. 72, 73). The Bully Creek sample contains a single clinopyroxene with a composition of pigeonite (Wo₉₋₁₁, En₃₅₋₃₈, Fs₅₃₋₅₅) (Fig. 83), however the Cottonwood sample contained two types of clinopyroxene: pigeonite (Wo₉₋₁₁, En₃₅₋₃₈, Fs₅₂₋₅₅) and augite (Wo₄₃₋₄₄, En₃₆₋₃₇, Fs₁₉₋₂₁) (Fig. 82).

The sample of Littlefield rhyolite has 7% phenocrysts, slightly lower than its Cottonwood counterparts. This sample contains a single clinopyroxene composition of ferrohedenbergite (Wo₄₁₋₄₂, En₃₋₇, Fs₅₂₋₅₅) (Fig. 85). Additionally, the Littlefield sample has fayalite, a mineral phase not found in either of the Cottonwood rhyolites. Compared to Cottonwood and Bully Creek, An content is slightly lower in the single plagioclase phase found in Littlefield (Or₅₋₁₆, An₁₇₋₃₀, Ab₆₄₋₆₉), thus its average plots as oligoclase (Fig. 76).

In the Cottonwood rhyolite, the clinopyroxene phenocrysts are often twinned. The mineral phases tend to be small phenocrysts that are sometimes found in little clusters. Feldspars of these units tend to be twinned and are less frequently zoned. Sieve texture is seen in most of the feldspar phenocrysts throughout each sample, and can be seen in some of the pyroxene crystals in the Cottonwood sample (Figs. 31, 32, 35).

3.3.4. Mahogany Mountain/Three Fingers Complex

For this complex, the range of phenocryst content is large from about 5 to 25% phenocrysts. The two Young McIntyre samples have the highest phenocryst content, whereas the Dam, Three Fingers, Spring Creek, and Old McIntyre samples are all much lower, around 5% phenocrysts. The Dam sample contains single plagioclase feldspar with a composition of labradorite (Or_{2-3} , An_{48-59} , Ab_{39-49}) (Fig. 70). The Old McIntyre, Spring Creek, two Young McIntyre, and the Three Fingers samples, on the other hand, contain single alkali-feldspar phenocrysts. The Young McIntyre and Three Fingers samples all plot similarly to each other as sanidine (Or_{42-48} , An_{0-3} , Ab_{50-56}) (Figs. 79, 80, 81). Feldspars of Old McIntyre and Spring Creek, however, plot as anorthoclase. Old McIntyre feldspar has higher Or (Or_{30-35} , An_{3-6} , Ab_{60-64}) (Fig. 78) than feldspar of the Spring Creek sample, which falls along the border of anorthoclase and oligoclase (Or_{9-21} , An_{13-22} , Ab_{65-70}) (Fig. 14).

The Three Fingers, Old McIntyre, and Spring Creek samples contain single pyroxene with a similar composition of ferrohedenbergite (Wo_{42-44} , En_{0-4} , Fs_{54-57}) (Figs. 86, 89, 90). The two Young McIntyre samples also contain single clinopyroxene; however, these plot as ferroaugite (Wo_{41-43} , En_{12-20} , Fs_{37-47}) (Figs. 87, 88). The Dam rhyolite is the only sample of this study that contains a single orthopyroxene with the composition of enstatite (Wo_{1-3} , En_{67-70} , Fs_{38-31}) (Fig. 81).

Figure 14. Feldspar ternary diagram displaying all measured plagioclase phenocrysts in sample MS-13-29 (Spring Creek) from the Mahogany Mountain rhyolites. This sample shows a relatively wide spread of feldspar compositions, with the average composition plotting as anorthoclase as indicated by the black plus symbol.

With regard to other mineral phases present throughout these rhyolites, Fe-Ti oxides were found in every rhyolite of this suite, but zircon was only found in the Young McIntyre, Old McIntyre, and Three Fingers samples. Additionally, quartz was found in the Three Fingers and the two Young McIntyre samples. The Spring Creek rhyolite has the fewest mineral phases present.

The two Young McIntyre, Dam, and Old McIntyre samples have perlitic textures indicating post emplacement hydration (Figs. 28, 37, 38, 39). Sieved feldspar can be

seen throughout most of the samples (with the exception of TF-153H) and many of the sieved feldspars appear zoned. While the Three Fingers sample also has very large feldspar phenocrysts, the phenocrysts tend to be twinned but they do not appear sieved (Fig. 41). Mineral phases often exist as small clusters of crystals and a large basalt xenolith can be seen in MS-13-24b. Flow features are seen in samples MS-13-29 and EJ-12-14, but aren't seen in the other representatives (Fig. 40).

3.4 Single Samples

3.4.1. Circle Bar (Malheur)

The Circle Bar rhyolite has one of the lowest percentage of phenocrysts within this study (3%). The groundmass is perlitic. The Circle Bar sample is one of only two samples in this study that has two types of feldspar, sanidine ($\text{Or}_{67-84}, \text{An}_{1-2}, \text{Ab}_{16-31}$) and labradorite ($\text{Or}_{4-6}, \text{An}_{46-59}, \text{Ab}_{38-48}$) (Fig. 69). Feldspar tends to be in small clusters and is often twinned.

Despite having a very low number of phenocrysts, Circle Bar rhyolite has the widest variety of mineral phases present of all samples of this study. Fe-Ti oxides, quartz, and apatite were found in the Circle Bar rhyolite, but what stands out the most with this sample against others is the existence of both biotite and amphibole. These two hydrous phases only occur together in one other sample of this study, U4b of the Unity rhyolites.

The phenocrysts are fairly small and sub- to anhedral and are often found as single crystals with the exception of feldspar clusters. Several lithics can also be seen in Circle Bar, including basalt xenoliths (Fig. 27).

3.4.2. Dooley Mountain Rhyolite

The Dooley Mountain sample has plagioclase as single feldspar with a composition of andesine ($\text{Or}_{2-4}, \text{An}_{31-48} \text{Ab}_{51-65}$) (Fig. 74). These phenocrysts tend to display zoning and twins, and are sometimes sieved. Pyroxene is also present as a single clinopyroxene of ferrohedenbergite ($\text{Wo}_{41-42}, \text{En}_{8-10}, \text{Fs}_{48-50}$) (Fig. 15). Mineral phases that are also present in this sample are Fe-Ti oxides and zircon. This rhyolite has a moderate percentage of phenocrysts (10%) within a glassy groundmass (Fig. 33).

Figure 15. Pyroxene ternary diagram displaying the compositions of all measured pyroxene phenocrysts of DR2 from the Dooley Mountain rhyolites. All compositions are tightly clustered, giving an average composition of ferrohedenbergite shown by the black plus symbol.

3.4.3. Dinner Creek Tuff

The Dinner Creek Tuff has feldspar that plots on the border between oligoclase and anorthoclase (Or₇₋₁₄, An₉₋₁₃ Ab₇₈₋₈₀) (Fig. 75). There are very few other mineral phases present in this sample, including Fe-Ti oxides, zircon, and apatite. The phenocrysts in Dinner Creek Tuff are very small, anhedral, and have a very low abundance (3%). This sample is devitrified and the minerals tend to cluster (Fig. 34). Zircon can be found within some oxide phenocrysts.

3.4.4. Jump Creek Rhyolite

Jump Creek has a fairly high phenocryst percentage of ~20%. The most abundant mineral phase is plagioclase, which appears as single feldspar with compositions falling between oligoclase and andesine (Or₆₋₁₂, An₂₄₋₃₅ Ab₅₉₋₆₆) (Fig. 77). Additionally, the sample contains Fe-Ti oxides, zircon, and apatite. The phenocrysts of plagioclase can be very large and tend to show sieve textures, especially in the largest of these crystals (Fig. 36). Additionally, the feldspar tend to be twinned and are often zoned. Phenocrysts in this sample are also found in small clusters.

3.5 Temperatures of Rhyolites

3.5.1. Results with Feldspar Geothermometers

The feldspar-liquid geothermometer could be utilized on every sample as it can estimate eruption temperatures using phenocrysts of either plagioclase or sanidine (Fig. 16). Bulk composition was used as a proxy for the liquid component. This is justified given the low phenocryst content and the similarity between matrix glass and bulk composition has been noted in other studies (Christensen et al., 2005; Putirka, 2008). Applying this on sanidine- and plagioclase-only bearing samples typically yield lower temperatures for those with sanidine than for rhyolites that contain plagioclase instead. This can lead to large differences in estimated eruption temperature within a single rhyolite center. For example, of the three Buchanan rhyolites of in this study, temperature of two of the samples (B010 and B114) is estimated using plagioclase whereas one (EJ-12-03) uses sanidine. As a result, the two with plagioclase yielded temperatures of 897

°C and 1043 °C, whereas EJ-12-03, the sample with sanidine, indicate an estimated temperature of 737°C. This trend is noted throughout all of the samples. In the case of A-type rhyolites with predominately sanidine or anorthoclase temperatures were estimated using the equation for alkali feldspar. As a result, the calculated temperatures for the A-type rhyolites appear to be much lower (~809 °C to 877 °C) than the I-type rhyolites that contained only plagioclase (~880 °C to 1050 °C). However, when solely considering the temperatures estimates using sanidine, the A-type rhyolites do show higher temperatures than the I-type rhyolites. This trend is not noted in temperatures derived from plagioclase. Some I-type rhyolites record higher plagioclase temperatures than the borderline group, which in turn record slightly higher temperatures than the A-type rhyolites that have plagioclase only.

Figure 16. Diagram displaying the average temperatures for LOVF rhyolites using the Feldspar-liquid and Two Feldspar geothermometers. Two samples, Circle Bar and U3a of Unity are the only samples that contain both plagioclase and alkali feldspar, thus are the only two samples where the Two Feldspar geothermometer could be employed. The error for silicate-based geothermometers is $\pm 30^{\circ}\text{C}$ as shown by error bars (Putirka, 2008).

There are only two samples that contained both plagioclase and alkali feldspar, the Circle Bar and one of the Unity rhyolites. The Circle Bar sample has both sanidine and plagioclase, so both equations could be used to estimate eruption temperatures. This exactly highlights the discrepancy in temperature using, on one hand, the equation for alkali-feldspar and, on the other hand, the one for plagioclase, as the temperature estimate was higher when using the equation for plagioclase. Using sanidine, the temperature is estimated at 813°C whereas plagioclase gives a temperature almost 100°C higher, 914°C . The temperature estimated using the two-feldspar thermometer yielded 789°C and is close to the estimated temperature using the sanidine-liquid geothermometer. One of the Unity samples (U3a) has plagioclase as well as sanidine and, again, the difference in temperature estimation can be noted. When using the plagioclase equation, the eruption

temperature is estimated at 883°C whereas the sanidine temperature is estimated at 823°C. The temperature estimated using the two-feldspar geothermometer yields a lower temperature than both the sanidine-liquid and plagioclase-liquid: 782°C. Variation between the two Unity samples can also be noted. There is a difference of almost 100°C in the calculated plagioclase-liquid temperatures for these two rhyolites.

For the borderline samples, all of the rhyolites in this group contain only plagioclase. As a result, the recorded temperatures for these rhyolites are fairly high: 949°C to 981°C. The Cottonwood and Bully Creek samples record the same temperature of 949°C.

Within the A-type rhyolites, sanidine is more prevalent and thus, the sanidine-liquid geothermometer can be used for most of the samples. As a result, many of the A-type temperatures that use the sanidine-liquid equation are lower than the borderline and I-type estimated temperatures, which use the plagioclase-liquid equation. Old McIntyre, Young McIntyre, Spring Creek, and Three Fingers rhyolites all record sanidine temperatures within the range of 809°C and 877°C. The two Young McIntyre samples display a temperature difference of almost 30°C. The other three A-type rhyolites use the plagioclase-liquid equation and thus, yield much higher temperatures than the A-type rhyolites containing sanidine. As a result, the Littlefield and Jump Creek samples give estimated temperatures of 953°C and 954°C, respectively. Dinner Creek tuff is the lowest estimated A-type rhyolite that has plagioclase, estimated at 873°C.

A test for equilibrium can be established between plagioclase and liquid, which in turn validates the usage of the plagioclase-liquid geothermometer (Table 3). This test

compares the calculated An-Ab exchange coefficient (K_d) with the ideal coefficient; the closeness of values is a test for equilibrium. For samples where the estimated temperature is less than 1050 °C, the K_d value should be 0.1 ± 0.05 . Every temperature estimated for this study using this geothermometer was less than 1050 °C. All but one sample using the plagioclase equation falls within this range, implying that the mineral phase is in equilibrium. The sample that does not fall within this range, B010, yields a K_d value of 0.03, implying this mineral phase was not in equilibrium. No such equilibrium test is applicable for alkali feldspar.

3.5.2. Results with Pyroxene Geothermometers

At least one of the three geothermometers that utilize pyroxene can be applied to eleven of the eighteen samples (Fig. 17). The two-pyroxene geothermometer was only used on one sample (B114) as it was the only sample that had both augite and enstatite phenocrysts. This geothermometer yielded a temperature of 985°C. Likewise, both the clinopyroxene- and orthopyroxene-liquid geothermometers could be applied to this sample. The orthopyroxene geothermometer estimated the same temperature as the two-pyroxene, however the clinopyroxene thermometer yielded a temperature of 967°C. Only one other sample, the Dam rhyolite, was suitable to utilize the orthopyroxene-liquid geothermometer as a result of the presence of enstatite. The Dam rhyolite was estimated at 990°C. No other samples had orthopyroxene phenocrysts.

