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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,
Oregon

by

Adam M. Large

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

Master of Science
in
Geology

Thesis Committee:
Martin J. Streck, Chair
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Portland State University
2016

Abstract

Two mid-Miocene (16.5-15 Ma) rhyolite volcanic centers in eastern Oregon, the Buchanan rhyolite complex and Dooley Mountain rhyolite complex, were investigated to characterize eruptive units through field and laboratory analysis. Results of petrographic and geochemical analysis add to field observations to differentiate and discriminate the eruptive units. Additionally, new geochemical data are used to correlate stratigraphically younger and older basalt and ash-flow tuff units with regional eruptive units to constrain the eruptive periods with modern Ar-Ar age dates.

Previous work at the Buchanan rhyolite complex was limited to regional mapping (Piper et al., 1939; Greene et al., 1972) and brief mention of the possibility of multiple eruptive units (Walker, 1979). Observed stratigraphic relationships and geochemical analysis were used to identify eight distinct eruptive units and create a geologic map of their distribution. Slight differences in trace element enrichment are seen in mantle normalized values of Ba, Sr, P, Ti and Nd-Zr-Hf and are used to differentiate eruptive units. New geochemical analyses are used to correlate the overlying Buchanan ash-flow tuff (Brown and McLean, 1980) and two underlying mafic units to the Wildcat Creek ash-flow tuff (~15.9 Ma, Hooper et al., 2002) and flows of the Upper Steens Basalt (~16.57 Ma, Brueseke et al., 2007), respectively, bracketing the eruptive age of the Buchanan rhyolite complex to between ~16.5 and ~15.9 Ma (Brueseke et al., 2007; Hooper et al., 2002).

The Dooley Mountain rhyolite complex was thoroughly mapped by the U.S. Geological Survey (Evans, 1992) and geochemically differentiated in a previous Portland State University M.S. thesis (Whitson, 1988); however, discrepancies between published interpretations and field observations necessitated modern geochemical data and revisions to geologic interpretations. Field and laboratory studies indicate that the Dooley Mountain rhyolite complex consists of multiple eruptive units that were effusive domes and flows with associated explosive eruptions subordinate in volume. At least four geochemically distinct eruptive units are described with variations in Ba, Sr, Zr and Nb. Picture Gorge Basalt flows and Dinner Creek Tuff units found within the study area both overly and underlie the Dooley Mountain rhyolite complex. These stratigraphic relationships are consistent with the one existing Ar-Ar age date 15.59 ± 0.04 Ma (Hess, 2014) for the Dooley rhyolite complex, bracketing the eruptive period between ~ 16.0 and ~ 15.2 Ma (Streck et al., 2015; Barry et al., 2013).

The findings of this study indicate that the Buchanan rhyolite complex and the Dooley Mountain rhyolite complex are the westernmost and northernmost rhyolite complexes among the earliest (16-16.5 Ma) mid-Miocene rhyolites associated with initiation of Yellowstone hot spot related volcanism.

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Introduction

During the mid-Miocene, initiation of volcanism likely related to the Yellowstone hotpot resulted in the eruption of the Columbia River Basalt Group (CRBG) flood basalts, and widespread eruptions of rhyolite ash flows and lava flows in eastern Oregon, southwest Idaho and northwest Nevada (Cummings et al., 2000; Hooper et al., 2002; Brueseke et al., 2008; Shervais and Hanan, 2008; Coble and Mahood, 2012). Coble and Mahood (2012) estimate that between 16.7 and 15.0 Ma, $\sim 234,000 \text{ km}^3$ of flood basalts (Steens and Columbia River basalt) and at least $\sim 3900 \text{ km}^3$ of silicic magma were emplaced across the region (Fig. 1).

It is generally accepted that some of the earliest (16.7-16.5 Ma) rhyolite volcanism occurred near the Oregon-Idaho-Nevada border and continued in a northeast-younging trend along the Snake River Plain-Yellowstone trend (Brueseke et al., 2008; Pierce and Morgan, 2009; Coble and Mahood, 2012). However, it is not clear if there was a northward progression of rhyolite volcanism in eastern Oregon originating at these early volcanic centers or rather there was widespread coeval rhyolite volcanism across the region. Coble and Mahood (2012) describe a “rapid northward shift of the locus of mafic intrusion” that “resulted in more dispersed silicic volcanism.” However, Streck et al. (2015) present age data that propose that the initiation of silicic volcanism was more widespread without a north-south trend.

Figure 1: Location of mid-Miocene rhyolite centers in relationship to Columbia River Basalt, Steens Basalt and Strawberry volcanics. DMRC-Dooley Mountain rhyolite complex; BRC-Buchanan rhyolite complex; LF-Littlefield Rhyolite; M/TF-Mahogany Mountain/Three Fingers caldera; MVF-McDermitt volcanic field. GIS data from Oregon Geospatial Enterprise Office: <http://www.oregon.gov/GEO/Pages/index.aspx>

This study intends to provide additional data regarding the timing, duration and characteristics of silicic volcanism at more distal locations in the region by focusing on two rhyolite volcanic complexes, one located at the western periphery and the other at the northern, and their stratigraphic relationships with surrounding volcanic units. To accomplish these ends we undertook field and laboratory studies.

The field component included identifying the volcanic stratigraphy within the study area, determining the extent of rhyolite eruptive units and collecting samples for laboratory analysis. In the laboratory, 48 thin sections were analyzed with petrographic microscope, whole-rock X-ray fluorescence (XRF) and inductively coupled plasma-mass spectrometry (ISP-MS) geochemical data were acquired for 71 samples (including four analyses from Hess (2014) and four unpublished analyses from Dr. Martin Streck), and phenocrysts in seven samples were analyzed with scanning electron microscope. These data allowed me to identify the characteristics of the Buchanan and Dooley Mountain volcanic complexes and put them into temporal context of rhyolite volcanism associated with the impingement of the Yellowstone hotspot.

Location Descriptions

This study focuses on two mid-Miocene rhyolite eruptive complexes. One is located in northeast Oregon and referred to by Gilluly (1937) as the “Dooley Rhyolite Breccia”, Evans (1992) as the “Dooley Volcanics” and Hess (2014) as the “Dooley Mountain rhyolite”. The other is located in central eastern Oregon and referred to by Piper, Robinson and Park (1939) as “older siliceous extrusive rocks”, Walker (1979) as “intrusive and extrusive silicic rocks”, Fiebelkorn et al. (1982) as “Buchanan dome” and

Hess (2014) as the “Buchanan dome complex”. In this study they will be referred to as the Dooley Mountain rhyolite complex and the Buchanan rhyolite complex, respectively.

Buchanan rhyolite complex is located in Harney County, Oregon, approximately 38 km east of Burns, Oregon (Fig. 1) along U.S. Route 20 (US 20) and Crane-Buchanan road south of Buchanan for approximately 13 km. Exposures studied here are located predominantly in the Mahon Creek and Stinkingwater Pass quadrangle and to a lesser extent the Buchanan and Carson Point quadrangle. Access to the exposures from Crane-Buchanan road is restricted, but possible with permission, due to private property. The Stinkingwater access road and tertiary jeep trails provide greater access across public lands to the interior of the study area.

Dooley Mountain rhyolite complex is located in Baker County, Oregon, approximately 18 km south of Baker City, Oregon (Fig. 1) along Oregon Route 245 (OR 245). Exposures studied here are located predominantly in the Dooley Mountain quadrangle and to a lesser extent the Brannan Gulch quadrangle. Highway 245 provides excellent access to exposures and has many road cuts along this steep and winding highway. USFS roads provide access to public lands throughout the quadrangle.

Background

Buchanan rhyolite complex

Previous work at the Buchanan rhyolite complex has been limited in scope. Regional mapping without differentiation of eruptive units was done by the U.S. Geological Survey during water resource investigations at 1:125,000 (Piper et al., 1939),

regional geologic mapping at 1:500,000 (Greene et al., 1972), and adapted by the State of Oregon Department of Geology and Mineral Industries from the previous two (Piper et al., 1939; Greene et al., 1972) at 1:62,500 by Brown and McLean (1980) to examine the geothermal resource potential of the Harney Basin.

Piper et al. (1939) described the units as “older siliceous extrusive rocks” to differentiate them from the younger Danforth formation and indicate that they are the only identified unit older than the Steens Basalt within the area. Walker (1979) revised the previous interpretation to include intrusive rocks and, with the aid of a K-Ar age date (14.74 ± 0.50 Ma) from McKee et al. (1976), determined they were “considerable younger than the Steens Basalt.” Fiebelkorn et al. (1982) recalculated the previous age to 15.1 ± 0.50 Ma. As part of a study by Hess (2014) an Ar-Ar age date was determined on a sample collected near the location given by McKee et al. (1976) and was determined to be 16.13 ± 0.11 Ma.

Geologic descriptions by Piper et al. (1939) and Walker (1979) are generalized and inclusive of many unrelated silicic units in the vicinity of Harney Basin. Whole rock geochemical data of the silicic units prior to this study are limited to two samples from Hess (2014).

This study focuses on identifying and differentiating eruptive units based on petrography and geochemical signatures, refine mapping of the Buchanan rhyolite complex and determining relative age dates by correlating stratigraphically younger and

older volcanic units (e.g. local basalt and ash-flow tuff units) to better understand the timing and duration of eruptive activity.

Dooley Mountain rhyolite complex

Previous work at the Dooley Mountain rhyolite complex has included numerous mapping projects and a master's thesis focused on the geochemical stratigraphy. The area that encompasses the Dooley Mountain 7 ½-minute quadrangle has been mapped 1:125,000 by Gilluly (1937), 1:250,000 by Brooks et al. (1976), 1:500,000 by Walker (1977) and 1:24,000 by Evans (1992). The mapping by Gilluly and Evans were products of mineral resource evaluation in the region, but do provide details about the units that provide questions that form the basis of this study.

Gilluly (1937) named the complex the Dooley rhyolite breccia and described it as “[consisting] of rhyolitic and subordinate andesitic breccias and flows.” The mapping of the quadrangle put the Dooley rhyolite breccia overlying Columbia River basalts and fluvial deposits; however, a disclaimer was made that two possibilities exist to explain this:

First, that the Dooley rhyolite breccia is in part contemporaneous with the Columbia River lava of this quadrangle; second, that rhyolitic rocks of two ages, one earlier than the Columbia River lava, the other younger than the lava or contemporaneous with it, have been erroneously mapped as a single formation. The second of these possibilities seems much more likely, but the problem must be solved in the field.

Additionally, Gilluly acknowledges that “[t]he stratigraphy of the formation is obscure, owing both to original complexities and to poor exposures brought about by the ready disintegration of the rocks composing it.”

Evans (1992) renamed the complex the Dooley Volcanics to encompass the “wide range of lithology present in the unit.” Evans determined there are 13 units and 16 sub-units principally described as tuff (only two units and 3 sub units are described as rhyolite flows and domes) differentiated by degree of welding “and, thus, resistant to weathering.” Stratigraphy was determined on a ridge-by-ridge basis matching the lithology, rock type and thickness of units.