Figure 17. Diagram displaying the average temperature estimates using the Orthopyroxene-Liquid, Clinopyroxene-Liquid, and Two Pyroxene geothermometers. B114 was the only sample containing both orthopyroxene and clinopyroxene and, thus, is the only sample on which the Two Pyroxene geothermometer could be used. The error for silicate-based geothermometers is 30°C as shown by error bars (Putirka, 2008)

The clinopyroxene-liquid geothermometer was the method most readily usable to estimate temperatures using pyroxene as augite and/or pigeonite was recorded in ten of the rhyolites. Temperatures progressively decrease from the I-type rhyolites to the A-type rhyolites with the most A-type rhyolites yielding the lowest estimated temperatures using the clinopyroxene geothermometer. The one I-type sample where the clinopyroxene-liquid geothermometer (B114) could be applied gave a much higher temperature (970°C) than most of the borderline and all of the A-type rhyolites. Augite and/or pigeonite were found in all three of the borderline samples. The Cottonwood and Bully Creek rhyolites gave similar clinopyroxene temperatures using pigeonite (967°C and 980°C, respectively) whereas the Mg-rich augite of the Cottonwood sample yielded

an estimate that is lower (903°C). Dooley Mountain rhyolite gave a much lower temperature (871°C) than its borderline counterparts.

Samples of the Mahogany Mountain/Three Fingers centers give a fairly large range in temperatures. The two Young McIntyre samples had a difference of 11°C, yielding estimates of 842 °C and 831 °C. Spring Creek rhyolite had a slightly higher estimated temperature of 859°C. The Old McIntyre sample gave the highest temperature of the A-types, 890°C. Three Fingers rhyolite, on the other hand, gave the lowest temperature of the entire sample set at 802°C.

The pyroxene geothermometers also include a test for equilibrium (Table 3). The acceptable K_d range using the clinopyroxene geothermometer is 0.27 ± 0.30 . For the I-type rhyolites, the Buchanan (B114) and DAM samples pass this test; however, the K_d value for the Circle Bar rhyolite falls outside this range, near 0.17. For the borderline samples, the Cottonwood and Bully Creek samples fall within the range, but the Dooley Mountain rhyolite is not in equilibrium. Lastly, for the A-type rhyolites, only the Old McIntyre sample passes the equilibrium test, implying that clinopyroxene for the rest of the A-type rhyolites is apparently not in equilibrium. The K_d range for the orthopyroxene geothermometer is 0.29 ± 0.06 . The one sample containing orthopyroxene, B114, passes this test with a K_d value of 0.25.

3.5.3. Results with Olivine-Liquid Geothermometer

The olivine-liquid geothermometer could only be applied to one sample: Littlefield (Fig. 18). This sample recorded a temperature of 984°C. This geothermometer

yields the highest temperature estimate for the upper Littlefield Rhyolite sample. An equilibrium test is included in this geothermometer (Table 3). The acceptable K_d range for this geothermometer is 0.30 ± 0.03 . The Littlefield rhyolite yields a K_d value of 0.25, implying that the mineral phase is slightly outside the recommended range for being in equilibrium.

3.5.4. Results with Amphibole-Plagioclase Geothermometer

As amphibole was found in only two of the rhyolites, this geothermometer could only be used on one of the Unity samples (U4b) and the Circle Bar rhyolite (Fig. 18). These two samples are classified as I-type,. The Circle Bar rhyolite yields an estimated temperature of 835°C whereas the Unity sample records a lower temperature, 750°C.

Figure 18. Diagram displaying average temperatures estimated using the Olivine-Liquid and Amphibole-Plagioclase geothermometers. Only two samples (Circle Bar and U4b of Unity) contained amphibole and could utilize the Amphibole-Plagioclase geothermometer. Likewise, only one sample (Littlefield) could use the Olivine-Liquid geothermometer due to the presence of fayalite. The error for silicate-based geothermometers is 30°C as shown by error bars (Putirka, 2008)

3.5.5. Results with Zircon Saturation Geothermometer

The zircon saturation geothermometer was used for each sample in this study (Fig. 19). The temperature estimate is based on the amount of Zr measured in whole rock analysis. It serves as either a minimum or a maximum temperature, dependent on whether or not zircon was found in thin section. For the samples in which zircon was found, the estimated temperature serves as a minimum as the temperature could have been higher at the onset of zircon crystallization. The trend seen in the previously mentioned geothermometers appears to reverse when applying zircon saturation geothermometry. The I-type rhyolites give estimated temperatures that are much lower than the temperatures estimated for the A-type rhyolites. Additionally, the majority of I-

type samples are maximum temperatures, i.e., zircon has not yet started to crystallize, therefore the onset of zircon crystallization could occur at a lower temperature, with the exception of one Buchanan sample, EJ-12-03, and one Unity rhyolite, U4b, in which zircon was found. For the maximum estimated temperatures, the range of temperatures for the I-type rhyolites is between 761°C and 793°C. The lone Buchanan sample records a minimum temperature of 839°C.

Figure 19. Diagram displaying average temperatures estimated using the Zircon Saturation geothermometer. For the samples in which zircon was detected, estimated temperatures serve as minimum values whereas if zircon was absent, the estimates serve as a maximum.

Of the borderline group, zircon was found in one of the three rhyolites, the Dooley Mountain sample. Therefore, one of the temperatures estimated using zircon saturation yields a minimum temperature, while the other two rhyolites record maximum temperatures. The minimum temperature estimated for Dooley Mountain is 860°C. The Cottonwood and Bully Creek samples yield temperatures that are just 5°C apart near 840 °C.

Lastly, the group of rhyolites giving the highest estimated temperatures with regard to zircon is the A-type group. Of the eight A-type rhyolites of this study, zircon was found in six. The two samples that give maximum temperatures using zircon saturation are the Littlefield and Spring Creek rhyolites, 875°C and 899°C, respectively. The other rhyolites that have been classified as A-type show a range of temperatures between 835°C and 933°C. For the Mahogany Mountain center, the temperatures range from 844°C to 933°C. The two Young McIntyre rhyolites record almost identical temperatures (a difference of 1°C). Old McIntyre and Three Fingers rhyolites, on the other hand, give similar temperatures that are almost 90°C higher than the Young McIntyre samples.

3.5.6. Results with Apatite Saturation Geothermometer

This geothermometer is similar to zircon saturation in that it utilizes the whole rock composition and yields either a minimum or maximum estimated temperature based on whether or not apatite is present in the sample. With apatite, the amount of phosphorous of the whole rock composition affects the temperature. Analogous to the zircon geothermometer, the apatite geothermometer will give a minimum estimate if apatite is present and a maximum if it is not found. One trend that was noted about the results of this geothermometer is that the maximum values tend to be lower than the minimum temperature estimates (Fig. 20). As a result, the A-type rhyolites appear to record lower temperatures than most of the I-type and borderline samples.

Of the I-type rhyolites, apatite was found in four of seven samples. EJ-12-03 of the Buchanan samples, sample U3a of Unity, and the DAM rhyolite do not contain apatite and thus, the calculated temperatures serve as maximum values. The temperature estimates for these samples range from 773°C and 905°C. In B010, B114, U4b, and the Circle Bar rhyolites, apatite was found and gave temperatures ranging from 786°C to 955°C. EJ-12-03 and B010 from Buchanan give the same temperature of 786°C, but one is a maximum and one is a minimum; the third Buchanan, B114, is estimated at a much higher minimum temperature of 954°C, and U4b is estimated near 902 °C.

Figure 20. Diagram displaying average temperatures estimated using the Apatite Saturation geothermometer. For the samples in which apatite was detected, estimated temperatures serve as minimum values whereas if apatite was absent, the estimates serve as a maximum.

The borderline samples are similar to the I-type in the sense that there is a mixture of minimum and maximum values. Again, apatite was found in two of the three samples, giving a range of minimum temperatures between 967°C and 973°C. The sample in

which apatite was not found is the Dooley Mountain rhyolite, recording a maximum value of 838°C

Apatite was found in very few of the A-type rhyolites; of the eight, there are two samples in which apatite was recorded: the Jump Creek rhyolite and Dinner Creek tuff. These two rhyolites give the highest temperatures of the A-type group and are minimum temperatures due to the presence of the mineral phase. Dinner Creek tuff is estimated at a minimum of 882°C whereas Jump Creek rhyolite is at 984°C. The rest of the A-type rhyolites have a lower range: 783°C to 864°C. The Mahogany rhyolites have temperatures within a close range, 783°C to 834°C, with the Young McIntyre samples yielding values with a difference of 14°C. Old McIntyre gives the lowest of this center: 783°C, whereas Spring Creek is estimated at the highest: 834°C.

3.6 Comparing All Temperatures

There are various degrees of closeness when comparing all geothermometers used for specific samples (Fig. 21). Some samples give close temperature ranges, the U3a sample (about 50°C difference, when not including the plagioclase-liquid temperature), Dinner Creek tuff (almost 50°C), Jump Creek rhyolite (about 80°C), and Young McIntyre (EJ-12-14) sample (roughly 90°C). On the other hand, there are multiple samples that give very large temperature ranges. This includes the Circle Bar sample (a range of 200°C), the U4b sample (a difference of 230°C), and Dam rhyolite (almost 210°C).

Figure 21. Diagram displaying average estimated temperatures by geothermometer for each center.

The highest temperatures given are often those given by the plagioclase-liquid geothermometer as a result of using plagioclase phenocrysts. Likewise, samples in which apatite was found also tend to give some of the highest temperatures as minimum values. Both of these high temperature estimates can be seen in U4b, where the feldspar-liquid (981°C) and apatite saturation (902°C) estimates are almost 150°C higher than the zircon saturation and amphibole-plagioclase estimates (757°C and 750°C, respectively). This trend can also be seen in the Circle Bar rhyolite (plagioclase and apatite are roughly 80°C and 120°C higher than the next highest estimated temperature of 835°C).

On the other hand, for the samples in which apatite was not found, the temperatures given by using the apatite-saturation geothermometer tend to give the lowest temperatures in their group. This is especially obvious in the Old McIntyre sample, where the estimated temperature is 44°C lower than the next lowest temperature.

The Dooley Mountain, Littlefield, one of the Unity samples, and the majority of samples belonging to the Mahogany/Three Fingers complex show this lower apatite temperature trend.

4. Discussion

4.1 Petrography

A-type rhyolites are considered to be hot, dry, and reduced magmas, typically exhibit a high Fe/Mg ratio, and often record high concentrations of both high field strength and rare earth elements, specifically incompatible elements (Anderson et al., 2008; Christensen et al., 2008). The A-type rhyolites of this study typically contain a single feldspar, Na-rich sanidine, anorthoclase, or low An plagioclase, Fe-rich pyroxene (such as ferrohedenbergite and ferroaugite), Fe-Ti oxides, and zircon. Fayalite was found in one sample. The occurrence of fayalite and Fe-rich pyroxene is in agreement with low oxygen fugacity, i.e. reduced conditions and with a high Fe/Mg ratio typical of A-type rhyolites. These two mineral phases are also often associated with elevated temperatures. And lastly, these are not hydrous phases as opposed to biotite and amphibole, and their occurrence is consistent with dry or drier conditions (Christensen et al., 2008; Honjo et al., 1992; Cathey and Nash, 2009). The only volatile containing phase in the A-type rhyolites is apatite that occurs in trace amounts and crystallizes as the main host of phosphorous. Also, volatiles in apatite are typically a mixture of Cl, F, and H₂O.

Fayalite was only found in the A-type rhyolites (the Littlefield sample, specifically). This is in agreement with a description of A-type rhyolites made by Whalen et al. (1987) that these rhyolites tend to be rich in iron. Additionally, when compared to mineral assemblages of Snake River Plain (SRP) rhyolites, Honjo et al. (1992), Christensen (2005) and Cathey and Nash (2009) also reported fayalite.

The mineral assemblages found in the A-type rhyolites of this study are consistent with those reported for the rhyolites of Snake River Plain (SRP). SRP rhyolites are most often described as anhydrous with high silica content (70-75% SiO₂), high FeO*/MgO, and elevated concentrations of high field strength elements (Zr+Nb+Ce+Y values between 500 and 1000 ppm reported) (Cathey and Nash, 2009; Christensen, 2005). Additionally, the common minerals reported for the rhyolites of SRP are as follows: plagioclase, alkali feldspar (sometimes as sanidine, less often as anorthoclase), Fe-rich pyroxene (usually as ferroaugite or pigeonite), Fe-Ti oxides, fayalite (rare) and accessory apatite and zircon (Andrews et al., 2008; Cathey and Nash, 2009; Christensen, 2005; Honjo et al., 1992).

Most of the rhyolites in this study that have been classified as I-type, along with some borderline samples, are petrographically similar (Table 2). I-type rhyolites are associated with cooler, wetter, and more oxidized magmas. The hydrous phases biotite and amphibole occur in multiple I-type rhyolites of this study. Neither of these mineral phases are seen in the A-type rhyolites, but at least one of these phases is found in four of the calc-alkaline samples. These mineral phases are in agreement that I-type rhyolites are more hydrated and cooler magmas. Both biotite and amphibole are common phases reported by other studies that are concerned with I-type rhyolites (Shane et al., 2008; Smith et al., 2005; Waters et al., 2013). Typical I-type rhyolites are found at subduction zones where magmas are commonly more water-rich than magmas from continental setting of rift zones and flood basalt provinces (Smith et al., 2005; Shane et al., 2008; Loewen and Bindeman, 2016).

Another distinction between the I-type and the A-type rhyolites is that orthopyroxene with lower Fe/Mg ratio is only found in two samples (Buchanan sample B114 and Dam rhyolite) that have been classified as an I-type rhyolite. This mineral phase is not found in any A-type or borderline rhyolites. I-type rhyolites tend to have lower Fe/Mg, thus the high-Mg enstatite of B114 and Dam rhyolites is consistent with this I-type classification. Enstatite with lower Fe, higher Mg is commonly found in rhyolites that have been classified as I-type in other studies and is sometimes found alongside low-Fe, higher-Mg augite phenocrysts (Shane et al., 2008; Smith et al., 2005; Stelton et al., 2012; Waters et al., 2013). There is only one I-type rhyolite (sample B114) from this study in which low-Fe, high-Mg clinopyroxene was found and it was alongside enstatite. Clinopyroxene (as low-Fe, high-Mg augite, ferrohedenbergite, or higher Fe pigeonite) was found in all of the borderline samples. In the Dooley Mountain rhyolite sample, ferrohedenbergite occurs. Pigeonite was recorded in the Bully Creek and Cottonwood samples. The Cottonwood rhyolite sample also contained low-Fe, high-Mg augite, which has been reported in published A-type rhyolite mineral assemblages (Andrews et al., 2008; Bolte et al., 2015).

Rhyolite samples with feldspar with compositions toward Ca-rich and Or-rich endmembers (i.e. high anorthite for plagioclase or high orthoclase content for sanidine) tend to be classified as I-type (Fig. 8). On the other hand, samples with feldspar that plot in the ternary feldspar range (anorthoclase) are classified as A-type. Rhyolites that had plagioclase as the single feldspar were often mildly A- or I-type whereas samples that had the highest An content or the highest Or concentration displayed strong I-type characteristics. As An content increases, the occurrence of A-type character decreases,

and I-type becomes more prevalent. Samples classified as A-type are not found to contain feldspar with An concentrations higher than 30%. Additionally, the only samples that have two types of feldspar (Circle Bar and Unity rhyolites) are I-type. Samples along the Snake River Plain also contain single feldspar, and more rarely, sanidine (Cathey and Nash, 2009; Andrews et al., 2008).

Sieve texture was found in the Jump Creek, Dam, Littlefield, Cottonwood, and Bully Creek samples. These centers represent a range of classifications as the Jump Creek and Littlefield rhyolites are classified as A-type, the Cottonwood and Bully Creek rhyolites are borderline, and the Dam rhyolite is I-type. Additionally, there are no similarities in phenocryst percentages among these five samples: Jump Creek contains 20%, Dam 5%, Littlefield 5%, and Cottonwood and Bully Creek rhyolites both contain 10%. Sieve textures in feldspar are common in the A-type rhyolites of the Snake River Plains (Andrews et al., 2008), but the occurrence of sieve texture is likely independent of whether a rhyolite is classified as A- or I-type.

In addition, glomerocrysts that contain pyroxene, plagioclase, and Fe-Ti oxides were common in the A-type rhyolites of this study. Multiple samples representing the Mahogany Mountain/Three Fingers complex and Jump Creek rhyolite often show clusters of these mineral phases. This feature was also commonly found in the rhyolites of Snake River Plain (Cathey and Nash, 2009), but, as with sieve texture, the occurrence of glomerocrysts is governed by other parameters, rather than being simply a function of whether magma has A-type or calc-alkaline affinities.

4.2 Evaluation of Obtained Temperatures

4.2.1. Comparing All Temperatures

If all estimated temperatures are taken into consideration, it appears that the I-type rhyolites tend to yield higher temperatures and display a much wider range of temperatures derived from different geothermometers than the A-type rhyolites. There are multiple geothermometers that consistently estimate elevated temperatures for the I-type rhyolites that appears to be mainly due to the influence of one elemental shift in the composition of the mineral used in these geothermometers and may result, not from higher temperature, but may be caused by other compositional controls. As a result, there are estimates for the I-type rhyolites that should be excluded. When discounting unrealistic estimates, the temperature ranges for the I-type rhyolites are reduced and overall, the I-type rhyolites tend to yield lower temperatures than the A-type rhyolites, with some overlap.

The feldspar-liquid geothermometer appears to be greatly affected by the proportion of anorthite measured in plagioclase phenocrysts (Fig. 22). Samples that solely use potassium feldspar to estimate temperatures tend to give much lower temperatures than those that solely utilize plagioclase. The phenocrysts of alkali feldspar measured in this study have anorthite contents of less than 10%, therefore the resulting approximated temperatures are lower than those estimated using phenocrysts of plagioclase. This trend can be noted in samples that have both plagioclase and alkali feldspar. The Circle Bar sample yields temperature estimates for both plagioclase and sanidine based geothermometers (Fig. 16). We observe the plagioclase-liquid

temperature is estimated at almost 100 °C higher than the temperature from the sanidine-liquid geothermometer (813 °C). This cannot reflect actual crystallization temperature, but must be induced by other compositional controls. This trend can especially be observed when anorthite content is plotted against temperatures (Fig. 22). The rhyolites that give the highest feldspar-liquid temperatures (Buchanan rhyolite complex, Dam rhyolite, Cottonwood rhyolite, Bully Creek rhyolite) also have the highest anorthite content. Likewise, the samples that give the lowest temperatures have the lowest anorthite content (one of the Unity rhyolites, Dinner Creek Tuff). The influence of An on temperature can also be seen in samples that record similar An contents that also yield similar estimated temperatures. Cottonwood, Bully Creek, and Dooley Mountain rhyolites record An content around 40% and give temperatures within 20 °C. Despite this, there are examples of samples where the influence of An is not as strong. Circle Bar rhyolite records an An content that is one of the highest of the entire sample set at 53%. Despite this, the temperature estimated for this sample is lower than most of the samples that use the same plagioclase-equation of the feldspar-liquid geothermometer. This trend can also be noted in sample B010 in the Buchanan rhyolites. The An content of this sample (41%) is similar to Cottonwood, Bully Creek, and Dooley Mountain, however the temperature estimate for this Buchanan sample is 50 °C lower, at 897 °C.

Figure 22. Anorthite content vs calculated temperatures using the feldspar-liquid geothermometer. Correlations between An content and temperature can specifically be seen in BDC, CMR, Bully Creek, Dooley Mountain, Unity, and Dinner Creek. Samples using the alkali feldspar equation record the lowest temperatures.

Similarly, the samples containing alkali feldspar display the lowest An content. Likewise, they also yield the lowest temperatures of the entire LOVF suite. This can be noted in Old McIntyre, Young McIntyre, Three Fingers, and the Buchanan sample that contains just alkali feldspar (EJ-12-03). The temperatures given by these samples are at least 30 °C and up to 140 °C lower than the lowest plagioclase feldspar temperature given. An content of these alkali feldspar ranges between 0% to 4% whereas the lowest An given by a plagioclase feldspar is 12%. It appears that the calculated temperature is directly correlated with (and greatly influenced by) the amount of anorthite in a phenocryst of feldspar. This brings into question the validity of the temperatures estimated for samples with high-anorthite plagioclase. The elevated temperature estimates that correlate with high An content indicate that the An content may not solely be induced by temperature. For the I-type rhyolites, these temperatures should not be

considered valid. In addition, sample B010 have an equilibrium value (K_d) that does not fall within the acceptable range and is thus considered to not be in equilibrium (Appendix). As a result, this temperature is not considered valid. However, the two feldspar and alkali feldspar equation for the feldspar-liquid geothermometer appear to consistently generate valid temperatures.

Samples that contain orthopyroxene tend to yield the highest temperatures of this entire sample set. Similarly, Buchanan, Cottonwood and Bully Creek rhyolites record the highest temperature estimates using the clinopyroxene geothermometer. The Cottonwood sample contains both augite and pigeonite. The pigeonite estimate is 70 °C higher than the augite estimate and is very similar to the temperature estimate for the Bully Creek sample. These samples yield equilibrium values that are within the acceptable range (Appendix).

For the A-type rhyolites, the clinopyroxene temperatures tend to be much lower than those estimated for the I-type and borderline samples. Additionally, the clinopyroxene measured in these samples are much lower in En content, higher in Fs than the augite of Buchanan and Cottonwood rhyolites, and higher in Wo, lower in En than the pigeonite in Bully Creek and Cottonwood rhyolite. The pyroxenes of the A-type rhyolites do not give equilibrium values (K_d) that fall within the acceptable range, with the exception of the Old McIntyre rhyolite (Appendix). As a result, the temperatures estimated by the clinopyroxene geothermometer are not considered valid.

Figure 23. Isotherms for estimating pyroxene temperatures (Lindsley and Anderson, 1983).

These temperatures are in agreement with published isotherm values from Lindsley and Anderson (1983) (Fig. 23). Augite from the Buchanan and Cottonwood samples plot between the 900 °C and 1000 °C isotherms. The Three Fingers and Old McIntyre samples contain the lowest amount of En compared to the rest of the A-type rhyolites. The Three Fingers sample records the lowest clinopyroxene temperature of the entire sample set (794 °C), which is slightly higher, but close in agreement with the isotherms of Lindsley and Anderson. The Old McIntyre sample, on the other hand, yields the highest clinopyroxene temperature of the A-type rhyolites (890 °C), which appears elevated compared to the published isotherms. The rest of the A-type rhyolites do not follow these published isotherms. The Littlefield sample contains less En and more Fs than both Dooley Mountain rhyolite and the two Young McIntyre samples, however yields a higher temperature of 908 °C compared to 860 °C and 831 °C, respectively. It appears that the isotherms can be used to estimate samples with higher En and lower Fs; however, this begins to break down as samples contain less En and higher values of Fs.

The Zircon/Apatite Saturation geothermometer determines “minimum” and “maximum” temperatures based on the presence or absence of zircon and/or apatite. Samples that contain zircon or apatite, for example, give “minimum” temperatures. In other words, if the mineral phase is present, the actual eruption temperature could be greater than or equal to the temperature estimated by the geothermometer. This implies that the estimated temperature is the eruption temperature, but zircon could have crystallized earlier. Likewise, samples that do not contain zircon or apatite are given as “maximum” temperatures. As such, for samples in which zircon or apatite is absent, the actual temperature is no greater than the value determined by the geothermometer. The temperature estimate is greatly influenced by the amount of certain elements in the whole rock, namely Zr for zircon and P for apatite. Increasing the concentration of either of these elements also increases the estimated temperature.

Samples in which zircon was recorded tend to give much higher temperatures than those in which zircon was not found. This can be seen in many of the I-type rhyolites, which zircon was typically not detected, when compared to A-type rhyolites. Minimum temperatures for A-type are between 835°C and 933°C compared to maximum I-type zircon temperatures of 761 °C to 793°C. This elevated temperature may be influenced by Zr being added due to the presence of zircon. Similarly, it can be noted that the Zr concentration of the I-type and most of the borderline samples is much lower in the samples that yield low temperatures. In other words, as samples become more A-type, the concentration of Zr also increases, even if zircon was not detected in the sample. There are two A-type samples in which zircon was not found: Littlefield rhyolite and Spring Creek of Mahogany Mountain rhyolites. These two samples still record higher

minimum temperatures (864 °C and 899 °C, respectively) than the I-type minimum temperatures due to the higher concentrations of Zr. Likewise, two I-type samples (Buchanan rhyolite complex, EJ-12-03, and Unity, U4b) had zircon and were estimated as minimum temperatures (839 °C and 757°C, respectively). These samples contained a higher concentration of Zr compared to the other I-type rhyolites, yet were still lower than the majority of the A-type minimum concentrations and thus, yield lower temperatures. The temperatures estimated using the zircon saturation geothermometer tend to yield the lowest temperatures for all of the geothermometers used on the I-type rhyolites. For these I-type samples, due to the absence of zircon, the actual temperature is less than or equal to the temperature given by the geothermometer. On the other hand, the temperatures estimated using this method tend to yield the highest temperatures for the A-type rhyolites when compared to all other geothermometers used in this study. Due to the presence of zircon in most of these A-type rhyolites, these samples serve as minimum values; in other words, the eruption temperature is greater than or equal to the temperature estimated by the zircon saturation geothermometer. This implies that these temperatures could be much higher than reported, which are already higher than temperatures given by other geothermometers.

Apatite was not detected in the majority of A-type rhyolites, with the exception of Jump Creek rhyolite and Dinner Creek Tuff. Due to the absence of apatite in these samples, the temperatures estimated serve as maximum values; in other words, the temperature is less than the temperature reported. Unlike the trends seen in the zircon saturation temperatures, no real trend is seen in the I-type to borderline samples. While apatite was found in many of the I-type and borderline samples, there is no trend in the

concentration of phosphorous as the samples become more A-type. Despite this, the affect of phosphorous on temperature is still apparent. This is obvious in the Circle Bar, Cottonwood, Bully Creek, and Jump Creek samples, which yield the highest temperatures. These samples lie between $\sim 940^{\circ}\text{C}$ to 970°C and give the highest concentrations of P (about 0.14 to 0.17 wt %). On the other hand, those samples that give the lowest temperatures, such as the entire Mahogany Mountain suite, one of the Unity samples (U3a), and two of the Buchanan samples (EJ-12-03 and B010), also have the lowest concentrations of phosphorous. Comparing the two Buchanan samples displays that the estimated temperature is not affected by the presence or absence of apatite, but rather is changed by the concentration of phosphorous. The temperatures estimated by the apatite saturation geothermometer tend to fall in the middle range when compared to all other geothermometer estimates, with the exception of Circle Bar, Cottonwood, Bully Creek, Dinner Creek, and Jump Creek samples. For these five samples, the apatite temperature is the highest estimated for those centers. The temperatures may be unrealistic for these centers, especially those that may be higher than the other estimates by several degrees (e.g. Circle Bar).

When discounting temperatures that appear to be greatly affected by single components, the I-type temperatures are typically lower than or similar to the low end of the A-type temperature range. With all geothermometers in consideration, the range for the I-type rhyolites is from 737°C to 1043°C , however, when discounting the questionable estimates, the average range is closer to 737°C to 900°C . This range is slightly lower than the A-type range, 783°C to 931°C ; however, the borderline samples record the highest average temperatures compared to I- or A-type.

4.2.2. Evaluation of Temperature Within Centers

4.2.2.1. Buchanan Rhyolite Complex

The samples representing the Buchanan rhyolite complex yield a large range of temperatures from 737 °C to 1043 °C. The average temperature of the sample EJ-12-03 is the lowest of the Buchanan samples, yielding a temperature range of 737 °C to 839 °C. Similarly, the temperatures estimated for sample B010 fall within the same range as EJ-12-03, with the exception of the feldspar temperature. In both Buchanan samples, B010 and B114, it is apparent that elevated An content leads to high temperature estimates by the plagioclase-liquid geothermometer. In sample B010, the feldspar temperature is 110 °C higher than the temperature estimated by the apatite saturation geothermometer. Similarly, the feldspar temperature estimated for B114 is the highest of any other temperature estimated by this study. The An concentration in the plagioclase phenocryst of this sample is also the highest of any other sample in this study. As a result, this temperature should be discounted for reasons discussed above.