Master’s thesis research by Whitson (1988) focused on determining geochemically based stratigraphic relationships principally with neutron activation analysis (NAA) and select XRF data. He concluded, through the use of a cluster analysis scheme, that there are nine subgroups within four main groups of rhyolitic samples. The interpretive geologic map accompanying the thesis does not differentiate these groups except in cross section.

This study addresses issues brought up by the previously mentioned authors by differentiating eruptive units based on petrography and geochemical signatures, use the data to propose a revision to the mapping of the Dooley mountain quadrangle and correlate stratigraphically younger and older volcanic units (e.g. local basalt and ash-flow tuff units) to better understand the timing and duration of eruptive activity.

Methods

Field Methods

Field mapping was conducted to identify distinct rhyolite units through stratigraphic relationships and lithologic differences. Particular attention was made to define the areal extent of exposed flows, domes, local pyroclastic units and underlying basalt flows.

Access to exposures at Buchanan rhyolite complex required private landowner permission, particularly along Crane-Buchanan road. Exposures located on public land often required crossing private land holdings, but can be hiked to from the Stinkingwater access road and several jeep trails.

Exposures at Dooley Mountain rhyolite complex are easily accessed along OR 245 and the extensive network of U.S. Forest service access roads.

Samples of rock with minimal weathering or alteration characteristics were collected for further petrographic and geochemical analysis in the laboratory. Sample coordinates were recorded with GPS. Dooley Mountain rhyolite complex hand sample descriptions and locations can be found in Appendix B-2.

Analytical Methods

Thin section and petrographic analysis

Forty eight hand samples total from both locations were selected for thin section preparation and analysis. Petrographic characteristics of samples were determined using

plane- and cross-polarized transmitted light. Phenocryst phase, size and abundance were used to differentiate samples. Descriptions of thin sections can be found in Appendix A-1 for samples from Buchanan rhyolite complex and Appendix B-2 for Dooley Mountain rhyolite complex.

Scanning Electron Microscopy

Qualitative and quantitative data were obtained with a Zeiss Sigma VP scanning electron microscope at Portland State University through high-resolution backscatter images and spot analysis using Energy-dispersive x-ray spectroscopy (EDS). The following SEM parameters were used during analysis:

- Backscatter detector (BSD) in compositional mode
- High accelerating voltage: 15-20 kV
- Large aperture: 60 μm (high current mode)
- Analytical working distance: 8.5 mm

Spectra were obtained from the selected phenocrysts via the EDS using the same settings. Spectrums were measured at multiple points within single phenocrysts and averaged to determine the average phenocrysts composition.

Geochemical analysis

Major and trace element analysis was performed at GeoAnalytical Lab at Washington State University using XRF and ICP-MS according to the methods of Johnson et al. (1999). Analytical uncertainties were estimated using select repeat analysis of samples of this study (Appendix A-2c) and compare well with uncertainties as given in

Johnson et al., (1999) and on the website of the Geoanalytical Lab (<http://cahnrs.wsu.edu/soe/facilities/geolab/technotes/>) that states for ICP-MS analysis an analytical precision at 5% (RSD) for Rare Earth Elements and 10% for the remaining trace.

XRF and ICP-MS analysis results for Buchanan rhyolite complex and Dooley Mountain rhyolite complex can be found in Appendix A-2 and B-3, respectively.

Data analysis

Effects of devitrification and silicification on geochemistry

High SiO₂ values (75 to 77.4 wt% are considered “high-silica rhyolite” (Hildreth, 1981), 12 samples from Buchanan rhyolite complex and 5 samples from Dooley Mountain rhyolite complex have SiO₂ values above the upper threshold of 77.4 wt%) in XRF analysis results indicate alteration from the original geochemical make-up. The effects of two post-emplacement processes, devitrification during cooling and silicification from external sources (e.g. hydrothermal alteration), were examined to determine which element abundances have been altered the most and which elements are useful for discriminating eruptive units.

Devitrified and vitric sample pairs collected in close proximity, from the same eruptive units, are compared to determine the effects of devitrification on the geochemical makeup of the rocks. Two pairs of samples are used to compare geochemical trends in the effect of devitrification (Table 1). The sample pair B121B/B121A (vitric/devitrified) has SiO₂ values that indicate that the differences are

likely only from devitrification. Sample pair B147/B148 (vitric/devitrified) has SiO_2 values that indicate secondary silicification also altered the geochemistry, in addition to devitrification.

Noticeable variations in major elements as a result of devitrification are seen in Table 1. Similar trends between the two sample pairs include an increase in SiO_2 , and P_2O_5 , and decreased values of FeO^* , MnO and MgO . The sample pair B147/B148 shows greater effects of alteration than sample pair B121B/121A due to secondary silicification which is further examined in Table 2, below.

Table 1: Comparison of major elements for vitric and devitrified samples. Positive values for % difference indicate an increase in major element oxide abundance from vitric to devitrified samples, negative values indicate a decrease.

	Vitric	Devitrified	% Difference	Vitric	Devitrified	% Difference
Sample	B121B	B121A		B147	B148	
SiO ₂	75.71	76.16	1	77.04	82.03	6
TiO ₂	0.19	0.20	4	0.12	0.15	23
Al ₂ O ₃	13.17	13.18	0	12.57	9.71	-23
FeO*	1.33	1.00	-25	1.01	0.91	-11
MnO	0.04	0.01	-70	0.03	0.01	-82
MgO	0.20	0.10	-51	0.11	0.05	-56
CaO	1.06	1.07	1	0.74	1.01	37
Na ₂ O	3.78	3.65	-4	3.53	2.58	-27
K ₂ O	4.49	4.60	2	4.82	3.53	-27
P ₂ O ₅	0.02	0.03	37	0.01	0.03	132

Table 2: Comparison of major elements for devitrified, lower and higher SiO₂ samples. Positive values for % difference indicate an increase in major element oxide abundance from vitric to devitrified samples, negative values indicate a decrease .

	Lower SiO ₂	Higher SiO ₂	% Difference	Lower SiO ₂	Higher SiO ₂	% Difference
Sample	B026	B025B		B156	B155	
SiO ₂	72.31	77.56	7	73.19	78.22	7
TiO ₂	0.38	0.19	-50	0.30	0.23	-24
Al ₂ O ₃	14.44	12.37	-14	13.63	11.76	-14
FeO*	2.29	0.82	-64	2.57	1.17	-55
MnO	0.05	0.01	-75	0.03	0.01	-61
MgO	0.38	0.06	-83	0.18	0.02	-91
CaO	1.75	1.02	-41	0.94	0.78	-17
Na ₂ O	3.63	3.83	5	3.90	3.30	-15
K ₂ O	4.71	4.10	-13	5.22	4.48	-14
P ₂ O ₅	0.08	0.03	-56	0.05	0.03	-46

The effects of secondary silicification on major element oxides are much more evident than the effects of devitrification alone. SiO₂ is the only oxide that is considerably increased. FeO*, MnO, MgO and P₂O₅ values decrease by more than 50% and Al₂O₃ decreases ~2-3 wt%. All other major oxides have variable decreases or

increases. The variability of major oxide wt% make their usefulness in differentiating eruptive units questionable, however, multi-element diagrams of mantle normalized trace element abundances preserve the geochemical signature of these eruptive units.

Figure 2: Multi-element diagrams comparing vitric (black) and devitrified (red) samples. Sample pairs are those found in Table 1, above. Concentrations normalized to mantle values of Sun and McDonough (1989)

Figure 2 shows that the trace element trends of eruptive units are well preserved when comparing vitric and devitrified samples. Comparison of B121B and B121A

(Figure 2, top) shows little alteration of trace element abundances from devitrification processes alone. Comparison of B147 and B148 (Figure 2, bottom) show that the trends are similar, however the effects of secondary silicification have depleted the majority of trace element abundances.

Figure 3: Multi-element diagrams of ratio values for (ppm devitrified sample) / (ppm vitric sample) for devitrified-vitric pairs. Sample pairs are those found in Table 1, above.

Figure 3 shows the change in trace element abundances due to devitrification. Devitrification alone (Figure 3, top) shows that there are slight changes (<10%) in abundances of all elements other than P, which is enriched in the devitrified sample. The same enrichment in P is seen in the sample pair B148/B147 (Figure 3, bottom), however the effects of secondary silicification are also seen in the depletion of the majority of trace elements. Similarities between the two include relatively unchanged Ba, Zr and Eu and slight increases in Sr and Ti.

Trace element trends of eruptive units are also well preserved when samples have undergone secondary silicification as seen in Figure 4, below. Similar to the trace element plot of B147 and B148 (Figure 2, bottom), there is a slight depletion of many trace elements due to secondary silicification.

Figure 4: Multi-element diagrams comparing lower SiO₂ (dark gray) and higher SiO₂ (orange) samples. Sample pairs are those found in Table 2 above. Concentrations normalized to mantle values of Sun and McDonough (1989)

When comparing the change in trace element abundances due to secondary silicification (Figure 5) similarities are difficult to identify. The predominant similarity is the slight depletion of the majority of trace elements in both multi-element diagrams. Similarities in depletion of individual elements are only seen in P and Ti, both being relatively more depleted than neighboring elements.

Figure 5: Multi-element diagrams of ratio values for (Higher SiO₂) / (Lower SiO₂) for secondary silicification pairs. Sample pairs are those found in Table 2, above.

Although there are not many similarities in the depletion trends due to secondary silicification between eruptive units, crude trends can be identified within samples from the same eruptive unit as in Figure 6 and are unique for each eruptive unit.

Figure 6: Multi-element diagram of ratio values for (Higher SiO₂) / (Lower SiO₂) for secondary silicification within one eruptive unit.

The effects of devitrification and secondary silicification can be seen in both major and trace element abundances. Alteration of major element abundances make using them unreliable for differentiating eruptive units; however, because alteration trends in trace element abundances can be identified within each eruptive unit, trace elements are predominantly used to differentiate the geochemical signatures of eruptive units.

In order to account for the likelihood that chemical alteration had either enriched or depleted element abundances in the analytical results data were initially grouped and compared based on stratigraphic and petrographic correlations. Bivariate plots of select oxide weight percent (wt%), trace element concentration and element ratios, as well as multi-element diagrams are used to differentiate and identify geochemical trends of eruptive units. Samples that were known to be stratigraphically correlative with a group of samples but had drastically different analytic results are omitted from the presented

data. Three samples (B153, B165 and B168) were omitted but the geochemical analysis result can be found in Appendix A-2.

Buchanan Rhyolite Complex

Results

Geography and stratigraphy of units

Over 175 hand samples from the Buchanan rhyolite complex were collected in the field. Approximate locations of all hand samples shown in Figure 7.

Figure 7: Location map for hand samples collected at Buchanan rhyolite complex. Map modified from Greene et al. (1972). Units identified by Green et al. (1972) that were sampled: Tba – basalt and andesite; Ttb – Ash-flow tuff near Buchanan; Trd – Rhyodacite.

Correlating stratigraphic relationships in the field is obscured by younger basalt flows and lack of full access to units due to private property; therefore, the stratigraphy of five geographically separated areas are described initially. Latitude and longitude are given for locations where stratigraphic relationships were best observed.

Figure 8: Overview map of geographically separated rhyolite exposures. Areas outlined with thick black border. Area 5 consists of two independent dome structures. Hashed area north of Area 4 represents private property that was not accessible. Map modified from Green et al (1972)

Area 1

Two distinct stratigraphic units are exposed in area 1. Unit 1A is exposed along US 20 (Figure 9) in road cut (latitude 43.645°, longitude -118.626), forms approximately 0.75 km of cliffs to the east of Crane-Buchanan road south of US 20 and is inferred to be covered with colluvium from Unit 1B for approximately 2 additional km along Crane-Buchanan road. Unit 1B basal breccia (Figure 13) overlies Unit 1A at latitude 43.638, longitude -118.619, and is exposed as rim rock east of Crane-Buchanan road for approximately 2 km.

Area 2

Two distinct stratigraphic units are exposed in area 2. Unit 2A is exposed along Crane-Buchanan road as cliff (latitude 43.602, longitude -118.626) and outcrops from approximately 3 km south of US 20 to the southern end of Laton Point. Unit 2B overlies 2A, exposed in outcrop (latitude 43.606, longitude -118.622) from approximately 3 km south of US 20 along Crane-Buchanan road and in a pit dug on the top of Laton point (Figure 16).

Area 3

Five stratigraphically distinct rhyolite units (3A-3E), one rhyolitic tuff (3F) and one mafic unit, are exposed in area 3. Unit 3A is exposed at and around latitude 43.597, longitude -118.595. Mafic unit b3A is exposed in a small outcrop at latitude 43.616, longitude -118.650 along Curtis Creek. Unit 3B is well exposed northwest of Unit 3A at latitude 43.614, longitude -118.565 along Curtis Creek. Unit 3C overlies unit 3B at latitude 43.616, longitude -118.561 and Unit 3A at latitude 43.611, longitude -118.568.

Unit 3D overlies Unit 3C at latitude 43.619, longitude -118.561 and was best exposed in outcrop at latitude 43.626, longitude -118.549. Unit 3E overlies Unit 3D at latitude 43.628, longitude -118.551. Tuff of Buchanan, unit 3F, overlies Unit 3B at latitude 43.645, longitude -118.570 and form the ridge continuing north approximately 3 km to Hwy 20.

Area 4

Three distinct rhyolite flow units and two distinct basaltic andesite units are exposed in Area 4. Rhyolite unit 4A is exposed at and around latitude 43.565, longitude -118.520. Rhyolite unit 4B is found between two basaltic andesite flows, b4A at latitude 43.565, longitude -118.528 and b4B at latitude 43.563, longitude -118.529 and overlies unit 4A. Unit 4C, at latitude 43.558, longitude -118.529, forms the ridge and hills that continue south-southwest for approximately 1 km. Previous mapping by Greene et al. (1972) indicate that rhyolite flows in Area 4 are exposed continuously to Area 3; however, lack of permission to access private property hindered confirmation and correlation at this time, yet acquired chemical and mineralogical data are instructive in discussing unit correlations between both areas (see below).

Area 5

Two geographically independent dome-like exposures, 5A and 5B, are located in the Northwest and Northeast of the mapped area, respectively. Unit 5A is located at latitude 43.633, longitude -118.605 approximately 1.5 km south-southeast of the Buchanan Springs rest area along Hwy 20. Unit 5B is located at latitude 43.651,

longitude -118.530, approximately 4.5 km south of Hwy 20 along Stinkingwater access road near Steer Ridge Reservoir.

Lithologic and petrographic characteristics of units

Macroscopic (outcrop and hand sample characteristics) and microscopic (mineral phase abundance, physical attributes, chemical composition (as determined by SEM)) characteristics of units are presented to aid in unit identification both in the field and with microscopy. Units are referred to with the nomenclature established based on geography and stratigraphy.

Area 1

Unit 1A

Figure 9: Photograph of road cut exposure of Unit 1A. View facing northeast along US 20.

Macroscopic characteristics: Exposed in road cut ~15 m tall near the intersection of US 20 and Crane-Buchanan road and ~40 m tall cliffs to the south for ~900 m. Contact alteration during the emplacement of overlying basalt is evident along the road cut exposure (Figure 9 and 10).

Hand samples are porphyritic with color ranging from white to medium gray. Phenocrysts include rounded quartz 1-2 mm and euhedral feldspar up to 3 mm.

Phenocryst abundance is approximately 10%. Samples collected toward the top of the unit have pervasive secondary silicification in the form of amorphous silica within fractures.

Microscopic characteristics: Phenocryst abundance is ~10% consisting of ~7% alkali feldspar and 3% quartz. Additional petrographic characteristics are noted in Appendix A-1, samples B005(p) and B005.

Figure 10: Photographs of of unit 1A. (Left) Road cut outcrop showing contact alteration from overlying basalt. View facing north on highway 20. (Right) Stream cut slot canyon through unit 1A, view facing southwest.

Figure 11: Thin section image of unit 1A (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

SEM analysis indicates that the alkali feldspar is sanidine (Figure 12). A mineral inclusion in a quartz phenocryst was also analyzed by SEM and was determined to be An₄₀ plagioclase (Table 3 and Figure 12).

Table 3: Feldspar composition for unit 1A calculated from data obtained by SEM.

B005 feldspar population, n=8	Or	Ab	An	B005 feldspar inclusion, n=1	Or	Ab	An
Mean	49	51	0	Mean	9	51	40
Minimum	48	49	0	Minimum	9	51	40
Maximum	51	52	0	Maximum	9	51	40
Standard Deviation	0.97	0.97	0.00	Standard Deviation	0.00	0.00	0.00

Figure 12: Feldspar ternary plot based on SEM data showing all analysis results for Unit 1A (dark blue) and averages for all other rhyolite units analyzed. Dark blue diamond is analysis results for a feldspar inclusion within a quartz phenocryst in Unit 1A.

Unit 1B

Macroscopic characteristics: Exposed overlying unit 1A as cap rock cliffs for approximately 2 km along Crane-Buchanan road. Basal breccia is exposed at latitude 43.639, longitude -118.619. Hand samples are porphyritic with color ranging from medium gray to dark gray with some pale pink in the basal breccia (Figure 13). Phenocrysts include euhedral feldspar up to 3mm and altered pyroxene ~1mm (Figure 14). Phenocryst abundance is approximately 15%. Samples collected toward the top of

the unit have pervasive secondary silicification in the form of amorphous silica within fractures.

Figure 13: Photograph of unit 1B basal breccia (hammer for scale)

Microscopic characteristics: Phenocryst abundance is ~15% consisting of ~14% plagioclase feldspar and 1% clinopyroxene (Figure 14). Additional petrographic characteristics are noted in Appendix A-1 for samples B010(p) and B010.

Figure 14: Thin section image of unit 1B (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

SEM results indicate that the feldspar are An₄₀ plagioclase (Table 4 and Figure 15).

Table 4: Feldspar composition for unit 1B calculated from data obtained by SEM.

B010 feldspar population, n=8	Or	Ab	An
Mean	4	56	40
Minimum	3	53	35
Maximum	4	61	44
Standard Deviation	0.49	2.28	2.72

Figure 15: Feldspar ternary plot based on SEM data showing all analysis results for Unit 1B (light blue) and averages for all other rhyolite units analyzed.

Area 2:

Unit 2A

Macroscopic characteristics: Exposed as ~10 m cliffs. Lithologies range from vitric to devitrified. The transition zone between vitric and fully devitrified has large spherulites that have been infilled and replaced with secondary silica forming thundereggs. Numerous excavation pits are dug to access the thundereggs exposing the devitrification transition of this unit.

Figure 16: Photograph of excavated pit in unit 2A on Laton Point.

Hand samples are porphyritic with devitrified sample color ranging from moderate pink to dusky red, vitric samples are medium dark gray. Flow banding is present in the majority of samples. Phenocrysts include euhedral blocky feldspar up to 3

mm and lathes up to 10 mm long. Phenocryst abundance is variable between ~1% and 10% and no apparent within-flow zoning of phenocryst abundance.

Microscopic characteristics: Phenocryst abundance is variable between ~1% and 10%. Phenocrysts are plagioclase feldspar. Additional petrographic characteristics are noted in Appendix A-1 for sample B175.

Figure 17: Thin section image of unit 2A (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left). The portion of the sample prepared for thin section has a low phenocryst compared to other handsamples from this unit.

Unit 2B

Macroscopic characteristics: Exposed overlying unit 2A as whitish bedrock outcrops up to 2 m tall. Unit 2B is a pyroclastic fall deposit composed of lapilli and ash sized, rarely block sized, mostly juvenile particles best observed in excavation pits on Laton Point (Figure 18). Northernmost exposures contain more and larger lithic fragments of what looks like clasts derived from unit 2A (dusky red color). Some lithic

clasts are up to 0.5 m near latitude 43.606, longitude -118.622 (inferred as possibly near eruption source) and quickly grade to smaller clasts further from this point.

Hand samples collected near a potential eruption source contain numerous angular lithic fragments of unit 2A in matrix support of fine-grained angular white fragments. Color ranges from yellowish gray to greenish gray where more silicified near the potential eruption source. Phenocrysts in white pyroclasts and ash and lapilli fall are euhedral feldspar up to 1mm. Phenocryst abundance is approximately 2%.

Figure 18: Photograph of unit 2B pyroclastic unit. Welded juvenile and lithic fragments found at northernmost exposures (left) and unwelded juvenile lapilli found in excavation pit on Laton point (right)

Microscopic characteristics: Phenocryst abundance is ~2% consisting of plagioclase feldspar. Additional petrographic characteristics are noted in Appendix A-1 for sample B178.

Figure 19: Thin section image of unit 2B (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

Area 3:

Unit 3A

Macroscopic characteristics: Exposed as 3 m tall cliffs forming low rolling hills (Figure 20). Exposures range from aphryic, very light gray, vesiculated glass to dense black obsidian nodules within vesiculated glass. Numerous exposures of hydrated obsidian with 0.5-5 cm nodules (“apache tears”) weathering out throughout the areal extent of the unit. Hand samples are aphryic with color ranging from very light gray to

black. Phenocrysts are not present. All samples are vitric however they have various degrees of hydration and vesiculation.

Figure 20: Photograph of unit 3A exposure.

Microscopic characteristics: Samples are aphyric and vitric. Additional petrographic characteristics are noted in Appendix A-1 for sample B185.