B114 records exceptionally high temperatures using the pyroxene and apatite saturation geothermometers, whereas the zircon saturation geothermometer yields temperatures more similar to the other Buchanan rhyolite samples. The orthopyroxene-liquid and two pyroxene geothermometers estimate the same temperature of 985 °C and the clinopyroxene thermometer gives a slightly lower temperature of 970 °C. Only two samples of this study contained orthopyroxene, and both resulting temperatures tended to be higher than other geothermometers used for the same samples. The augite recorded in sample B114 has much higher En and lower Fs than most of the other clinopyroxenes

recorded in this study. As a result, the temperature estimated using the clinopyroxene geothermometer is elevated in comparison.

For sample EJ-12-03, all estimated temperatures are realistic. In sample B010, the zircon and apatite saturation temperatures fall in line with published calc-alkaline rhyolite temperatures; however, the feldspar-liquid value may be elevated due to the high An concentration. Additionally, the equilibrium value for B010 is outside of the acceptable range, implying that it is not in equilibrium, and thus, the temperature should not be considered valid. Sample B114 has multiple elevated temperatures that record values much higher temperatures than published values; however, the zircon saturation temperature falls in line with the other temperatures estimated for the Buchanan rhyolites.

4.2.2.2. Circle Bar (Malheur) Rhyolite

The majority of temperatures for this sample fall in a small 100 °C band between 750 °C and 850 °C. The exceptions are the estimates of apatite saturation and the plagioclase equation of the feldspar-liquid geothermometer. Again, the plagioclase of the Circle Bar rhyolite is An₅₃, which appears to have an effect on the temperature estimated by the geothermometer. In contrast, the two-feldspar and alkali feldspar equation of the feldspar-liquid geothermometer yield temperatures that are almost 100 °C lower than the plagioclase-liquid temperature. For this sample, the plagioclase-liquid temperature is not in line with the temperatures estimated using the other four geothermometers, appear to be greatly influenced by the high An content of the plagioclase and is excluded. Additionally, the apatite saturation temperature appears unrealistically elevated in

comparison to the other estimated temperatures and should also be discounted. The Circle Bar rhyolite did not fall in the acceptable range for the equilibrium test of the clinopyroxene geothermometer. As a result, the temperature estimated using this geothermometer should not be considered valid.

4.2.2.3. Dam Rhyolite

The Dam rhyolite has a very wide range of temperatures from 781 °C to 990 °C. Similar to trends seen in other samples containing high An plagioclase, the temperature estimated using the plagioclase equation of the feldspar-liquid geothermometer (990 °C) is elevated compared to other temperatures for this sample. The temperature for orthopyroxene is also elevated and yields a similarly high temperature to the only other sample that contains orthopyroxene (956 °C). Likewise, the apatite saturation temperature is almost above 900 °C; however, the zircon saturation temperature is more in line with other I-type rhyolites, giving a temperature of 781 °C.

4.2.2.4. Unity Rhyolite

Sample U3a of the Unity rhyolites has a narrow range of temperatures, from 773 °C to 883 °C compared to the other Unity rhyolite, U4b, which records a range of 750 °C to 981 °C. While both samples contain plagioclase, the feldspar-liquid geothermometer yields a much higher plagioclase temperature for sample U4b than U3a. Similarly, the An content is higher in U4b than U3a at An₂₆ compared to An₁₇. In addition, the affect of

An can be seen within U3a itself as the alkali feldspar and two feldspar geothermometers yield lower temperatures of 823 °C and 773 °C, respectively. These two values fall more in line with the temperatures estimated by zircon and apatite saturation. For U3a, with the exception of the plagioclase temperature, all geothermometers yield temperatures falling in the 750 °C to 850 °C range, similar to other I-type samples. U4b, on the other hand, has two temperatures, given by the amphibole-plagioclase, apatite, and zircon saturation geothermometers that give similar temperatures to U3a, however, plagioclase-liquid temperatures are much higher and should be excluded.

4.2.2.5. Cottonwood and Littlefield Rhyolites

The Cottonwood and Bully Creek rhyolites record temperatures that are similar to each other. Both samples contain plagioclase feldspar and yield temperatures near 950 °C. Again, the higher An content of 40% for plagioclase appears to dictate the temperature estimate given by this geothermometer. Likewise, both samples contain pigeonite, clinopyroxene with lower Wo and slightly higher En contents than the clinopyroxene of the A-type rhyolites. As a result, the temperature estimated for this clinopyroxene is much higher than other clinopyroxene temperatures in this study. Additionally, the Cottonwood sample contains augite that is similar in composition to the augite found in the Buchanan rhyolite. The temperature estimated for this augite is lower than that of the pigeonite in this sample. The zircon and apatite saturation temperatures for these two samples are almost identical.

The Littlefield rhyolite sample has a temperature range that is similar to the Cottonwood and Bully Creek samples, falling between 864 °C and 984 °C. Once again, the feldspar-liquid geothermometer yields a higher value than most other geothermometers applied to this sample (953 °C), however, this appears less influenced by An content than other samples that yield similar temperatures. The plagioclase of the Littlefield rhyolite An_{24} whereas the Cottonwood rhyolites yield a similar temperature of 949 °C yet contains plagioclase with An_{40} . The olivine-liquid temperature is slightly higher than that of the feldspar-liquid, however the other three geothermometers yield temperatures between 864 °C and 908 °C. The equilibrium value for the Olivine-liquid geothermometer applied to the Littlefield rhyolite is not within an acceptable range. As a result, the temperature estimated for this sample is not valid. All of the other geothermometers applied to these samples appear valid.

4.2.2.6. Dooley Mountain Rhyolite

The temperatures estimated for this sample fall within a small range of 838 °C to 860 °C, with the exception of the temperature estimated by the feldspar-liquid geothermometer, which yields a temperature of 974 °C. This estimated temperature, again, seems highly influenced by the amount of An measured in the plagioclase phenocrysts of this sample, An_{39} . The temperature obtained by the feldspar-liquid geothermometer should be excluded for the Dooley Mountain rhyolite. Additionally, this sample did not yield an equilibrium value within the acceptable range using the

clinopyroxene geothermometer and thus, the estimated temperature using clinopyroxene should not be considered valid.

4.2.2.7. Dinner Creek Tuff

The temperatures estimated for the Dinner Creek Tuff fall within a small range of 835 °C to 882 °C. The plagioclase used in the feldspar-liquid geothermometer has An content of 12% and plots as ternary feldspar, oligoclase. As a result of this low An content, the geothermometer does not appear to be influenced by An and all estimated temperatures appear valid.

4.2.2.8. Jump Creek Rhyolite

The estimates for Jump Creek rhyolite are within 80 °C of each other, with the highest estimate given by the apatite saturation geothermometer.

4.2.2.9. Mahogany Mountain/Three Fingers Complex

The majority of temperatures estimated for all 5 samples representing this group are within 100 °C of each other. The exceptions to this are found within the Old McIntyre and Spring Creek samples. The Old McIntyre gives a very wide range of temperatures, with the highest two temperatures separated by at least 50 °C from the feldspar-liquid and apatite saturation equations, which yield temperatures similar to the

other samples in this complex. The Zircon saturation temperature for the Old McIntyre and Three Fingers samples is much higher than those estimated for the rest of the group using the same geothermometer. The temperatures calculated for the Spring Creek sample fall in a small range of 60 °C, but are slightly elevated compared to the rest of the group.

All of the samples representing this complex contain alkali feldspar, thus the feldspar-liquid geothermometer is not affected by the An content. The Spring Creek sample contains anorthoclase, and the influence of elevated An can be seen in the resulting temperature for this sample; however, the estimate is realistic.

With regard to the clinopyroxene geothermometer, only one sample in the Mahogany Mountain/Three Fingers suite can be considered valid. The Old McIntyre rhyolite is the only sample that yielded an equilibrium value within the acceptable range. As such, the temperatures estimated for the other samples of this suite (i.e., Young McIntyre, Spring Creek, and Three Fingers) should not be considered valid.

4.2.3. Results of This Study Compared to Other Studies

There are several publications that deal with the mineralogy and geothermometry of rhyolites. Specifically, the rhyolites of the Yellowstone hotspot track have been a large focus in the past 20 years (Hildreth et al., 1984; Honjo et al., 1992; Perkins and Nash, 2002; Cathey and Nash, 2004). The petrology of the eruptive centers along the hotspot track has been well documented and geothermometry has been applied using

various methodologies. In addition, there are multiple studies that consider calc-alkaline rhyolites and their associated eruption temperatures.

As noted in previous sections, mineral assemblages for the A-type rhyolites of this study mirror the assemblages found in other studies (e.g., Cathey and Nash, 2004; Girard and Stix, 2009). The geothermometers applied in these other studies are often the same or comparable to those used in this study. The two-feldspar, feldspar-liquid, Ca-QUILF, and Fe-Ti oxide thermometers were used in several of the published studies (Cathey and Nash, 2004; Christensen, 2005).

The temperatures for all A-type rhyolites of this study range between 783 °C and 984 °C. This range appears consistent with published values for Snake River Plain. Many studies utilize the two-feldspar, Fe-Ti oxide, Ca-QUILF (for pyroxenes), and the two-pyroxene geothermometers to estimate temperatures for Snake River Plain rhyolites. In these other studies, temperatures range as follows: 740 °C to 976 °C (Cathey and Nash, 2004), 822 °C to 1000 °C (Honjo et al., 1992), 850 °C to 1000 °C (Andrews et al., 2008), and 825 °C to 950 °C (Bolte et al., 2015). Considering these ranges, the temperatures estimated for the A-type rhyolites of this study are realistic. The lowest temperatures calculated for the A-type rhyolites of this study are slightly higher than published ranges; 783 °C is the lowest estimated temperature for any A-type rhyolite of this study, whereas the lowest range in publications discussed in this study is 740 °C. Similarly, the highest temperatures estimated for the A-type rhyolites of the LOVF are very similar to published values. The highest temperature estimated by any geothermometer for any A-

type rhyolites of this study is 984 °C, whereas the highest temperatures cited for Snake River Plain rhyolites is ~1000 °C (Honjo et al., 1992; Andrews et al., 2008).

The range of temperatures for the I-type rhyolites of this study is 737 °C to 900 °C, after excluding unrealistic estimates. For the majority of I-type samples in this study, the geothermometers that yield realistic temperatures are the alkali feldspar-liquid, two feldspar, zircon saturation, amphibole-plagioclase, and sometimes, the apatite saturation geothermometers. While many studies utilize pyroxene geothermometers, the temperatures estimated for this study are very high (between 950 °C and 1000 °C) and appear to be affected by compositional controls rather than purely temperature influenced.

Published studies that consider the eruption temperatures of calc-alkaline rhyolites tend to utilize the Fe-Ti oxide, Ti-in-Zircon, amphibole-plagioclase, and two-pyroxene geothermometers. The temperatures provided by these studies vary, but tend to be lower than published A-type rhyolite temperatures, with some overlap: 724 °C to 794 °C at the Okareka center in New Zealand (Shane et al., 2008), 640 °C to 868 °C for rhyolites at South Sister of the Oregon Cascades (Stelten et al., 2012), 700 °C to 950 °C for Okataina and Taupo centers in New Zealand (Smith et al., 2005), and 779 °C to 940 °C for obsidians found in the Mexican and Cascade Arcs (Waters et al., 2013). Multiple authors noted that the samples that contained pyroxene tended to yield higher temperatures than the rhyolites that did not. In addition, Smith et al. (2005) mentions that the samples that are dominated by orthopyroxene would give higher temperatures than those that contained both amphibole and orthopyroxene, and the rhyolites that contained

clinopyroxene would give the highest temperatures. Likewise, the Dam rhyolite contains orthopyroxene and yields a higher average temperature than many of the other I-type rhyolites. The lowest temperatures noted for each center were those samples that contained biotite and/or amphibole. These trends appear consistent with what is observed in the I-type rhyolites of this study. The temperatures given for the Circle Bar rhyolite, which contains both amphibole and biotite, yield much lower average temperatures than the Buchanan sample (B114) that contains pyroxene. The majority of geothermometers for the Circle Bar rhyolite give temperatures between 760 °C and 840 °C whereas the range of temperatures for the B114 sample is 950 °C to 1040 °C. Additionally, one Buchanan sample (B010) contains biotite and yields lower average temperatures than other I-type rhyolites of the sample set that do not contain biotite. Both of the Unity samples contain biotite and one (U4b) also contains amphibole. These two samples give comparatively low temperatures: U3a gives a temperature range of about 770 °C to 830 °C when the plagioclase equation of the feldspar-liquid geothermometer is not included. Similarly, the zircon saturation and amphibole-plagioclase geothermometers give similar temperatures near 750 °C for U4b whereas the feldspar-liquid geothermometer yields a very high temperature of 980 °C. The lowest temperatures estimated for the I-type rhyolites are similar to published calc-alkaline temperatures. The lowest estimate for this study is 737 °C whereas the low end of the published temperatures range from 640 °C (Stelton et al., 2012) to 779 °C (Waters et al., 2013). The highest temperatures for the calc-alkaline rhyolites in this study, however, tend to be higher than published values. For example, the highest estimated temperature for an I-type rhyolite of this study is 1043 °C, whereas the high end of the ranges for published temperatures are from 794 °C to 950

°C. While some of the highest temperatures estimated for the calc-alkaline rhyolites this study still lie within published ranges, the range considered realistic, 737 °C to 900 °C, is more in line with published temperatures.

In general, the samples of this study are comparable to the published temperatures for their associated groups. There appears to be geothermometers that yield temperatures that consistently fall out of line with other estimated temperatures, such as the pyroxene geothermometers for the I-type rhyolites, and the plagioclase equation for the feldspar-liquid geothermometer, both of which consistently estimate elevated temperatures compared to other geothermometers used for the same samples.