Figure 21: Thin section image of unit 3A (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left). Texture of samples due to elongated vesicles.

Mafic unit b3A

Macroscopic characteristics: Only one occurrence of this mafic unit was identified in area 3. Mafic unit b3B underlies unit 3B; however, the stratigraphic relationship with unit 3A is unclear. Exposed as boulders and ~5m bedrock outcrop. Hand samples are porphyritic basalt to basaltic andesite with medium gray color. Phenocrysts consist of feldspar and the groundmass is comprised of microlites. Phenocryst abundance is approximately 1%.

Unit 3B

Macroscopic characteristics: Exposed along Curtis creek (Figure 22) as ~50 m tall cliffs. Hand samples are porphyritic with color ranging from pale red purple to olive gray. Phenocrysts include euhedral equant and tabular feldspar up to 2mm and 4 mm long, respectively. Phenocryst abundance is approximately 15%. Samples collected toward the top of the unit are more altered to a greenish gray color. Some samples have lithic fragments of green aphanitic clasts.

Figure 22: Photograph of unit 3B along Curtis creek. (top) View to the southwest. (bottom) View to the North.

Microscopic characteristics: Phenocryst abundance is ~10% consisting of ~8% plagioclase feldspar and ~2% alkali feldspar (Figure 23). Additional petrographic characteristics are noted in Appendix A-1 for samples B155 and B155(p).

Figure 23: Thin section image of unit 3B (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

SEM analysis confirms that there are two populations of feldspar, sanidine and An₂₂ plagioclase (Table 5 and Figure 24).

Table 5: Feldspar composition for unit 3B calculated from data obtained by SEM.

Feldspar population 155-1 n=6				Feldspar population 155-2 n=8			
	Or	Ab	An		Or	Ab	An
Mean	9	69	22	Mean	58	42	0
Minimum	7	66	20	Minimum	56	41	0
Maximum	10	70	27	Maximum	59	43	2
Standard Deviation	1.12	1.16	2.29	Standard Deviation	0.72	0.41	0.77

Figure 24: Feldspar ternary plot based on SEM data showing all analysis results for Unit 3B (dark pink) and averages for all other rhyolite units analyzed.

Unit 3C

Macroscopic characteristics: Exposed overlying unit 3B along Curtis creek

(Figure 25) as 50 m cliffs and as bedrock outcrop and cliffs south and west of Curtis

Creek (Figure 26). Hand samples are aphanitic with variable colors including dark gray, medium gray, greenish gray and grayish red. Phenocryst abundance (if phenocrysts are present) is < 1% and consist of euhedral feldspar <1mm.

Figure 25: Photograph of unit 3C along Curtis creek. (top) View to the southwest. (bottom) View to the North.

Figure 26: Photographs of unit 3C boulder (left) and cliff (right) outcrops. Image on right shows basal breccia of unit 3C overlying glassy unit 3A.

Microscopic characteristics: Phenocryst abundance is ~1% consisting of euhedral to subhedral feldspar (Figure 27). Additional petrographic characteristics are noted in Appendix A-1 for samples B159(p) and B163.

Figure 27: Thin section image of unit 3C (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

SEM results indicate that the analyzed feldspar are An₃₃ plagioclase (Table 6 and Figure 28).

Table 6: Feldspar composition for unit 3C calculated from data obtained by SEM.

B159 feldspar population, n=5	Or	Ab	An
Mean	8	59	33
Minimum	3	49	25
Maximum	13	62	48
Standard Deviation	3.47	5.01	8.20

Figure 28: Feldspar ternary plot based on SEM data showing all analysis results for Unit 3C (pale pink) and averages for all other rhyolite units analyzed.

Unit 3D

Macroscopic characteristics: Exposed as ~20 m tall cap rock cliffs on ridge north of Curtis creek (Figure 29) and is the dominate bedrock unit forming the valley and ridge to the east. Hand samples are porphyritic with variable colors including yellowish gray, pale pink and brownish gray. Phenocrysts include euhedral feldspar up to 3mm. Phenocryst abundance is variable and ranges from ~2% to ~10%. The majority of samples are flow banded.

Figure 29: Photograph of unit 3D along Curtis creek. View to the north.

Microscopic characteristics: Phenocryst abundance in thin sections examined is ~5-8%, consisting of euhedral plagioclase feldspar (Figure 30). Additional petrographic characteristics are noted in Appendix A-1 for samples B165 and B165(p).

Figure 30: Thin section image of unit 3D (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

SEM analysis indicates that the analyzed feldspar are An_{36} plagioclase (Table 7 and Figure 31).

Table 7: Feldspar composition for unit 3D calculated from data obtained by SEM.

B165 feldspar population, n=14	Or	Ab	An
Mean	4	60	36
Minimum	4	58	32
Maximum	5	63	38
Standard Deviation	0.34	1.20	1.46

Figure 31: Feldspar ternary plot based on SEM data showing all analysis results for Unit 3D (medium pink) and averages for all other rhyolite units analyzed.

Unit 3E

Macroscopic characteristics: Exposed as bedrock outcrops on the top of the north-eastern ridge in area 3. Hand samples are aphyric to phyric with variable colors including grayish pink, yellowish gray, light gray to dark gray and dark reddish brown. Phenocryst abundance is ~0-5%.

Microscopic characteristics: Phenocryst abundance is ~0-5%, consisting of subhedral to euhedral plagioclase feldspar (Figure 30). Additional petrographic characteristics are noted in Appendix A-1 for samples B165 and B165(p).

Figure 32: Two thin section image of unit 3E. (top) Aphyric sample (bottom) Phyrlic sample

SEM analysis indicates that the analyzed feldspar are An₃₁ plagioclase (Table 8 and Figure 33).

Table 8: Feldspar composition for unit 3E calculated from data obtained by SEM.

B172 feldspar population, n=13	Or	Ab	An
Mean	5	64	31
Minimum	3	54	27
Maximum	6	67	43
Standard Deviation	0.87	3.55	4.37

Figure 33: Feldspar ternary plot based on SEM data showing all analysis results for Unit 3E (light pink) and averages for all other rhyolite units analyzed.

Unit 3F

Macroscopic characteristics: Exposed as ridge forming bedrock outcrop in the north of the study area and smaller isolated areas. Unit 3F is an ash-flow tuff. One small outcrop was found to be incipiently welded however most occurrences are strongly welded. This unit was previously identified as the Buchanan ash-flow tuff by Brown and McLean (1980).

Figure 34: Photograph of unit 3F incipiently welded exposure.

Hand samples are tuffaceous with color ranging from medium light gray to light olive gray. Samples consist of ash, ~30% pumice and ~10% lithic fragments, with deformation of the pumice variable based on the degree of welding. Phenocrysts include euhedral feldspar up to 2mm.

Microscopic characteristics: Phenocryst abundance is ~5%, consisting of euhedral plagioclase feldspar (Figure 35). Additional petrographic characteristics are noted in Appendix A-1 for samples B191.

Figure 35: Thin section image of unit 3F (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

Area 4:

Unit 4A

Macroscopic characteristics: Exposed in bedrock outcrops and ~10 m tall cliffs near Mahon creek. Hand samples are porphyritic with color ranging from medium gray to pale pink. Phenocrysts are sparse and consist of euhedral feldspar. Phenocryst abundance is approximately 1%.

Figure 36: Photograph of unit 4A. Devine Canyon tuff caps the ridge and unit 4A is exposed on slopes.

Microscopic characteristics: Phenocryst abundance is approximately 1% consisting of plagioclase feldspar. Additional petrographic characteristics are noted in Appendix A-1 for sample B175.

Figure 37: Thin section image of unit 4A (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

Mafic unit b4A

Macroscopic characteristics: Exposed as boulder outcrops. Hand samples are porphyritic basalt to basaltic andesite with colors ranging from medium gray to light brownish gray. Phenocrysts consist of feldspar and the groundmass is comprised of microlites. Phenocryst abundance is approximately 1%.

Microscopic characteristics: Phenocryst abundance is approximately 1% consisting of plagioclase feldspar. Additional petrographic characteristics are noted in Appendix A-1 for sample B175.

Figure 38: Thin section image of unit b4A (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

Unit 4B

Macroscopic characteristics: Exposed as obsidian nodules and vitric bedrock between basaltic andesite units b4A and b4B. Thickness of unit is ~10m. Hand samples are aphyric with color ranging from black to medium gray.

Mafic unit b4B

Macroscopic characteristics: Exposed as bedrock outcrop and boulders overlying unit 4B. Hand samples are porphyritic basalt to basaltic andesite with colors ranging from medium gray to grayish black. Phenocryst abundance is ~15% and consists of blocky and tabular feldspar up to 1mm and 3 mm long, respectively. Irregular shaped vesicles up to 2mm are common.

Unit 4C

Macroscopic characteristics: Exposed as bedrock outcrops and boulders forming a ridge and several hills. Hand samples are porphyritic with color predominantly medium gray. Phenocrysts include euhedral feldspar up to 3mm and altered pyroxene ~1mm. Phenocryst abundance is approximately 10-15%.

Figure 39: Photograph of unit 4C on top of ridge.

Microscopic characteristics: Phenocryst abundance is approximately 10% consisting of plagioclase feldspar and minor amounts of clinopyroxene and biotite (Figure 40). Additional petrographic characteristics are noted in Appendix A-1 for samples B112, B114 and B114(p).

Figure 40: Thin section images of unit 4C (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

SEM analysis indicates that the analyzed feldspar are An₅₂ plagioclase (Table 9 and Figure 41).

Table 9: Feldspar composition for unit 4C calculated from data obtained by SEM.

B114 feldspar population, n=10	Or	Ab	An
Mean	2	46	52
Minimum	1	37	35
Maximum	4	61	61
Standard Deviation	0.85	7.61	8.35

Figure 41: Feldspar ternary plot based on SEM data showing all analysis results for Unit 4C (purple) and averages for all other rhyolite units analyzed.

Area 5:

Unit 5A

Macroscopic characteristics: Exposed as obsidian float around the base of a hill and low density boulders and bedrock outcrop forming a hill approximately 1.3 km south-southeast from Buchanan Springs rest area along highway 20. All samples of this units are vitric and aphyric.

Unit 5B

Macroscopic characteristics: Exposed along the Stinkingwater access road approximately 4.5 km south of highway 20. Outcrops are sparse and occur within a large depression visible in aerial photography (Figure 42).

Figure 42: Aerial photograph of Area 5B (Google, 2016).

Hand samples are phenocryst poor with color ranging from redish brown to dark gray. Phenocrysts include rounded quartz <1 mm and euhedral feldspar <1 mm. Phenocryst abundance is <1-3%.

Microscopic characteristics: Phenocryst abundance is approximately 3% consisting of euhedral plagioclase feldspar (Figure 43). Additional petrographic characteristics are noted in Appendix A-1 for samples B025b.

Figure 43: Thin section image of unit 5B (upper right) with highlighted area shown in image under transmitted and cross-polarized light (lower left).

Major and trace element geochemistry

Bivariate plots of Oxide weight percent (wt%), trace element concentration and element ratios, as well as multi-element diagrams are used to differentiate and identify geochemical signatures of stratigraphic units. Ratio components are mantle normalized after Sun and McDonough (1989) except Eu/Eu^* which use chondrite concentrations after McDonough and Sun (1995) for normalization purposes.

Ba^* is determined by calculating the geometric mean of mantle normalized values of Rb and Th,

$$(\text{Rb}_{N_m} * \text{Th}_{N_m})^{1/2},$$

Sr^* is determined by calculating the geometric mean of mantle normalized values of Pr and Nd,

$$(Pr_{N_m} * Nd_{N_m})^{1/2},$$

and Eu* is determined by calculating the geometric mean of chondrite normalized values of Sm and Gd:

$$(Sm_{N_{c1}} * Gd_{N_{c1}})^{1/2}.$$

Area 1:

As seen in Figure 44, 1A has lower total iron as FeO (FeO*) and TiO₂, lower Ba and similar concentrations of Zr, Nb and La, and lower values of Eu/Eu* and Ba/Ba* than 1B. Unit 1A feldspar phenocrysts are alkali feldspar while 1B has plagioclase feldspar.

Figure 44: Bivariate plots for units 1A (dark blue) and 1B (light blue).

Comparison of units 1A and 1B with multi-element diagram (Figure 45) display differences in Ba, Sr, P, Eu and Ti. Unit 1A is more depleted in the former elements than unit 1B.

Figure 45: Multi-element diagram for units 1A (dark blue) and 1B (light blue). Concentrations normalized to mantle values of Sun and McDonough (1989)

Area 2:

The two units of Area 2 can be differentiated geochemically based on their major and trace elemental composition (Figure 46 and 47). Unit 2A has higher FeO* compared to 2B; 2A has slightly lower Zr and Nb, and higher Ba and La than 2B. 2A has slightly lower Eu/Eu*, higher La/Sm and lower Ba/Ba* than 2B.

Figure 46: Bivariate plots for units 2A (light green) and 2B (dark green).

Comparison of units 2A and 2B with multi-element diagram (Figure 47) display greater overall enrichment in unit 2A compared to unit 2B. Notable are higher HREE in 2A, P trough in 2B, higher Sr in 2B, and contrasting pattern from Rb to U between the two units.

Figure 47: Multi-element diagram for units 2A (light green) and 2B (dark green). Concentrations normalized to mantle values of Sun and McDonough (1989)

Area 3:

The six rhyolitic stratigraphic units of area 3 indicate subtle compositional differences and thus can be differentiated geochemically. These six units are presented in groups of two units in each plot to provide clarity in presentation of data. Mafic unit b3A is differentiated following the rhyolites of area 5 along with mafic units b4A, b4B and MS-13-SWB.

Units 3A and 3B

Figure 48: Bivariate plots for units 3A (light pink) and 3B (dark pink).

The two stratigraphic units, 3A and 3B, show subtle differences on major and trace element plots (Figure 48 and 49); 3A has lower TiO_2 , Ba, and Nb compared to 3B. 3A has lower Eu/Eu^* , higher La/Sm and lower Ba/Ba^* than 3B. Outliers in the diagrams may be due to element mobility during devitrification and/or alteration.

Comparison of units 3A and 3B with multi-element diagram (Figure 49) shows similar enrichment in Rb-Sr, and slightly greater enrichment in P-Lu in unit 3B. Principle differences in enrichment are in Zr and Hf whereas the crystal poor unit 3A has less enrichment than the crystal rich unit 3B.

Figure 49: Multi-element diagram for units 3A (light pink) and 3B (dark pink). Concentrations normalized to mantle values of Sun and McDonough (1989)

Units 3C and 3D

Comparing units 3C and 3D (Figure 50), 3C has higher FeO^* and TiO_2 compared to 3D. 3C has lower Zr, Ba, Nb and La than 3D. 3C has slightly higher Eu/Eu^* , slightly lower La/Sm and lower Ba/Ba^* than 3D.

Figure 50: Bivariate plots for units 3C (light pink) and 3D (bright pink).

Comparison of units 3C and 3D with multi-element diagram (Figure 51) show similar enrichment in both LIL and HFS elements. Unit 3C is more enriched in Sr, P and Ti and less enriched in Zr and Hf than unit 3D.

Figure 51: Multi-element diagram of units 3C (light pink) and 3D (bright pink). Concentrations normalized to mantle values of Sun and McDonough (1989)

Units 3E and 3F

As seen in Figure 52, 3E has lower FeO* and TiO₂ compared to 3F. 3E has lower Zr, Nb and La, and higher Ba than 3F (one outlier value in unit 3F of Ba greater than 3E). 3E has lower Eu/Eu*, higher La/Sm and lower Ba/Ba* than 3F.

Figure 52: Bivariate plots for units 3E (pink) and 3F (light blue).

Comparison of units 3E and 3F with multi-element diagram (Figure 53) show greater enrichment in most elements of 3F than 3E. 3F has less enrichment than 3E for elements Rb, Th and U, and similar enrichment for K and Pb.

Figure 53: Multi-element diagram of units 3E (pink) and 3F (light blue). Concentrations normalized to mantle values of Sun and McDonough (1989)

Unit 3A-3F averages

Comparison of average values for area 3 units with multi-element diagram (Figure 54) show notable differences. Unit 3F is distinctly different than units 3A-3E. Units 3A-3E have similar patterns with slight differences seen in Sr, P, Zr, Hf and Ti. The differences are emphasized in Figure 55.

Figure 54: Multi-element diagram of all average values of area 3 units. Concentrations normalized to mantle values of Sun and McDonough (1989)

Overall depletion relative to other elements of Sr for units 3A-3E from greatest to least depleted is: 3B, 3D, 3A, 3C, 3E. Depletion of P and Ti from greatest to least is: 3A, 3D, 3E, 3B, 3C. Enrichment of Zr and Hf from greatest to least is: 3A, 3E, 3C, 3D, 3B.

Figure 55: Part of multi-element diagram displaying average values of area 3 units. Concentrations normalized to mantle values of Sun and McDonough (1989)

Area 4:

The 5 stratigraphic units in area 4 are made up of two main two groups: rhyolitic units 4A-4C and basaltic andesite and basalt units b4A, b4B and MS-13-SWB. The mafic units are differentiated following the rhyolites of area 5 along with unit b3A.

Units 4A, 4B and 4C

Three rhyolitic stratigraphic units of area 4 are differentiated with Figure 56 and 57. 4A has higher FeO* and TiO₂ compared to 4B and lower FeO* and TiO₂ compared to 4C. 4A has higher Zr, Nb and Ba, and lower La compared to 4B. 4A has higher Nb and Ba, and similar Zr and La compared to 4C. 4A has higher Eu/Eu*, similar La/Sm and higher Ba/Ba* compared to 4B. 4A has similar Eu/Eu*, higher La/Sm and lower Ba/Ba* compared to 4C.

Figure 56: Bivariate plots for units 4A (lavender), 4B (dark pink) and 4C (dark purple).

Comparison of units 4A-4C with multi-element diagram (Figure 57) shows 4A differs from 4B in Ba whereas 4A has a positive Ba spike and 4B has a slight negative trend. Similarly 4A has more enrichment in Zr and Hf than 4B. 4C is similar to 4A in LIL elements and slightly more enriched in HFS elements with Sr, P and Ti being considerably more enriched.

Figure 57: Multi-element diagram of units 4A (lavender), 4B (dark pink) and 4C (purple). Concentrations normalized to mantle values of Sun and McDonough (1989)

Area 5:

Figure 58 shows the geochemical trends of the two units in Area 5. 5A has lower Zr, Nb and La, and slightly higher Ba than 5B. 5A has slightly lower Eu/Eu* and Ba/Ba*, and slightly higher La/Sm compared to 5B.

Figure 58: Bivariate plots for units 5A (bright yellow) and 5B (orange).

Units 5A and 5B display similar overall enrichment in units (Figure 59); however, unit 5B has slightly greater enrichment in Zr and Hf than unit 5A.

Figure 59: Multi-element diagram of units 5A (bright yellow), and 5B (orange). Concentrations normalized to mantle values of Sun and McDonough (1989)

Mafic Units b3A, b4A, b4B and MS-13-SWB

Figure 60 shows that b3A and b4A have lower FeO* and TiO₂ compared to b4B and MS-13-SWB. Units b3A and b4A also have lower Zr, Nb, Ba and La compared to b4B, and lower Zr, Nb and La, and slightly higher Ba compared to MS-13-SWB. Unit b4B has slightly higher Zr, lower Nb and higher Ba than MS-13-SWB. Units b3A and b4A have lower Eu/Eu*, La/Sm and Ba/Ba* compared to b4B and lower Eu/Eu*, Ba/Ba* and higher La/Sm than MS-13-SWB.

Figure 60: Bivariate plots for units b3A (black diamond), b4A and b4B (dark gray circle) and MS-13-SWB (light gray circle). Unit b4A plots on top of unit b3A, only the edges of the black diamond are visible.

Comparison of units b3A, b4A, b4B and MS-13-SWB with multi-element diagram (Figure 61) show that b3A and b4A is less enriched in both LIL and HFS elements compared to b4B. MS-13-SWB is generally less depleted in high field strength (HFS) elements and less enriched in large ion lithophile (LIL) elements compared to both b4A and b4B resulting in an overall smoother pattern. Units b3B and b4A have similar enrichment trends.

Figure 61: Multi-element diagram of units b3A, b4A, b4B and MS-13-SWB. b3A: black diamond, b4A and b4B: medium gray circles, MS-12-SWB: light gray circle. Concentrations normalized to mantle values of Sun and McDonough (1989)

Defining stratigraphic units with trace element trends

Correlation of stratigraphic units across the study area are based on the results of field, petrographic and geochemical analysis. Trace element trends of 9 rhyolitic eruptive units, including the unit previously identified as the Buchanan ash-flow tuff (Brown and McLean, 1980), and 3 basalt/basaltic andesite units are described and presented in stratigraphic order from earliest to most recent. Additionally, Table 10 provides analyzed ranges for select major and trace element and ratio values.

Table 10: Geochemical ranges for TiO₂, FeO* (wt%), select trace elements (ppm) and ratios for eruptive units at Buchanan rhyolite complex. Units R1-R8 are rhyolitic units local to Buchanan rhyolite complex, unit RT was previously identified as the Buchanan ash-flow tuff (Brown and McLean, 1980) and units Ba1, Ba2 and BaU are mafic units.