Summary and Conclusion

This study investigated the correlation of the geochemistry with the mineralogy and estimated eruption temperatures of a series of mid-Miocene rhyolites that erupted in eastern Oregon. Eighteen samples collected in previous studies were selected to represent eleven different silicic centers of the Lake Owyhee Volcanic Field (LOVF). Samples were classified as “A-type”, “I-type” or “borderline” using discrimination techniques used for granitic rocks by Whalen et al. (1987). Of the eighteen samples used in this study, seven are classified as I-type, eight as A-type, and three are borderline of A- and I-type.

Samples that are classified as I-type tend to contain plagioclase feldspar with higher An content such as andesine and labradorite. Additionally, these I-type rhyolites may also contain high-Or sanidine. The only samples of the entire sample set that contain both plagioclase and alkali feldspar are I-type rhyolites. Orthopyroxene and the two hydrous minerals biotite and amphibole are only found in I-type rhyolites. In contrast, A-type rhyolites tend to have lower-An plagioclase, such as oligoclase. The alkali feldspar of the A-type rhyolites tend to have lower Or contents as well, with two samples plotting as anorthoclase. A-type rhyolites often contain Fe-rich clinopyroxene, such as ferroaugite and ferrohedenbergite.

Appropriate geothermometers were applied to samples based on their mineral assemblages. The A-type rhyolites record temperatures in the range of 783 °C to 984 °C, which is consistent with other temperatures that have been published for A-type rhyolites, such as the Snake River Plain. The I-type rhyolites, on the other hand, are more

complicated. These rhyolites yield a range of 737 °C to 900 °C, with some outlier temperatures given by pyroxene geothermometers. Certain geothermometers appear to be greatly influenced by elevated concentrations of certain components. This is very apparent in the temperatures estimated for the I-type rhyolites using the feldspar-liquid equation. The samples with the highest An content yield the highest temperature and show a correlation in that as An content decreases, temperature also decreases. This affect of An on temperature appears to yield anomalously high values for the I-type rhyolites, sometimes giving temperatures that are 100 °C higher than the next highest estimate for the same sample. Of note is that samples containing hydrous minerals such as amphibole and/or biotite recorded lower temperatures than other similarly classified rhyolites. This is consistent with generally lower temperatures of crystallization to stabilize such mineral phases. Likewise, samples that contained orthopyroxene or higher En clinopyroxene recorded elevated temperatures compared to similar rhyolites.

In all, the temperature estimates for each classification type fall in line with published estimates A- and I-type rhyolites from other studies; however, some geothermometers applied to the I-type rhyolites yield outlier temperatures. The I-type and A-type samples contain specific mineral assemblages that are characteristic for their compositional designation. Additionally, as a whole, the A-type rhyolites record slightly higher temperatures overall than the I-type rhyolites.

The data of this study illustrate variations of mineral assemblages and estimated eruption temperatures that occur among rhyolites within a single center as well as among centers. There is a clear correlation of mineral assemblages with compositional

characteristics used to define A- versus I-type character. On the other hand, estimated eruption temperatures are more complicated and vary considerably with used geothermometers. This hinders to establish strong evidence that A-type magmas have higher temperatures than I-type rhyolites, although a weaker correlation can be established. Causes for why these observed variations among the rhyolites of LOVF exist are currently not well understood, but a multitude of variables are likely responsible. This study highlights the need for further study to shed light on processes and controls that cause these observed variations among rhyolites of the LOVF.

References

- Anderson, J.L., Barth, A.P., Wooden, J.L., and Mazdab, F., 2008, Thermometers and Thermobarometers in Granitic Systems: Reviews in Mineralogy and Geochemistry, v. 69, p. 121–142, doi: 10.2138/rmg.2008.69.4.
- Anderson, J.L., Barth, A.P., Wooden, J.L., Mazdab, F., Andrews, G.D.M., Branney, M.J., Bonnicksen, B., McCurry, M., Beattie, P., Bindeman, I.N., Valley, J.W., Blundy, J.D., Holland, T.J.B., Boehnke, P., et al., 2008, Single-pyroxene geothermometry and geobarometry: Contributions to Mineralogy and Petrology, v. 61, p. 1–19, doi: 10.2138/am-2016-5591.
- Andrews, G.D.M., Branney, M.J., Bonnicksen, B., and McCurry, M., 2008, Rhyolitic ignimbrites in the Rogerson Graben, southern Snake River Plain volcanic province: Volcanic stratigraphy, eruption history and basin evolution: Bulletin of Volcanology, v. 70, p. 269–291, doi: 10.1007/s00445-007-0139-0.
- Bachmann, O., and Bergantz, G.W., 2009, Rhyolites and their Source Mushes across Tectonic Settings: Journal of Petrology, v. 49, p. 2277–2285, doi: 10.1093/petrology/egn068.
- Barry, T.L., Kelley, S.P., Camp, V., Self, S., Jarboe, N., and Duncan, R., 2013, Eruption chronology of the Columbia River Basalt Group: Geological Society of America Special Papers, v. 2497, p. 45–66, doi: 10.1130/2013.2497(02).
- Benson, T.R., and Mahood, G.A., 2016, Geology of the Mid-Miocene Rooster Comb Caldera and Lake Owyhee Volcanic Field, eastern Oregon: Silicic volcanism associated with Grande Ronde flood basalt: Journal of Volcanology and Geothermal Research, v. 309, p. 96–117, doi: 10.1016/j.jvolgeores.2015.11.011.
- Blundy, J.D., and Holland, T.J.B., 1990, Mineralogy and Calcic amphibole equilibria and a new amphibole- plagioclase geothermometer: Contributions to Mineralogy and Petrology, v. 104, p. 208–224.
- Boehnke, P., Watson, E.B., Trail, D., Harrison, T.M., and Schmitt, A.K., 2013, Zircon saturation re-revisited: Chemical Geology, v. 351, p. 324–334, doi: 10.1016/j.chemgeo.2013.05.028.
- Bolte, T., Holtz, F., Almeev, R., and Nash, B., 2015, The Blacktail Creek Tuff: an analytical and experimental study of rhyolites from the Heise volcanic field, Yellowstone hotspot system: Contributions to Mineralogy and Petrology, v. 169, doi: 10.1007/s00410-015-1112-0.

- Camp, V.E., Ross, M.E., and Hanson, W.E., 2003, Genesis of flood basalts and Basin and Range volcanic rocks from Steens Mountain to the Malheur River Gorge, Oregon: Geological Society of America Bulletin, v. 115, p. 105–128.
- Cathey, H.E., and Nash, B.P., 2004, The Cougar Point Tuff: Implications for Thermochemical Zonation and Longevity Silicic Magmas of the Miocene Yellowstone Hotspot: Journal of Petrology, v. 45, p. 27–58, doi: 10.1093/petrology/egg081.
- Cathey, H.E., and Nash, B.P., 2009, Pyroxene thermometry of rhyolite lavas of the Bruneau–Jarbidge eruptive center, Central Snake River Plain: Journal of Volcanology and Geothermal Research, v. 188, p. 173–185, doi: 10.1016/j.jvolgeores.2009.05.024.
- Chappell, B.W., and White, A.J.R., 2001, Two contrasting granite types : 25 years later: Australian Journal of Earth Sciences, p. 489–499.
- Christiansen, E.H., and McCurry, M., 2008, Contrasting origins of Cenozoic silicic volcanic rocks from the western Cordillera of the United States: Bulletin of Volcanology, v. 70, p. 251–267, doi: 10.1007/s00445-007-0138-1.
- Coble, M.A., and Mahood, G.A., 2012, Initial impingement of the Yellowstone plume located by widespread silicic volcanism contemporaneous with Columbia River flood basalts: Geology, v. 40, p. 655–658, doi: 10.1130/G32692.1.
- Colón, D.P., Bindeman, I.N., Stern, R.A., and Fisher, C.M., 2015, Isotopically diverse rhyolites coeval with the Columbia River Flood Basalts: evidence for mantle plume interaction with the continental crust: Terra Nova, v. 27, p. 270–276, doi: 10.1111/ter.12156.
- Cummings, M.L., Evans, J.G., Ferns, M.L., and Lees, K.R., 2000, Stratigraphic and structural evolution of the middle Miocene synvolcanic Oregon-Idaho graben: Geological Society of America Bulletin, v. 112, p. 668–682, doi: 10.1130/0016-7606(2000)112<668:SASEOT>2.0.CO;2.
- Ellis, B.S., Wolff, J.A., Boroughs, S., and Mark, D.F., 2013, Rhyolitic volcanism of the central Snake River Plain : a review: Geology, v. 42, p. 431–434, doi: 10.1007/s00445-013-0745-y.
- Ferns, M.L., and McClaughry, J.D., 2013, Stratigraphy and volcanic evolution of the middle Miocene to Pliocene La Grande–Owyhee eruptive axis in eastern Oregon, *in* Geological Society of America Special Papers, v. 497, p. 401–427, doi: 10.1130/2013.2497(16).

- Ford, M.T., Grunder, A.L., and Duncan, R.A., 2013, Bimodal volcanism of the High Lava Plains and Northwestern Basin and Range of Oregon : Distribution and tectonic implications of age-progressive rhyolites: *Geochemistry, Geophysics, Geosystems*, v. 14, p. 2836–2857, doi: 10.1002/ggge.20175.
- Girard, G., and Stix, J., 2009, Buoyant replenishment in silicic magma reservoirs : Experimental approach and implications for magma dynamics, crystal mush remobilization, and eruption: *Journal of Geophysical Research*, v. 114, doi: 10.1029/2008JB005791.
- Girard, G., and Stix, J., 2009, Magma Recharge and Crystal Mush Rejuvenation Associated with Early Post-collapse Upper Basin Member Rhyolites , Yellowstone Caldera , Wyoming: *Journal of Petrology*, v. 50, p. 2095-2125, doi: 10.1093/petrology/egp070.
- Hess, E.N., 2014, Strontium , Lead , and Oxygen Isotopic Signatures of Mid-Miocene Silicic Volcanism in Eastern Oregon [MS Thesis]: Portland, Portland State University.
- Hildreth, W.E.S., Christiansen, R.L., and Geological, U.S., 1984, Catastrophic Isotopic Modification of Rhyolitic Magma at Times of Caldera Subsidence , Yellowstone Plateau Volcanic Field: *Journal of Geophysical Research*, v. 89, p. 8339–8369.
- Hildreth, W., 1981, Gradients in Silicic Magma Chambers ' Implications for Lithospheric Magmatism: *Journal of Geophysical Research*: v. 86, p. 10153-10192
- Holland, T., and Blundy, J., 1994, Non-ideal interactions in calcic amphiboles and their bearing on amphibole-plagioclase thermometry: *Contributions to Mineralogy and Petrology*, v. 116, p. 433–447.
- Honjo, N., Bonnicksen, B., Leeman, W.P., and Stormer Jr., J.C., 1992, Mineralogy and geothermometry of high-temperature rhyolites from the central and western Snake River Plain: *Bulletin of Volcanology*, v. 54, p. 220–237.
- Hooper, P.R., Binger, G.B., and Lees, K.R., 2002, Ages of the Steens and Columbia River flood basalts and their relationship to extension-related calc-alkalic volcanism in eastern Oregon: *Geological Society of America Bulletin*, v. 114, p. 43–50, doi: 10.1130/0016-7606(2002)114<0043:AOTSAC>2.0.CO;2.
- Large, A.M., 2016, Silicic Volcanism at the Northern and Western Extent of the Columbia River Basalt Rhyolite Flare-up : Rhyolites of Buchanan Volcanic Complex and Dooley Mountain Volcanic Complex [MS Thesis]: Portland, Portland State University, 189 p.

- Loewen, M.W., and Bindeman, I.N., 2016, Oxygen isotope thermometry reveals high magmatic temperatures and short residence times in Yellowstone and other hot-dry rhyolites compared to cold-wet systems: *American Mineralogist*, v. 101, p. 1222–1227, doi: 10.2138/am-2016-5591.
- Marcy, P.I., 2013, Revisiting Volcanology and Composition of Rhyolites and Associated REE Rich Mafic Clasts of the Three Fingers Caldera in SE Oregon [MS Thesis]: Portland, Portland State University, 214 p.
- Orr, A.A., 2019, Physical Parameters Based on Fe-Ti Oxide Compositions and Their Correlation with Geochemical Signatures of mid-Miocene Rhyolites, Eastern Oregon [B.S. Honors Thesis]: Portland, Portland State University, 16 p.
- Perkins, M.E., and Nash, B.P., 2002, Explosive silicic volcanism of the Yellowstone hotspot : The ash fall tuff record: *Geological Society of America Bulletin*, v. 114, p. 367–381.
- Putirka, K.D., 2008, Thermometers and Barometers for Volcanic Systems: Reviews in *Mineralogy and Geochemistry*, v. 69, p. 61–120, doi: 10.2138/rmg.2008.69.3.
- Shane, P., Nairn, I.A., Smith, V.C., Darragh, M., Beggs, K., and Cole, J.W., 2008, Silicic recharge of multiple rhyolite magmas by basaltic intrusion during the 22 . 6 ka Okareka Eruption Episode , New Zealand: *Lithos*, v. 103, p. 527–549, doi: 10.1016/j.lithos.2007.11.002.
- Smith, V.C., Shane, P., and Nairn, I.A., 2005, Trends in rhyolite geochemistry , mineralogy , and magma storage during the last 50 kyr at Okataina and Taupo volcanic centres , Taupo Volcanic Zone , New Zealand: *Journal of volcanology and geothermal research*, v. 148, p. 372–406, doi: 10.1016/j.volgeores.2005.05.005.
- Stelten, M.E., and Cooper, K.M., 2012, Constraints on the nature of the subvolcanic reservoir at South Sister volcano , Oregon from U-series dating combined with sub-crystal trace-element analysis of plagioclase and zircon: *Earth and Planetary Science Letters*, v. 313–314, p. 1–11, doi: 10.1016/j.epsl.2011.10.035.
- Streck, M.J. and Ferns, M., 2012, The rhyolite flare-up of the Columbia River Basalt province and its bearing on plume vs non-plume models. *Am. Geophys Union*, Fall Meeting 2012, abstract #DI53A-2372.
- Streck, M.J., Ferns, M.L., and McIntosh, W., 2015, Large, persistent rhyolitic magma reservoirs above Columbia River Basalt storage sites: The Dinner Creek Tuff Eruptive Center, eastern Oregon: *Geosphere*, v. 11, p. 226–235, doi: 10.1130/GES01086.1.