Unit	TiO ₂	FeO*	Ba	Nb	La	Zr	Eu/Eu*	Ba/Ba*
R1 (n=3)	0.08-0.09	0.67-1.02	98-153	9-13	18-32	210-282	0.18-0.20	0.08-0.11
R2 (n=4)	0.11-0.15	0.91-1.04	1051-1138	7-11	20-29	111-127	0.36-0.54	0.95-1.42
R3 (n=3)	0.47-0.65	3.51-4.17	1107-1763	9-11	23-26	211-253	0.70-0.89	1.70-2.84
R4 (n=3)	0.23-0.30	1.17-2.57	1373-1509	11-13	21-29	272-311	0.53-0.75	1.17-1.36
R5 (n=6)	0.19-0.49	0.82-3.45	1265-1507	7-11	23-27	147-284	0.57-0.70	1.31-2.15
R6 (n=8)	0.10-0.23	0.69-1.52	627-1603	8-11	27-36	192-241	0.45-0.62	0.75-1.81
R7 (n=2)	0.13-0.25	0.61-1.11	1011-1709	6-10	18	168-244	0.60-0.70	1.89-3.18
R8 (n=6)	0.19-0.33	1.00-2.08	1406-1612	8-10	21-26	145-166	0.47-0.59	1.38-1.69
RT (n=3)	0.23-0.98	2.79-4.64	1315-1572	19-22	36-54	311-371	0.61-0.81	2.02-2.56
Ba1 (n=2)	0.73-1.09	7.40-8.36	582-733	5-7	11-13	105-123	0.87-0.94	2.40-3.58
Ba2 (n=1)	1.13	8.13	1456	8	21	141	0.97	4.03
BaU (n=1)	2.5	11.99	465	12	21	133	1.02	3.58

Rhyolite unit R1

Porphyritic rhyolite recognized in the northwest of the study area as unit 1A.

Quartz and alkali feldspar phenocrysts are easily visible with the unaided eye and are distinct to this unit. Ar-Ar age dating obtained by Hess (2014) determined rhyolite unit R1 is 16.13 ± 0.11 Ma.

Distinct geochemical signatures include major element oxide wt% of $\text{FeO}^* < 1$, $\text{TiO}_2 < 0.1$ and $\text{MgO} \sim 0$. Trace element concentrations of Ba 98-153ppm and trace element ratio values of $\text{Eu}/\text{Eu}^* < 0.2$ and $\text{Ba}/\text{Ba}^* < 0.1$. Multi-element diagram, Figure 62, displays the average enrichment and depletion trends for this unit.

Figure 62: Multi-element diagram of Rhyolite unit R1 (dark blue) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Basaltic Andesite unit Ba1

Porphyritic basaltic andesite recognized in the center of the study area as b3B and south as b4A. Plagioclase feldspar phenocrysts are easily visible with the unaided eye.

Distinct geochemical signatures include major element oxide wt% of $\text{TiO}_2 < \sim 1$ and $\text{P}_2\text{O}_5 < \sim 0.2$. Trace element concentrations of Ba 582-733ppm, Nb 4.62-6.54 and Ba/Ba* trace element ratio value 2.4-3.6. Multi-element diagram, Figure 63, displays the average enrichment and depletion trends for this unit.

Figure 63: Multi-element diagram of basaltic andesite unit Ba1 in comparison to other basalt groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolite unit R2

Aphyric rhyolite recognized in the center and south of the study area as units 3A and 4B. All occurrences are either obsidian nodules in vesiculated vitric matrix or vesiculated vitric bedrock slopes.

Distinct geochemical signatures include major element oxide wt% of $\text{FeO}^* < \sim 1$ and $\text{TiO}_2 < 0.15$. Trace element concentrations of Ba 1051-1138 ppm, Zr 111-127 ppm and trace element ratio values of $\text{Eu}/\text{Eu}^* < .4$ and $\text{La}/\text{Sm} > 3.86$. Multi-element diagram, Figure 64, displays the average enrichment and depletion trends for this unit.

Figure 64: Multi-element diagram of Rhyolite unit R2 (bright green) in comparison to average of other groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Basaltic Andesite unit Ba2

Porphyritic basaltic andesite recognized in the south of the study area as b4B.

Phenocryst abundance is ~15% tabular plagioclase feldspar phenocrysts that are easily visible with the unaided eye.

Distinct geochemical signatures include major element oxide wt% of $\text{TiO}_2 > \sim 1$ and $\text{P}_2\text{O}_5 \sim 0.5$. Trace element concentrations of Ba 1456 ppm, Nb 8.28 and Ba/Ba* trace element ratio value 6.6. Multi-element diagram, Figure 65, displays the average enrichment and depletion trends for this unit.

Figure 65: Multi-element diagram of basaltic andesite unit Ba2 (poppy red) in comparison to other basalt groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolite unit R3

Porphyritic rhyolite recognized in the northwest of the study area as unit 1B and south as 4C. Phenocryst abundance is ~10-15% plagioclase feldspar phenocrysts that are easily visible with the unaided eye.

Distinct geochemical signatures include major element oxide wt% of FeO* 3.5-4.2 and TiO₂ 0.47-0.65. Trace element concentrations of Ba are variable, 1107-1763ppm, likely due to alteration, and trace element ratio values of Eu/Eu* 0.71-0.88. Multi-element diagram, Figure 66, displays the average enrichment and depletion trends for this unit.

Figure 66: Multi-element diagram of Rhyolite unit R3 (green) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolite unit R4

Porphyritic rhyolite recognized in the center of the study area as unit 3B.

Phenocryst abundance is ~10-15% plagioclase and sanidine phenocrysts that are easily visible with the unaided eye.

Distinct geochemical signatures include major element oxide wt% of FeO* 1.2-2.6 and TiO₂ 0.25-0.3. Trace element concentrations of Ba 1373-1509 ppm, Zr 272-311 ppm and trace element ratio values of Eu/Eu* >0.5 and La/Sm 3.0-3.4. Multi-element diagram, Figure 67, displays the average enrichment and depletion trends for this unit.

Figure 67: Multi-element diagram of Rhyolite unit R4 (medium green) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolite unit R5

Porphyritic rhyolite recognized in the center of the study area as unit 3C and northeast as 5B. Phenocryst abundance is ~1%.

Distinct geochemical signatures include major element oxide wt% of TiO₂ 0.2-0.5 and variable FeO* between 0.8-3.45. Trace element concentrations of Ba 1265-1507 ppm, Zr 147-284 ppm and trace element ratio values of Eu/Eu* 0.57-0.70 and La/Sm 3.6-4.0. Multi-element diagram, Figure 68, displays the average enrichment and depletion trends for this unit.

Figure 68: Multi-element diagram of Rhyolite unit R5 (olive green) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolite unit R6

Porphyritic rhyolite recognized in the west as unit 2A, the center as unit 3D, and the southeast as unit 4A. Phenocryst abundance is variable between ~1-5%.

Distinct geochemical signatures include major element oxide wt% of FeO* 0.69-1.52 and TiO₂ 0.18-0.23. Trace element concentrations of Ba 1434-1603 ppm, Zr 192-241 ppm and trace element ratio values of Eu/Eu* 0.45-0.68 and La/Sm 2.73-4.20. Multi-element diagram, Figure 69, displays the average enrichment and depletion trends for this unit.

Figure 69: Multi-element diagram of Rhyolite unit R6 (yellow) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolite pyroclastic unit R7

Welded lithic tuff and lapilli ash-fall tuff recognized in the west as unit 2B.

Distinct geochemical signatures include major element oxide wt% of FeO* 0.61-1.11 and TiO₂ 0.13-0.25. Trace element concentrations of Ba 1011-1709 ppm, Zr 168-244 ppm and trace element ratio values of Eu/Eu* 0.60-0.70 and La/Sm 2.65-2.75. Multi-element diagram, Figure 70, displays the average enrichment and depletion trends for this unit.

Figure 70: Multi-element diagram of Rhyolite unit R7 (dark green) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolite unit R8

Porphyritic rhyolite recognized in the center of the study area as unit 3E and northwest as unit 5A. Phenocryst abundance is variable between ~0-5%.

Distinct geochemical signatures include major element oxide wt% of FeO* 1.00-2.08 and TiO₂ 0.19-0.33. Trace element concentrations of Ba 1406-1612 ppm, Zr 145-166 ppm and trace element ratio values of Eu/Eu* 0.48-0.50 and La/Sm 3.98-4.22. Multi-element diagram, Figure 71, displays the average enrichment and depletion trends for this unit.

Figure 71: Multi-element diagram of Rhyolite unit R8 (pale green) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Rhyolitic Tuff unit RT

Porphyritic pumiceous tuff recognized throughout the study area but most prominently in the north as unit 3F. Phenocryst abundance is 1-5% plagioclase feldspar. Undeformed pumice comprises ~20% of incipiently welded tuff volume.

Distinct geochemical signatures include major element oxide wt% of FeO* 2.79-4.64 and TiO₂ 0.23-0.98. Trace element concentrations of Ba 1315-1572 ppm, Zr 311-371 ppm, Nb 18.98-22.22 and trace element ratio values of Eu/Eu* 0.61-0.81 and La/Sm 2.48-3.23. Multi-element diagram, Figure 72, displays the average enrichment and depletion trends for this unit.

Figure 72: Multi-element diagram of Rhyolite unit RT (tawny orange) in comparison to average of other rhyolite groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Undifferentiated Basalt BaU

Undifferentiated basalt flows exposed throughout the study area are the youngest units.

Distinct geochemical signatures of one unit analyzed (sample MS-13-SWB) include major element oxide wt% of FeO* 12, TiO₂ 2.5 and P₂O₅ 0.64. Trace element concentrations of Ba 465 ppm, Nb 12.36 and trace element ratio values of Eu/Eu* 1.03 and Ba/Ba* 4.0. Multi-element diagram, Figure 73, displays the average enrichment and depletion trends for this unit. Additionally, sample MS-12-SWB has an Ar-Ar age date of $13.79 \pm 0.09\text{Ma}$.

Figure 73: Multi-element diagram of basaltic andesite unit BaU (dark red) in comparison to other basalt groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

Discussion and Conclusions

Trace element trends of rhyolite units

The rhyolites at the Buchanan volcanic complex have subtle differences in trace element abundances. The differences are most notable in Ba, Sr, P, Ti and Nd-Zr-Hf.

Figure 74: Multi-element diagram of average Buchanan rhyolite complex rhyolite (dark gray), calculated from groups R2-R8, in comparison to groups R2-R8 (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989).

With the exception of unit R1, the rhyolite units are variably enriched in Ba with values of Ba/Ba* ranging from 1.0 to 3.2. Sr is variably depleted, when compared to Pr and Nd, with Sr/Sr* values ranging from 0.18 to 0.62 (Figure 75).

Figure 75: Values of Ba/Ba^* and Sr/Sr^* for units R1-R8.

P and Ti are depleted in all rhyolites, which could result from crystal fractionation of apatite and Ti-Fe oxide minerals, respectively. Differences in Nd-Zr-Hf are also seen in the rhyolites. The apparent depletion of Zr could result from crystal fractionation of zircon or relative enrichment of Nd and Hf; conversely, enrichment of Zr could result from the presence of zircon inclusions in phenocrysts. The latter possibility seems more

likely with these rhyolites as greater enrichment in Zr tends to correlate with greater phenocryst abundance and observed inclusions. Additionally, Streck and Grunder (1997) show that although Zr and Hf behave geochemically similar, changes in Zr/Hf can occur during fractionation of zircon.

Trace element trends of basalt units

The stratigraphy of Buchanan rhyolite complex divides the three basaltic andesite units between pre/coeval-rhyolite-emplacement (units Ba1 and Ba2) and post-rhyolite-emplacement (unit BaU). Multiple post-rhyolite basalts are found within the study area, but were not differentiated and analyzed beyond one sample, MS-13-SWB from Streck that has an age of 13.79 ± 0.09 (unpublished data; Wright et al., 2016). Similarities among all samples include enrichment in Ba and Pb and depletion in Nb-Ta; however, the depletion of Nb-Ta and enrichment in Pb are much greater in Ba1 and Ba2 (Figure 76).

Units Ba1 and Ba2 have similar enrichment trends in Rb-Pr with Ba2 being slightly more enriched except in Th and U. These units also show similar depletion of Ti which is not seen in unit BaU. Differences between Ba1 and Ba2 are seen in the elements from Sr to Sm. Ba2 is enriched in Sr and P relative to Pr and Nd, and slightly depleted in Zr-Hf relative to Nd and Sm. Ba1 does not have any relative Sr enrichment, is depleted in P, is neither enriched or depleted in Zr-Hf and is slightly depleted in Sm.

The depletion in Nb, Ta and Ti in units Ba1 and Ba2 could be caused by crystal fractionation of Ti-Fe oxides. The slight depletion of P in Ba1 could be the result of fractionation of a small amount of apatite.

Figure 76: Multi-element diagram of mafic units Ba1 (bright red, solid line), Ba2 (dark red, solid line) and BaU (medium red, dashed line). Concentrations normalized to mantle values of Sun and McDonough (1989).

Definitive correlation of unit Ba1 with regional mafic units older than the age date of 16.13 ± 0.11 Ma (Hess, 2014) on rhyolite unit R1 (e.g. Steens or Grande Ronde Basalt) encounters geochemical discrepancies. Figure 77 illustrates the trace element averages for units Ba1 and Ba2 compared to the average values of Steens and Grande Ronde Basalts. Both regional basalt units contain units that share geochemical trends with the mafic units of Buchanan rhyolite complex such as Ba enrichment and depletion of Nb-Ta and Ti. When plotting K_2O vs. TiO_2/P_2O_5 (Figure 78) after Camp et al. (2002) units Ba1 and Ba2 more closely correlate to the Birch Creek and Hunter Creek Basalt

Figure 77: Multi-element diagram of mafic units Ba1 (bright red) and Ba2 compared to average values of Grande Ronde Basalt (olive green squares) and Upper Steens Basalt (dark grey squares). Grande Ronde Basalt and Steens Basalt averages data from Wolff et al. (2008). Concentrations normalized to mantle values of Sun and McDonough (1989).

than the Upper Pole Creek, which is indistinguishable from Innaha Basalt. Camp (2002) does however remark that some flows of the Upper Steens have some similarities with the Birch Creek flows. Brueseke et al. (2007) describes the geochemical characteristics of the Upper Steens as $Ba > 300$ ppm and K_2O concentrations greater than 1 wt% (Figure 79) which both basaltic andesite units Ba1 and Ba2 have. The age of the Upper Steens is $\sim 16.57 \pm 0.04$ Ma (Bruseke et al., 2007) and would be stratigraphically conformable with the age of 16.13 ± 0.11 Ma for unit R1 (Hess, 2014).

Figure 78: Plot of Na₂O + K₂O vs SiO₂ modified from Camp (2002). Samples from basaltic andesite units Ba1 (red) and Ba2 (dark red) overlain.

Figure 79: Plot of K₂O vs. TiO₂/P₂O₅ after Brueske et al. (2007). Upper Steens: gray upward facing triangle, Lower Steens: gray down pointing triangle, Ba1: bright red, Ba2: dark red.

Trace element trends of Buchanan ash-flow tuff

Three samples of rhyolitic tuff unit RT, previously mapped as the Buchanan ash-flow tuff (Brown and McLean, 1980), have variability within select trace elements. This variability is accounted for by the mafic lithic fragments and pumice within the whole rock samples. Figure 80 shows the strongest variability with Sr, P and Ti. Similarities with samples are seen as enrichment in Ba, U, K and Pb relative to neighboring elements, and depletion in Nb-Ta. Nd-Eu and Tb-Lu are also similarly enriched between samples.

The grayed lines in Figure 80 show the trace element trends for samples of Wildcat Creek ash-flow tuff collected for a Master's degree thesis that is in progress from Sales (unpublished data). There is slightly more variability within samples of Wildcat

Figure 80: Multi-element diagram of samples within unit RT overlain on unpublished Wildcat Creek ash-flow tuff data (grayed) (Sales, M.S. thesis in progress). RT samples B013: circle, B126: square and B191: triangle. Concentrations normalized to mantle values of Sun and McDonough (1989).

Creek (this is to be expected with a large samples size and variable mafic inclusions within whole rock samples), however the trends of enrichment and depletion of individual elements are the same as RT samples. RT sample B191 closely follows the dominant trend of Sales' samples and the trace of sample B126 completely obscures the trace of one of the Wildcat Creek samples that were collected ~50 km away, near Shumway reservoir (Sales, personal communication). Sample B013 from this study, marked with circles in Figure 80, has the greatest depletion in P which is also similar to one of the samples of Wildcat Creek tuff.

An Ar-Ar age date was determined by Hooper et al. (2002) of 15.9 ± 0.2 Ma for the Wildcat Creek ash-flow tuff, however he considered the date invalid due to inconsistencies with the stratigraphic age. If this date were accepted it would mean that eruptions at the Buchanan rhyolite complex and emplacement of the Wildcat Creek ash-flow tuff were nearly coeval.

Geologic map of Buchanan rhyolite complex

Figure 81: Geologic map of Buchanan rhyolite complex. Location of study area indicated with a star on inset map of Oregon. 1: Hess (2014), 2: (Bruseke et al., 2007). Map scale: 1:35,000

Geologic timeline of Buchanan rhyolite complex

The Buchanan rhyolite complex consists of at least eight rhyolite eruptive units, seven of which are flows or domes and the other is a local pyroclastic unit. The underlying basaltic andesite unit Ba1 has been loosely correlated with basalts of the Upper Steens and is $\sim 16.57 \pm 0.04$ Ma (Brueseke et al., 2007). Rhyolite unit R1 has an Ar-Ar age date from Hess (2014) of 16.13 ± 0.11 Ma and is thought to be the earliest rhyolite unit of the complex. Overlying the rhyolite eruptive units are several thin basalt flows, one of which has an age of 13.79 ± 0.09 Ma from Streck (unpublished data), the Devine Canyon Tuff at 9.7 Ma (Hooper et al., 2002), and the Buchanan ash-flow tuff, correlated to the Wildcat Creek ash-flow tuff dated by Hooper et al. (2002) at 15.9 ± 0.2 but considered invalid.

Age constraints on the initiation of rhyolite volcanism at Buchanan rhyolite complex are better defined than constraints on the conclusion of rhyolite volcanism. Rhyolitic eruptions began $\sim 16.13 \pm 0.11$ Ma (Hess, 2014), and if the date by Hooper et al. (2002) of 15.9 ± 0.2 Ma is accepted for the Wildcat Creek ash-flow tuff, emplacement of all rhyolite units would have been over a short amount of time and possibly coeval with the eruption of the Wildcat Creek ash-flow tuff. A younger age for the Wildcat Creek ash flow tuff is preferred by Hooper et al. (2002) and by this study, but more data are needed.

The early age date of $\sim 16.13 \pm 0.11$ Ma (Hess, 2014) suggests that the Buchanan rhyolite complex is an early eruptive center associated with the impingement of the Yellowstone hotspot. This rhyolite volcanic center is the western most silicic center yet identified associated with initiation of Yellowstone related volcanism.

Dooley Mountain Rhyolite Complex

Results

Lithologic and petrographic characteristics of units

Over 100 hand samples from the Dooley Mountain rhyolite complex were collected in the field. Approximate locations of all hand samples shown in Figure 82.

Figure 82: Location map for hand samples collected at Dooley Mountain rhyolite complex. Map modified from Evan (1992).

At least five groups of rhyolite are observed from macroscopic characteristics of hand samples. Major phenocryst phases present and visible with either no magnification or with a 10x hand lens include quartz, feldspar and amphibole. Phenocryst abundance ranges from 0-15% and size varies from much less than 1 mm to 3 mm. Samples also vary from vitric to devitrified with spherulites up to 3 cm. The five groups identified in the field are described as follows and are later correlated with geochemical groups:

- Aphyric, vitric to devitrified
- Porphyritic, ~1% quartz and feldspar phenocrysts <1 mm, vitric to devitrified
- Porphyritic, ~5% feldspar phenocrysts up to 2 mm, vitric to devitrified
- Porphyritic, ~5% feldspar and amphibole up to 2 mm, vitric to devitrified
- Porphyritic, ~10-15% feldspar up to 3 mm, vitric to devitrified

In addition to the above five groups, at least three distinct basalt flows and four tuff outcrops were identified in the field. The major phenocryst phases identified in the basalt units include feldspar and olivine. Phenocryst abundance ranges from ~1-30% and size varies from <1 mm to 2 mm. Three basalt units are described as follows:

- Porphyritic, ~1% feldspar phenocrysts <1 mm, medium-dark gray, locally vesiculated
- Porphyritic, ~3-5% feldspar and olivine phenocrysts up to 3 mm, dark gray
- Porphyritic, ~15-30% feldspar phenocrysts up to 10 mm, black

The four tuff units are differentiated as follows:

- Many undeformed pumice up to 10 cm, contains white lithic fragments, phenocrysts are absent, light gray, incipiently welded
- Pumice/fiamme up to 5 cm, mafic lithic fragments up to 1 cm, ~2% feldspar phenocrysts up to 2mm, black-dark gray
- Fiamme up to 3 cm, lithic fragments up to 5 mm, ~2% feldspar phenocrysts, tan-dark gray
- Deformed pumice up to 2cm, obsidian clasts up to 2cm, 0-5% feldspar phenocrysts

Stratigraphic relationships

Identifying widespread stratigraphic relationships in the field is difficult due to similar lithology of units confirming observations by Evans (1992). Local stratigraphic relationships were observed however and are later paired with the results of geochemical analysis.

In roadcut, along highway 245 near latitude 44.5259, longitude -117.8428, a brecciated aphyric unit (samples EJ-23B, DM44) overlies a massive, porphyritic, ~1% phenocryst unit (samples EJ-23A, DM48), seen in Figure 83.