- Streck, M.J., 2014, Evaluation of crystal mush extraction models to explain crystal-poor rhyolites: *Journal of Volcanology and Geothermal Research*, v. 284, p. 79–94, doi: 10.1016/j.jvolgeores.2014.07.005.
- Streck, M.J., and Grunder, A.L., 2012, Temporal and crustal effects on differentiation of tholeiite to calcalkaline and ferro-trachytic suites, High Lava Plains, Oregon, USA: *Geochemistry, Geophysics, Geosystems*, v. 13, p. 1–23, doi: 10.1029/2012GC004237.
- Waters, L.E., and Lange, R.A., 2013, Crystal-poor , multiply saturated rhyolites (obsidians) from the Cascade and Mexican arcs : evidence of degassing- induced crystallization of phenocrysts: *Contributions to Mineralogy and Petrology*, v. 166, p. 731–754, doi: 10.1007/s00410-013-0919-9.
- Watson, E.B., and Harrison, T.M., 1983, Zircon saturation revisited: temperature and composition effects in a variety of crustal magma types: *Earth and Planetary Science Letters*, v. 64, p. 295–304, doi: 10.1016/0012-821X(83)90211-X.
- Webb, B.M., Streck, M.J., McIntosh, W.C., Ferns, M.L., 2018, The Littlefield Rhyolite and associated mafic lavas : Bimodal volcanism of the Columbia River magmatic province, with constraints on age and storage sites of Grande Ronde Basalt magmas: *Geosphere*, v. 15, p. 60–84.
- Webb, B.M., 2017, The Littlefield Rhyolite , Eastern Oregon : Distinct Flow Units and Their Constraints on Age and Storage Sites of Grande Ronde Basalt Magmas [MS Thesis]: Portland, Portland State University, 144 p.
- Whalen, J.B., Currie, K.L., and Chappell, B.W., 1987, A-type granites: geochemical characteristics, discrimination and petrogenesis*: *Contrib Mineral Petrol*, v. 95, p. 407–419.

Appendix A: Thin Section Scans

Figure 24. Scan of the thin section for Buchanan sample EJ-12-03.

Figure 25. Scan of the thin section for Buchanan sample B010.

Figure 26. Scan of the thin section for Buchanan sample B114.

Figure 27. Scan of the thin section for Circle Bar sample EJ-12-05b.

Figure 28. Scan of the thin section for Dam sample EJ-12-15.

Figure 29. Scan of the thin section for Unity sample U3a.

Figure 30. Scan of the thin section for Unity sample U4b.

Figure 31. Scan of the thin section for Cottonwood sample EJ-12-16.

Figure 32. Scan of the thin section for Bully Creek sample EJ-12-17.

Figure 33. Scan of the thin section for Dooley Mountain, DR2.

Figure 34. Scan of the thin section for Dinner Creek sample EJ-12-08.

Figure 35. Scan of the thin section for Littlefield sample EJ-12-10.

Figure 36. Scan of the thin section for Jump Creek sample EJ-12-13b.

Figure 37. Scan of the thin section for Old McIntyre sample EJ-12-12.

Figure 38. Scan of the thin section for Young McIntyre sample EJ-12-14.

Figure 39. Scan of the thin section for Young McIntyre sample MS-13-24b.

Figure 40. Scan of the thin section for the Spring Creek sample MS-13-29.

Figure 41. Scan of the thin section for Three Fingers sample TF-153H.

Appendix B: Additional Geochemistry Figures

Figure 42. Diagram illustrating FeO versus SiO₂ concentration in rhyolites from Buchanan Rhyolite complex. Samples used in this study are denoted in red.

Figure 43. Diagram illustrating the sum of trace elements (Zr + Nb + Y + Ce) versus 10000Ga/Al for rhyolites from the Buchanan rhyolite complex. Samples that plot within the box (where $x=2.6$ and $y=350$) are classified as I-type whereas those that fall outside of the box are A-type.

Figure 44. Diagram illustrating Zr versus SiO₂ concentration in rhyolites from the Buchanan rhyolite complex. Samples used in this study are denoted in red. Samples that plot under the line (where y=250) are classified as I-type whereas those that fall above the line are A-type

Figure 45. Diagram illustrating FeO versus SiO₂ concentration in rhyolites from the Malheur River area. Samples used in this study are denoted in red.

Figure 46. Diagram illustrating the sum of trace elements (Zr + Nb + Y + Ce) versus 10000Ga/Al for rhyolites from the Malheur River area. Samples used in this study are denoted in red. Samples that plot within the box (where $x=2.6$ and $y=350$) are classified as I-type whereas those that fall outside of the box are A-type.

Figure 47. Diagram illustrating Zr versus Nb concentration in rhyolites from the Malheur River area. Samples used in this study are denoted in red. Samples that plot in the box (where $x=250$, $y=20$) are classified as I-type whereas those that fall above the line are A-type.

Figure 48. Diagram illustrating Zr versus SiO₂ concentration in rhyolites from the Malheur River area. Samples used in this study are denoted in red. Samples that plot under the line (where y=250) are classified as I-type whereas those that fall above the line are A-type.

Figure 49. Diagram illustrating FeO versus SiO₂ concentration in rhyolites from the Unity area. Samples used in this study are denoted in red.

Figure 50. Diagram illustrating the sum of trace elements (Zr + Nb + Y + Ce) versus 10000Ga/Al for rhyolites from the Unity area. All samples plot within the box (where $x=2.6$ and $y=350$) and thus all samples from the Unity area plot as I-type.

Figure 51. Diagram illustrating Zr versus Nb concentration in rhyolites from the Unity area. Samples that plot in the box (where $x=250$, $y=20$) are classified as I-type whereas those that fall above the line are A-type.

Figure 52. Diagram illustrating Zr versus SiO₂ concentration in rhyolites from the Unity area. All samples plot below the line (where y=250) thus all samples are classified as I-type.

Figure 53. Diagram illustrating FeO versus SiO₂ concentration in rhyolites from the Cottonwood/Littlefield complex. Samples used in this study are denoted in red (Cottonwood) and pink (Littlefield). Open diamonds denote upper Littlefield, dark blue represent lower Littlefield, and light blue are Cottonwood.

Figure 54. Diagram illustrating Zr versus Nb concentration in rhyolites from the Cottonwood/Littlefield complex. All samples plot outside of the box (where $x=250$, $y=20$), thus all samples plot as A-type.

Figure 55. Diagram illustrating Zr versus SiO₂ concentration in rhyolites from the Cottonwood/Littlefield complex. All samples plot above the line (where $y=250$) and thus all of the samples are classified as A-type.

Figure 56. Diagram illustrating the sum of trace elements (Zr + Nb + Y + Ce) versus 10000Ga/Al for rhyolites from Dooley Mountain. Samples that plot within the box (where $x=2.6$ and $y=350$) are classified as I-type whereas those that fall outside of the box are A-type.

Figure 57. Diagram illustrating Zr versus Nb concentration in rhyolites from Dooley Mountain. Samples that plot in the box (where $x=250$, $y=20$) are classified as I-type whereas those that fall above the line are A-type.

Figure 58. Diagram illustrating Zr versus SiO₂ concentration in rhyolites from Dooley Mountain. Samples that plot under the line (where y=250) are classified as I-type whereas those that fall above the line are A-type.

Figure 59. Diagram illustrating FeO versus SiO₂ concentration in rhyolites of Dinner Creek tuff. Samples used in this study are denoted in red.

Figure 60. Diagram illustrating the sum of trace elements (Zr + Nb + Y + Ce) versus 10000Ga/Al for rhyolites of Dinner Creek tuff. All samples plot outside the box (where $x=2.6$ and $y=350$), thus all samples plot as A-type.

Figure 61. Diagram illustrating Zr versus Nb concentration in rhyolites of Dinner Creek tuff. All samples plot outside of the box (where $x=250$, $y=20$), and thus are classified as A-type.

Figure 62. Diagram illustrating Zr versus SiO₂ concentration in rhyolites from of Dinner Creek tuff. All of the samples plot above the line (where y=250) and thus all of the samples are classified as A-type.

Figure 63. Diagram illustrating FeO versus SiO₂ concentration in rhyolites from the Mahogany Mountain/Three Fingers complex. Samples used in this study are denoted in shades of red. Dark red closed square represents the Dam rhyolite, open square is Jump Creek, closed bright red is Mahogany Mountain rhyolites, and pink is Three Fingers rhyolite. Likewise, the dark blue diamond is Dam rhyolite, blue is Mahogany Mountain rhyolite, and light blue is Three Fingers.

Figure 64. Diagram illustrating the sum of trace elements (Zr + Nb + Y + Ce) versus 10000Ga/Al for rhyolites from the Mahogany Mountain/Three Fingers complex. Samples that plot within the box (where $x=2.6$ and $y=350$) are classified as “I-type” whereas those that fall outside of the box are “A-type”.

Figure 65. Diagram illustrating Zr versus SiO₂ concentration in rhyolites from the Mahogany Mountain/Three Fingers rhyolite complex. Samples that plot under the line (where $y=250$) are classified as I-type whereas those that fall above the line are A-type.

Appendix C: Summary Tables

Table 3. Summary table for sample EJ-12-03 from Buchanan Rhyolite.

Buchanan Rhyolite - EJ-12-03				
Bulk Composition Wt %, Normalized		Feldspar		
		Comp.	St. Dev.	
		Wt %, Un-normalized		
SiO2	78.81			
TiO2	0.09	Na2O	5.41	0.29
Al2O3	11.22	Al2O3	18.97	0.77
FeO*	0.80	SiO2	66.97	2.62
MnO	0.02	K2O	8.27	0.30
MgO	0.00	CaO	0.21	0.17
CaO	0.05	Total	99.73	
Na2O	2.36			
K2O	6.65			
P2O5	0.01	%An	0.96%	
Total	100.00	%Ab	49.51%	
		%Or	49.53%	
XRF, ppm		Accepted Range for SEM Data		
Ni	1.6	94 - 104 wt. %		
Cr	4.1			
Sc	4.1			
V	5.5			
Ba	148.9			
Rb	173.7			
Sr	6.1			
Zr	271.6			
Y	36.3			
Nb	16.1			
Ga	15.4			
Cu	6.4			
Zn	68.8			
Pb	45.6			
La	33.7			
Ce	48.9			
Th	16.2			

Table 4 Summary table for sample B010 from Buchanan Rhyolite.

Buchanan Rhyolite - B010					
Bulk Composition		Feldspar		Biotite	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Un-normalized			
SiO ₂	77.02	Na ₂ O	6.03	0.33	-
TiO ₂	0.12	Al ₂ O ₃	25.93	1.1	3.94
Al ₂ O ₃	12.60	SiO ₂	58.28	1.76	52.02
FeO*	1.04	K ₂ O	0.56	0.12	6.28
MnO	0.04	CaO	8.130	0.730	0.470
MgO	0.10	FeO	0.54	0.59	22.32
CaO	0.74	MgO	-	-	3.16
Na ₂ O	3.52				
K ₂ O	4.81				
P ₂ O ₅	0.01				
Total	100.00				
XRF, ppm		%An	41.26%		
Ni	3	%Ab	55.33%		
Cr	4	%Or	3.41%		
Sc	4	Mg #		19.59	
V	3				
Ba	1071				
Rb	128				
Sr	54				
Zr	121				
Y	30				
Nb	11				
Ga	14				
Cu	6				
Zn	27				
Pb	18				
La	27				
Ce	53				
Th	12				

Table 5. Summary table for sample B114 from Buchanan Rhyolite.

Buchanan Rhyolite - B114								
Bulk Composition		Feldspar			Pyroxene 1		Pyroxene 2	
Wt %, Normalized		Comp.	St. Dev.		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Un-normalized						
SiO ₂	69.01	Na ₂ O	4.68	0.83	-	-	-	-
TiO ₂	0.588	Al ₂ O ₃	28.15	1.43	1.07	0.25	2.09	0.57
Al ₂ O ₃	14.83	SiO ₂	54.22	2.74	52.1	1.01	51.2	1.22
FeO*	4.10	K ₂ O	0.32	0.18	-	-	-	-
MnO	0.091	CaO	10.87	1.67	1.36	0.12	19.4	2.03
MgO	0.96	FeO	0.52	0.08	23.48	2.27	11.34	1.7
CaO	3.18	MgO	-	-	20.54	1.64	13.78	1.14
Na ₂ O	3.70	TiO ₂	-	-	0.33	0.05	0.53	0.14
K ₂ O	3.36							
P ₂ O ₅	0.175							
Total	100.00							
XRF, ppm		%An	57.40%					
Ni	4.8	%Ab	41.02%					
Cr	4.4	%Or	1.59%					
Sc	10.0							
V	55.6	%Wo			2.83%		42.19%	
Ba	1296.8	%En			59.04%		39.60%	
Rb	78.0	%Fs			18.20%		18.20%	
Sr	239.5							
Zr	208.0							
Y	33.2							
Nb	10.1							
Ga	15.3							
Cu	17.4							
Zn	54.2	Accepted Range for SEM Data						
Pb	11.5	96 - 101 wt. %						
La	24.8							
Ce	48.1							
Th	6.9							

Table 6. Summary table for sample EJ-12-05B (Circle Bar) from Malheur Rhyolite.

Circle Bar - EJ-12-05B (Malheur)										
Bulk Composition		Feldspar 1			Feldspar 2		Amphibole		Biotite	
Wt %, Normalized		Comp.		St. Dev.	Comp.		St. Dev.	Comp.		St. Dev.
SiO2	75.34	Wt %, Un-normalized								
TiO2	0.198	Na2O	2.85	0.86	5.71	0.26	-	-	1.51	0.06
Al2O3	13.08	Al2O3	19.14	0.22	23.41	2.36	1.18	0.05	8.63	0.22
FeO*	1.4	SiO2	65.57	0.98	53.62	2.19	48.97	0.06	43.32	0.45
MnO	0.049	K2O	12.04	1.45	0.57	0.12	-	-	0.97	0.07
MgO	0.23	CaO	0.21	0.08	7.2	1.58	17.25	0.04	11.06	0.51
CaO	1.15	FeO	-	-	0.66	0.04	12.98	0.1	20.00	0.50
Na2O	2.8	MgO	-	-	-	-	12.95	0	9.05	0.22
K2O	5.65	TiO2	-	-	-	-	0.46	0.05	1.89	0.09
P2O5	0.099									
Total	100.00									
XRF, ppm		%An	1.04%		53.01%					
Ni	2	%Ab	19.11%		42.68%					
Cr	5	%Or	79.84%		4.31%					
Sc	3									
V	14	Mg #					38.72		34.31	
Ba	500									
Rb	168									
Sr	104									
Zr	117									
Y	23									
Nb	13.5	Accepted Range for SEM Data								
Ga	15	93 - 103 wt. %								
Cu	4									
Zn	30									
Pb	23									
La	25									
Ce	48									
Th	17									

Table 7. Summary table for sample EJ-12-15 from Dam Rhyolite.

Dam Rhyolite - EJ-12-15					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Un-normalized			
SiO ₂	72.78	Na ₂ O	4.45	0.42	-
TiO ₂	0.257	Al ₂ O ₃	26.26	1.5	1.27
Al ₂ O ₃	14.44	SiO ₂	51.21	2.94	49.3
FeO*	1.86	K ₂ O	0.35	0.05	-
MnO	0.054	CaO	9.87	0.62	0.89
MgO	0.57	FeO	0.42	0.08	16.87
CaO	2.05	MgO	-	-	22.07
Na ₂ O	3.23	MnO	-	-	0.8
K ₂ O	4.68				0.09
P ₂ O ₅	0.076				
Total	100.00				
XRF, ppm		%An	53.92%		
Ni	6	%Ab	43.79%		
Cr	5	%Or	2.27%		
Sc	6				
V	23	%Wo		1.99%	
Ba	1520	%En		68.59%	
Rb	87	%Fs		29.43%	
Sr	245				
Zr	156				
Y	17				
Nb	9.4	Accepted Range for SEM Data			
Ga	14	93 - 104 wt. %			
Cu	9				
Zn	35				
Pb	16				
La	21				
Ce	41				
Th	7				

Table 8. Summary table for sample CR-U3A from Unity Rhyolite.

Unity Rhyolite - CR-U3A								
Bulk Composition		Feldspar 1			Feldspar 2		Biotite	
Wt %, Normalized		Comp.	St. Dev.		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized						
SiO ₂	76.10	Na ₂ O	8.2	0.42	4.16	0.26	0.52	0.05
TiO ₂	0.090	Al ₂ O ₃	21.64	0.85	19.06	0.48	12.84	0.55
Al ₂ O ₃	13.34	SiO ₂	62.67	1.81	62.89	1.71	33.06	1.2
FeO*	1.19	K ₂ O	1.19	0.27	9.02	0.59	8.08	0.34
MnO	0.025	CaO	3.31	0.48	0.38	0.49	-	-
MgO	0.06	FeO	0.42	0.33	1.23	0.72	28.67	1.03
CaO	0.72	MgO	-	-	-	-	4.36	0.46
Na ₂ O	3.25	TiO ₂	-	-	-	-	4.43	0.33
K ₂ O	5.22	BaO	0.38	0.07	2.66	0.5	0.91	0.21
P ₂ O ₅	0.011							
Total	100.00							
XRF, ppm		%An	16.96%		1.36%			
Ni	0	%Ab	75.76%		40.97%			
Cr	1	%Or	7.28%		57.68%			
Sc	3							
V	0	Mg #					20.48	
Ba	1102							
Rb	107							
Sr	64							
Zr	125							
Y	27							
Nb	17.2							
Ga	17	Accepted Range for SEM Data						
Cu	1	96 - 100 wt. %						
Zn	51							
Pb	15							
La	31							
Ce	59							
Th	13							

Table 9. Summary table for sample CR-U4B from Unity Rhyolite.

Unity Rhyolite - CR-U4B								
Bulk Composition		Feldspar			Amphibole		Biotite	
Wt %, Normalized		Comp.	St. Dev.		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized						
SiO ₂	72.07	Na ₂ O	7.53	1.22	1.6	0.24	0.61	0.11
TiO ₂	0.270	Al ₂ O ₃	25.28	2.35	8.04	1.22	13.98	1.09
Al ₂ O ₃	15.30	SiO ₂	62.73	5.79	48.06	2.02	37.24	2.15
FeO*	1.68	K ₂ O	0.76	0.36	0.53	0.07	8.42	0.77
MnO	0.053	CaO	6.26	2.02	11.07	0.38	-	-
MgO	0.48	FeO	0.34	0.16	15.82	0.86	17.46	1.58
CaO	2.12	MgO	-	-	13.63	0.89	12.45	1.25
Na ₂ O	4.10	TiO ₂	-	-	1.63	0.36	4.74	0.34
K ₂ O	3.84	BaO	0.38	0.07	-	-	0.69	0.11
P ₂ O ₅	0.080							
Total	100.00							
XRF, ppm		%An	26.19%					
Ni	0	%Ab	68.85%					
Cr	5	%Or	4.96%					
Sc	4							
V	21							
Ba	794	Mg #			60.81		55.75	
Rb	82							
Sr	263							
Zr	118							
Y	16							
Nb	12.3							
Ga	16	Accepted Range for SEM Data						
Cu	1	94 - 105 wt. %						
Zn	39							
Pb	13							
La	25							
Ce	45							
Th	10							

Table 10. Summary table for sample EJ-12-16 from Cottonwood Rhyolite.

Cottonwood Rhyolite - EJ-12-16								
Bulk Composition		Feldspar			Pyroxene 1		Pyroxene 2	
Wt %, Normalized		Comp.	St. Dev.		Comp.	St. Dev.	Comp.	St. Dev.
SiO2	73.04	Wt %, Unnormalized						
TiO2	0.717	Na2O	6.01	0.17	-	-	-	-
Al2O3	12.74	Al2O3	25.29	0.42	0.47	0.04	0.84	0.03
FeO*	3.51	SiO2	58.85	0.73	48.55	1.17	52.13	0.52
MnO	0.078	K2O	0.78	0.06	-	-	-	-
MgO	0.34	CaO	7.85	0.38	4.45	0.17	20.6	0.33
CaO	1.64	FeO	0.56	0.06	30.49	0.65	12.63	0.5
Na2O	2.81	MgO	-	-	11.84	0.4	12.49	0.22
K2O	4.99	TiO2	-	-	0.34	0.03	0.64	0.05
P2O5	0.145							
Total	100.00							
XRF, ppm		%An	39.98%					
Ni	4	%Ab	55.30%					
Cr	3	%Or	4.73%					
Sc	12							
V	12	%Wo			9.94%		43.07%	
Ba	1369	%En			36.86%		36.31%	
Rb	147	%Fs			53.20%		20.62%	
Sr	179							
Zr	295							
Y	42							
Nb	19.2							
Ga	18							
Cu	3	Accepted Range for SEM Data						
Zn	91	98 - 102 wt. %						
Pb	24							
La	48							
Ce	89							
Th	17							

Table 11. Summary table for sample EJ-12-17 (Bully Creek) from Cottonwood Rhyolite.

Bully Creek Rhyolite - EJ-12-17 (Cottonwood)					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized			
SiO ₂	72.4	Na ₂ O	5.94	0.29	-
TiO ₂	0.704	Al ₂ O ₃	24.85	0.94	0.48
Al ₂ O ₃	12.65	SiO ₂	57.77	1.95	46.58
FeO*	3.92	K ₂ O	0.75	0.09	-
MnO	0.089	CaO	7.72	0.43	4.18
MgO	0.4	FeO	0.53	0.04	29.54
CaO	1.74	MgO	-	-	11.27
Na ₂ O	2.59	TiO ₂	-	-	0.34
K ₂ O	5.37				
P ₂ O ₅	0.145				
Total	100.00				
XRF, ppm		%An	39.92%		
Ni	3	%Ab	55.48%		
Cr	1	%Or	4.60%		
Sc	12				
V	14	%Wo		9.74%	
Ba	1287	%En		36.52%	
Rb	151	%Fs		53.73%	
Sr	169				
Zr	293				
Y	41				
Nb	19.9				
Ga	18				
Cu	4	Accepted Range for SEM Data			
Zn	87	96 - 103 wt. %			
Pb	25				
La	46				
Ce	93				
Th	17				

Table 12. Summary table for sample DR2 from Dooley Mountain Rhyolite.

Dooley Mountain Rhyolite - DR2					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized			
SiO ₂	73.91	Na ₂ O	6.18	0.37	-
TiO ₂	0.331	Al ₂ O ₃	24.93	0.88	1.1
Al ₂ O ₃	14.11	SiO ₂	57.65	2.03	47.8
FeO*	2.08	K ₂ O	0.45	0.07	-
MnO	0.037	CaO	7.44	0.59	18.22
MgO	0.03	FeO	0.34	0.04	27.31
CaO	2.08	MgO	-	-	3.06
Na ₂ O	3.78	TiO ₂	-	-	0.59
K ₂ O	3.62				
P ₂ O ₅	0.032				
Total	100.00				
XRF, ppm		%An	38.82%		
Ni	0	%Ab	58.38%		
Cr	2	%Or	2.80%		
Sc	11				
V	6	%Wo		41.68%	
Ba	1480	%En		9.30%	
Rb	77	%Fs		49.02%	
Sr	193				
Zr	363				
Y	46				
Nb	14.1				
Ga	20				
Cu	3				
Zn	84				
Pb	13				
La	36				
Ce	68				
Th	9				

Table 13. Summary table for sample EJ-12-08 from Dinner Creek tuff.

Dinner Creek Tuff - EJ-12-08					
Bulk Composition			Feldspar		
	EJ-12-08	Avg. DIT1		Comp.	St. Dev.
	Wt %, Normalized			Wt %, Unnormalized	
SiO2	77.92	76.01	Na2O	8.59	0.31
TiO2	0.159	0.19	Al2O3	21.09	0.76
Al2O3	11.42	12.70	SiO2	65.84	1.51
FeO*	1.66	2.07	K2O	1.51	0.29
MnO	0.015	0.05	CaO	2.28	0.33
MgO	0.23	0.10	FeO	0.38	0.05
CaO	0.59	0.63			
Na2O	4.39	3.24			
K2O	3.58	4.99	%An	11.79%	
P2O5	0.035	0.02	%Ab	79.39%	
Total	100.00	100.00	%Or	8.68%	
	XRF, ppm				
Ni	1.9	2.1			
Cr	3.2	3.3			
Sc	4.6	3.9			
V	12.4	6.0			
Ba	1327.7	1354.5			
Rb	68.4	75.5			
Sr	39.7	35.2			
Zr	290.6	429.8			
Y	68.6	90.9			
Nb	22.2	24.0			
Ga	19.7	21.5			
Cu	4.7	3.0			
Zn	121.4	148.6			
Pb	10.4	18.0			
La	38.7	44.7			
Ce	85.3	94.0			
Th	7.7	8.2			

Accepted Range for SEM Data

99 - 102 wt. %

Table 14. Summary table for sample EJ-12-10 from Littlefield Rhyolite.

Littlefield Rhyolite - EJ-12-10								
Bulk Composition		Feldspar			Pyroxene		Fayalite	
Wt %, Normalized		Comp.	St. Dev.		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized						
SiO ₂	71.08	Na ₂ O	6.92	0.48	-	-	-	-
TiO ₂	0.434	Al ₂ O ₃	21.57	1.78	0.85	0.35	2.83	0.02
Al ₂ O ₃	12.44	SiO ₂	59.43	3.41	45.43	2.7	40.98	1.85
FeO*	5.79	K ₂ O	1.36	0.31	-	-	-	-
MnO	0.138	CaO	4.44	0.72	17.35	3	1.14	0.01
MgO	0.23	FeO	0.92	0.78	29.35	1.89	32.54	1.46
CaO	1.62	MgO	-	-	1.46	0.31	2.67	1.14
Na ₂ O	4.16	TiO ₂	-	-	0.48	0.06	0.29	0
K ₂ O	4.04							
P ₂ O ₅	0.059							
Total	100.00							
XRF, ppm		%An	23.78%					
Ni	5	%Ab	67.39%					
Cr	3	%Or	8.82%					
Sc	8							
V	3	%Wo			41.85%			
Ba	1654	%En			4.64%			
Rb	111	%Fs			53.50%			
Sr	143							
Zr	534							
Y	87							
Nb	36.3							
Ga	26							
Cu	8	Accepted Range for SEM Data						
Zn	173	92 - 101 wt. %						
Pb	21							
La	64							
Ce	126							
Th	13							

Table 15. Summary table for sample EJ-12-13B from Jump Creek Rhyolite.

Jump Creek Rhyolite - EJ-12-13B				
Bulk Composition Wt %, Normalized		Feldspar		
		Comp.	St. Dev.	
SiO2	73.52	Wt %, Unnormalized		
TiO2	0.511	Na2O	6.86	0.38
Al2O3	13.99	Al2O3	23.56	1.12
FeO*	1.81	SiO2	61.74	2.89
MnO	0.021	K2O	1.52	0.25
MgO	0.03	CaO	5.38	0.57
CaO	1.46	FeO	0.36	0.03
Na2O	4.11	BaO	0.47	0.05
K2O	4.38			
P2O5	0.154			
Total	100.00	%An	27.29%	
		%Ab	63.40%	
		%Or	9.24%	
XRF, ppm				
Ni	4			
Cr	3			
Sc	8			
V	12			
Ba	2000			
Rb	83			
Sr	274			
Zr	575			
Y	52			
Nb	44.1	Accepted Range for SEM Data		
Ga	22	94 - 103 wt. %		
Cu	1			
Zn	103			
Pb	25			
La	83			
Ce	165			
Th	9			

Table 16. Summary table for sample EJ-12-12 (Old McIntyre Ridge) from Mahogany Mountain Rhyolite.

Old McIntyre Ridge Rhyolite - EJ-12-12 (Mahogany Mountain)					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized			
SiO ₂	74.19	Na ₂ O	6.63	0.35	-
TiO ₂	0.31	Al ₂ O ₃	19.82	0.72	0.45
Al ₂ O ₃	12.92	SiO ₂	66.79	0.91	47.37
FeO*	3.15	K ₂ O	5.35	0.34	-
MnO	0.07	CaO	0.81	0.14	18.84
MgO	0.51	FeO	0.52	0.4	31.56
CaO	1.05	MgO	-	-	1.02
Na ₂ O	4.41	TiO ₂	-	-	0.51
K ₂ O	3.38	BaO	1.47	0.39	-
P ₂ O ₅	0.02				
Total	100.00				
XRF, ppm		%An	4.24%		
Ni	2.5	%Ab	62.53%		
Cr	2	%Or	33.23%		
Sc	0.6				
V	1				
Ba	1438.5	%Wo		43.34%	
Rb	160.7	%En		0.02%	
Sr	33.9	%Fs		56.04%	
Zr	726.7				
Y	100				
Nb	44.9				
Ga	25.9				
Cu	2.6	Accepted Range for SEM Data			
Zn	180.9	97 - 102 wt. %			
Pb	24.8				
La	66.1				
Ce	147				
Th	15.4				

Table 17. Summary table for sample EJ-12-14 (Young McIntyre Ridge) from Mahogany Mountain Rhyolite.

Young McIntyre Ridge Rhyolite - EJ-12-14 (Mahogany Mountain)					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized			
SiO ₂	77.14				
TiO ₂	0.15	Na ₂ O	5.5	0.76	-
Al ₂ O ₃	12.17	Al ₂ O ₃	17.72	2.07	0.4
FeO*	1.40	SiO ₂	61.87	7.09	48.49
MnO	0.04	K ₂ O	6.72	0.76	-
MgO	0.14	CaO	-	-	18.33
CaO	0.49	FeO	-	-	23.98
Na ₂ O	3.70	MgO	-	-	4.6
K ₂ O	4.74	TiO ₂	-	-	0.35
P ₂ O ₅	0.02				0.06
Total	100.00				
XRF, ppm		%An	0.00%		
Ni	2.6	%Ab	54.76%		
Cr	1.7	%Or	45.24%		
Sc	1.3				
V	4				
Ba	247.1	%Wo		42.19%	
Rb	140.4	%En		14.73%	
Sr	20.4	%Fs		43.07%	
Zr	296.8				
Y	88				
Nb	36.8				
Ga	23.3				
Cu	4.5	Accepted Range for SEM Data			
Zn	105.3	90 - 100 wt. %			
Pb	20.8				
La	65.3				
Ce	125.5				
Th	13.5				

Table 18. Summary table for sample MS-13-24b (Young McIntyre Ridge) from Mahogany Mountain Rhyolite.

Young McIntyre Ridge Rhyolite - MS-13-24b (Mahogany Mountain)					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized			
SiO ₂	76.35	Na ₂ O	5.52	0.65	-
TiO ₂	0.16	Al ₂ O ₃	18.51	1.51	0.41
Al ₂ O ₃	12.16	SiO ₂	66.21	1.70	48.75
FeO*	1.59	K ₂ O	7.32	0.5	-
MnO	0.03	CaO	0.52	0.07	18.63
MgO	0.11	FeO	0.7	0.45	24.68
CaO	0.53	MgO	-	-	4.78
Na ₂ O	3.26				
K ₂ O	5.80				
P ₂ O ₅	0.02				
Total	100.00				
XRF, ppm		%An	2.20%		
Ni	3.57	%Ab	52.13%		
Cr	2.18	%Or	45.67%		
Sc	1.88				
V	6.05	%Wo		41.77%	
Ba	261.59	%En		15.15%	
Rb	126.38	%Fs		43.08%	
Sr	22.72				
Zr	311.19				
Y	86.90				
Nb	36.31				
Ga	22.12				
Cu	5.46	Accepted Range for SEM Data			
Zn	103.66	96 - 101 wt. %			
Pb	20.44				
La	62.60				
Ce	127.97				
Th	13.69				

Table 19. Summary table for sample MS-13-29 (Spring Creek tuff) from Mahogany Mountain Rhyolite.

Spring Creek Tuff - MS-13-29 (Mahogany Mountain)					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized			
SiO ₂	72.97	Na ₂ O	7.08	0.86	-
TiO ₂	0.38	Al ₂ O ₃	20.78	1.97	0.68
Al ₂ O ₃	12.42	SiO ₂	63.19	1.69	46.68
FeO*	4.72	K ₂ O	2.43	0.65	-
MnO	0.12	CaO	3.03	0.61	18.31
MgO	0.08	FeO	0.51	0.57	30.73
CaO	1.49	MgO	-	-	0.73
Na ₂ O	3.57	TiO ₂	-	-	0.6
K ₂ O	4.21				0.04
P ₂ O ₅	0.03				
Total	100.00				
XRF, ppm		%An	16.36%		
Ni	1.59	%Ab	69.09%		
Cr	1.88	%Or	14.54%		
Sc	3.17				
V	3.67	%Wo		43.06%	
Ba	1709.32	%En		0.53%	
Rb	184.02	%Fs		56.41%	
Sr	108.92				
Zr	582.01				
Y	94.14				
Nb	37.70				
Ga	24.30				
Cu	2.98	Accepted Range for SEM Data			
Zn	164.28	96 - 99 wt. %			
Pb	20.63				
La	63.88				
Ce	134.71				
Th	15.28				

Table 20. Summary table for sample TF-153H from Three Fingers Rhyolite.

Three Fingers Rhyolite - TF-153H					
Bulk Composition		Feldspar		Pyroxene	
Wt %, Normalized		Comp.	St. Dev.	Comp.	St. Dev.
		Wt %, Unnormalized			
SiO ₂	77.20	Na ₂ O	5.8	0.14	0.54
TiO ₂	0.17	Al ₂ O ₃	18.45	0.31	0.29
Al ₂ O ₃	11.71	SiO ₂	65.86	0.98	46.52
FeO*	1.95	K ₂ O	7.33	0.14	-
MnO	0.03	CaO	0.15	0.03	18.42
MgO	0.06	FeO	0.33	0.03	30.31
CaO	0.51	TiO ₂	-	-	0.33
Na ₂ O	2.88				
K ₂ O	5.48				
P ₂ O ₅	0.01				
Total	100.00	%An	0.81%		
		%Ab	54.09%		
		%Or	45.11%		
XRF, ppm					
Ni	2.8				
Cr	3.5				
Sc	0.2	%Wo		43.76%	
V	5.0	%En		0.00%	
Ba	165.4	%Fs		56.24%	
Rb	142.5				
Sr	11.4				
Zr	672.3				
Y	113.2				
Nb	47.2				
Ga	26.2				
Cu	6.7	Accepted Range for SEM Data			
Zn	191.5	95 - 100 wt. %			
Pb	26.3				
La	69.4				
Ce	143.8				
Th	16.5				

Appendix D: Additional Feldspar Plots

Figure 66. Feldspar ternary diagram for Buchanan sample EJ-12-03. Average feldspar composition is given by black plus symbol.

Figure 67. Feldspar ternary diagram for Buchanan sample B010. Average feldspar composition is given by black plus symbol.

Figure 68. Feldspar ternary diagram for Buchanan sample B114. Average feldspar composition is given by black plus symbol.

Figure 69. Feldspar ternary diagram for Circle Bar (Malheur) sample EJ-12-05b. Sample contains two types of feldspar: labradorite and sanidine. Average feldspar composition is given by black plus symbol.

Figure 70. Feldspar ternary diagram for Dam rhyolite sample EJ-12-15. Average feldspar composition is given by black plus symbol.

Figure 71. Feldspar ternary diagram for Unity sample U4b. Average feldspar composition is given by black plus symbol.

Figure 72. Feldspar ternary diagram for Cottonwood sample EJ-12-16. Average feldspar composition is given by black plus symbol.

Figure 73. Feldspar ternary diagram for Bully Creek sample EJ-12-17. Average feldspar composition is given by black plus symbol.

Figure 74. Feldspar ternary diagram for Dooley Mountain sample DR2. Average feldspar composition is given by black plus symbol.

Figure 75. Feldspar ternary diagram for Dinner Creek Tuff sample EJ-12-08. Average feldspar composition is given by black plus symbol.

Figure 76. Feldspar ternary diagram for Littlefield sample EJ-12-10. Average feldspar composition is given by black plus symbol.

Figure 77. Feldspar ternary diagram for Jump Creek sample EJ-12-13b. Average feldspar composition is given by black plus symbol.

Figure 78. Feldspar ternary diagram for Old McIntyre sample EJ-12-12. Average feldspar composition is given by black plus symbol.

Figure 79. Feldspar ternary diagram for Young McIntyre sample EJ-12-14. Average feldspar composition is given by black plus symbol.

Figure 80. Feldspar ternary diagram for Young McIntyre sample MS-13-24b. Average feldspar composition is given by black plus symbol.

Figure 81. Feldspar ternary diagram for Three Fingers sample TF-153H. Average feldspar composition is given by black plus symbol.

Appendix E: Additional Pyroxene Plots

Figure 82. Pyroxene ternary diagram for Dam sample EJ-12-15. Average pyroxene composition is given by black plus symbol.

Figure 83. Pyroxene ternary diagram for Cottonwood sample EJ-12-16. Average pyroxene composition is given by black plus symbol.

Figure 84. Pyroxene ternary diagram for Bully Creek sample EJ-12-17. Average pyroxene composition is given by black plus symbol.

Figure 85. Pyroxene ternary diagram for Littlefield rhyolite sample EJ-12-10. Average pyroxene composition is given by black plus symbol.

Figure 86. Pyroxene ternary diagram for Old McIntyre sample EJ-12-12. Average pyroxene composition is given by black plus symbol.

Figure 87. Pyroxene ternary diagram for Young McIntyre sample EJ-12-14. Average pyroxene composition is given by black plus symbol.

Figure 88. Pyroxene ternary diagram for Young McIntyre sample MS-13-24b. Average pyroxene composition is given by black plus symbol.

Figure 89. Pyroxene ternary diagram for Spring Creek sample MS-13-29. Average pyroxene composition is given by black plus symbol.

Figure 90. Pyroxene ternary diagram for Three Fingers sample TF-153H. Average pyroxene composition is given by black plus symbol.

Appendix F: Tests for Equilibrium (K_d)

Table 21. Putrika et al. (2008) provides tests for phase equilibrium for multiple geothermometers.

			Plagioclase-Liquid	Clinopyroxene	Orthopyroxene	Olivine-Liquid
I-Type	BDC	B010	0.03			
		B114	0.11	0.25	0.25	
		EJ-12-03	-			
	MAL	EJ-12-05b	0.07	0.17		
	DAM	EJ-12-15	0.07	0.24		
Borderline	UNI	CR-U3a	0.12			
		CR-U4b	0.17			
	CMR	EJ-12-16	0.09	0.24		
		EJ-12-17	0.11	0.24		
	DMR	DR2	0.10	0.16		
A-Type	DIT	EJ-12-08	0.09			
	LIT	EJ-12-10	0.13	0.21		0.49
	JCR	EJ-12-13b	0.10			
	MAH/TFI	EJ-12-12	-	0.24		
		EJ-12-14	-	0.23		
		MS-13-24b	-	0.21		
		MS-13-29	-	0.17		
		TF-153H	-	0.18		

The Plagioclase-liquid geothermometer compares An-Ab exchange as the equilibrium test. For samples with $T < 1050^\circ\text{C}$, the value should be 0.1 ± 0.05 . Every temperature estimated using this geothermometer is less than 1050°C . B010 of the Buchanan rhyolites and CR-U4b of the Unity rhyolites are the only two samples that do not fall within this range. This test is not applicable in samples that solely contain alkali feldspar. For the clinopyroxene geothermometer, equilibrium between the phase and liquid is tested by comparing the observed and predicted values for Fe-Mg exchange. This value should be 0.27 ± 0.03 . There are multiple samples that fall outside of this range including: Circle Bar of Malheur (EJ-12-05b), Dooley Mountain rhyolite (DR2), Littlefield rhyolite (EJ-12-10), Young McIntyre (EJ-12-14 and MS-13-24b) and Spring Creek (MS-13-29)

of the Mahogany Mountain rhyolite and the Three Fingers rhyolite (TF-153H). This test is T-sensitive. The orthopyroxene geothermometer utilizes a similar test to the clinopyroxene geothermometer in that the exchange of Fe-Mg is used to estimate equilibrium. For this test, the constant value to compare to is 0.29 ± 0.06 . Only one sample, B114 of the Buchanan rhyolites, contains orthopyroxene and the K_d value for this falls within the accepted range. Lastly, the olivine-liquid geothermometer uses Fe-Mg exchange as a means of estimating equilibrium. For this test, a constant value of 0.30 ± 0.3 compared to the estimated K_d for the sample. In this study, only one sample contained fayalite, the Littlefield rhyolite, and the K_d value is much higher than the constant value. This may be a result of using FeOt instead of FeO, which appears to nominally impact the resulting equilibrium value.