Figure 83: Photograph of sharp contact between brecciated aphyric unit (EJ-23B) overlying massive porphyritic <1% phenocryst unit (EJ-23A). Location of photograph at latitude 44.5259, longitude -117.8428. Image from Google maps.

Along highway 245, near latitude 44.5896, longitude -117.8513, an ash and pumice dike (sample MS-11-22DR) cross cuts a massive rhyolite flow with ~5% feldspar phenocrysts (sample DM202), seen in Figure 84, below.

Figure 84: Photograph of cross cutting relationship of tuff dike (MS-11-22DR) through a massive rhyolite unit (DM202). Location of photograph at latitude 44.5896, longitude -117.8513. Tuff dike is stratigraphically younger than massive rhyolite unit.

In outcrop, along NF-1118, near latitude 44.5113, longitude -117.8130, an eruptive sequence is exposed with a breccia at the base (sample DM265A), ash and lapilli fall in the middle (samples DM265) and a glassy breccia at the top (sample DM265A), seen in Figure 85. To the south of this exposure, massive rhyolite cliffs (sample DM264, Figure 86) are either continuous with DM265A, with DM265A as a basal breccia, or overlies this sequence.

Figure 85: Photograph of vitrophyric breccia (DM265A) overlying lapilli and ash fall (DM265) and breccia (DM265B). Location of photograph at latitude 44.5222, longitude -117.8139. 265A is either continuous as the basal breccia or underlies a massive rhyolite unit directly to the south of this photo (sample DM264).

Figure 86: Photograph of massive rhyolite cliffs (DM264). Location of photograph at latitude 44.5105, longitude -117.8109.

Approximately 0.5 km south of NF-040 near latitude 44.5274, longitude - 117.8028 a stratigraphic sequence is exposed along the southern slope of a hill. The lowest unit in the sequence is the Burnt River schist (DM254). Overlying the Burnt River schist are two basalt units, one with ~3% phenocrysts (DM255A) and one with ~15% phenocrysts (DM255B), however the stratigraphic relationship between the two basalts is unclear. Overlying the basalt units is a welded lithic tuff unit with ~2% phenocrysts (DM256). Capping the sequence is an aphyric rhyolite unit with a glassy base (vitrophyre) and devitrified interior (DM258 and DM259).

Geochemical groups

Rhyolitic Units

Geochemical groups of silicic units are identified by pairing major and trace element analysis results with distinct stratigraphic relationships from two locations. Samples EJ-23B, EJ-23A (Hess, 2014), MS-13-22DR (from Streck, unpublished data) and DM202 are identified with light blue, yellow, green and red, respectively, as seen in Figure 83 and 84. The bivariate plots of major element oxides or trace elements vs. TiO_2 display seven geochemical groups (Figure 87), four rhyolite lava flows and geochemically related local tuffs, and three geochemically distinct tuffs.

The plot of SiO_2 vs. TiO_2 (Figure 87) shows a slight increase in TiO_2 with decreasing SiO_2 , however our baseline samples for establishing stratigraphic relationships show similar SiO_2 content at differing TiO_2 . Because of this, SiO_2 and other major element oxides are not very helpful in defining the geochemical groups. The best

discriminator for defining groups was found in plots of trace elements against TiO₂ indicating seven groups (Figure 87 and Table 11).

Table 11: Geochemical ranges for TiO₂ (wt%) and select trace elements (ppm) for rhyolite groups at Dooley Mountain rhyolite complex.

Group	TiO ₂	Zr	La	Lu	Rb	Nb
R1(n=4)	0.05-0.06	75-87	23-25	0.51-0.54	116-131	9-10
R2(n=3)	0.11-0.12	172-184	36-40	0.55-0.58	93-111	9-10
R3(n=6)	0.28-0.34	303-389	35-45	0.72-0.86	78-94	10-16
R4(n=10)	0.15-0.21	216-323	36-41*	0.65-0.90	90-101	13-15
T1(n=1)	0.19	387	37	1.49	64	20
T2(n=1)	0.28	362	39	1.05	62	20
T3(n=1)	0.57	310	35	1.1	71	14

* one outlier in group four has La >61 ppm ; n=number of samples

These rhyolitic geochemical groups can roughly be correlated with petrographic groups. Group R1 has 0 to <1% quartz and alkali feldspar phenocrysts and Group R2 has ~3 to 5% plagioclase, alkali feldspar and minor amphibole phenocrysts. Group R3 has the greatest variability in phenocryst abundance with 0 to 10% plagioclase and alkali feldspar and Group R4 has minor amounts, 0 to 1%, of quartz and alkali feldspar phenocrysts. Tuff groups T1 and T2 are described above as containing fiamme up to 3 cm, lithic fragments up to 5mm and tan-dark gray. Group T3 has more mafic pumice/fiamme up to 5 cm and is black-dark gray.

Figure 87: Bivariate plots of SiO_2 and 5 trace elements vs. TiO_2 . Sample EJ-23-A (Yellow) overlies EJ-23-B (light blue), sample MS-11-22DR (green) crosscuts DM202 (red). Samples from rhyolite flow/dome deposits are indicated with circles. Pyroclastic deposits are indicated by diamonds. Geochemical groups are indicated by dashed lines in plot of Nb vs. TiO_2 .

Multi-element diagrams for rhyolite groups

Multi-element diagrams for each geochemical group are displayed below with average values for each group. Additional multi-element diagrams with average unit values in relation to all samples of a unit can be found in Appendix B-3.

Rhyolite R1:

Group one includes four samples: DR4, EJ23B, DM247 and DM258. Defining trace element characteristics as seen in multi-element normalization diagram (Figure 88) include a negative Ba anomaly compared to Rb and Th, a negative Zr anomaly compared to Nd and Hf, less enrichment of La, Ce, Sr and Eu than other groups, less enrichment of Tb-Lu (<10) than the other groups and depletion of Ti ($<<1$) and P (<1).

Figure 88: Multi-element diagram of average geochemical group R1 (light blue) in comparison to average of other groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989). Additional multi-element diagrams with average unit value overlain on within-group samples can be found in Appendix B-3.

Rhyolite R2:

Group two includes three samples: EJ-23A, DM234 and DM235. Defining trace element characteristics as seen in multi-element diagram (Figure 89) include a positive Ba anomaly compared to Rb and Th, a slight negative Zr anomaly compared to Nd and Hf, less enrichment in Ta, relative low concentrations of Tb-Lu at ~10 or below and depletion of Ti (<1) and P (<1).

Figure 89: Multi-element diagram of average geochemical group R2 (yellow) in comparison to average of other groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989). Additional multi-element diagrams with average unit value overlain on within-group samples can be found in Appendix B-3.

Rhyolite R3:

Group three includes six samples: DR2, DM202, DM220, DM240, DM241 and DM250. Defining trace element characteristics as seen in multi-element diagram (Figure 90) include a positive Ba anomaly compared to Rb and Th, minor Zr and Hf enrichment comparable to Nd and Sm, less depletion of Eu, higher Tb-Lu (>10), and less depletion of P and Ti than group 1 or 2.

Figure 90: Multi-element diagram of average geochemical group R3 (red) in comparison to average of other groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989). Additional multi-element diagrams with average unit value overlain on within-group samples can be found in Appendix B-3.

Rhyolite R4:

Group four includes ten samples: MS-11-22DR, DM044B, DM048, DM223, DM238, DM264, DM265A, DM265, DM265B and DM273A. Defining trace element characteristics as seen in multi-element diagram (Figure 91) include a positive Ba anomaly compared to Rb and Th, lower Zr and Hf than group 3, Ti depletion ~1 and enrichment of Tb-Lu >10. Two samples, DM044B and DM048, have outlier values for Ba, Pb and Sr, likely resulting from post emplacement alteration.

Figure 91: Multi-element diagram of average geochemical group R4 (green) in comparison to average of other groups (grayed). Concentrations normalized to mantle values of Sun and McDonough (1989). Additional multi-element diagrams with average unit value overlain on within-group samples can be found in Appendix B-3.

Tuff Groups:

The three tuff groups exposed in the study area have geochemical signatures unrelated to the rhyolite units and can be further discriminated and identified.

Comparison with geochemical data for the four eruptive units of the Dinner Creek Tuff (Streck et al., 2015) indicate that the three groups, T1, T2 and T3, correlate with eruptive units 1 (DIT1), 2 (DIT2) and 4 (DIT4) of the Dinner Creek Tuff, respectively (Figure 92).

DIT1 and Dooley Mountain volcanic complex unit T1 have low TiO_2 ($<\sim 0.2$ wt%), low Sr ($<\sim 40$ ppm), high Y ($>\sim 80$ ppm) and high Nb ($>\sim 20$ ppm). High silica varieties of DIT2 ($\text{SiO}_2 >\sim 74$ wt%) and T2 have TiO_2 between ~ 0.2 - 0.3 wt%, Sr ~ 80 - 120 ppm and Nb ~ 20 - 21 . The correlation of DIT4 and T3 are best seen in the plot of Nb vs. Sr (Figure 92) and in handsample. The variability of lithic fragments and mafic pumice within the analyzed sample of unit T3 and samples of DIT4 may have contributed to the differences in TiO_2 and Y.

Figure 92: Bivariate plots of tuff units T1 (magenta), T2 (dark pink) and T3 (light pink), compared to Dinner Creek Tuff eruptive units. Dinner Creek Tuff eruptive units DIT 1 (light gray circles), DIT 2 (gray squares), DIT 3 (dark gray diamonds) and DIT 4 (black triangles) defined by Streck (2015). T1 is comparable to DIT 1, T2 is comparable to DIT 2 and T3 is comparable to DIT 4. Dinner Creek Tuff data from Streck (2015)

Multi-element diagrams (Figure 93, 94 and 95) of units T1, T2 and T3 compared to DIT1, DIT2 and DIT4 display the similarities in trace element enrichment between the average values of Dinner Creek Tuff units and samples from the study area.

Figure 93: Multi-element diagram of average geochemical group T1 (magenta) in comparison to average of DIT1 (black line w/ black circles) and within group DIT1 samples (grayed). DIT data from Streck et al. (2015). Concentrations normalized to mantle values of Sun and McDonough (1989).

Figure 94: Multi-element diagram of average geochemical group T2 (dark pink) in comparison to average of DIT2 (black line w/ black circles) and within group DIT2 samples (grayed). DIT data from Streck et al. (2015). Concentrations normalized to mantle values of Sun and McDonough (1989)

Figure 95: Multi-element diagram of average geochemical group T3 (light pink) in comparison to average of DIT4 (black line w/ black circles) and within group DIT4 samples (grayed). DIT data from Streck et al. (2015). Concentrations normalized to mantle values of Sun and McDonough (1989)

Basalt Units:

There are three geochemically distinct basalt groups that correspond to the three groups defined by physical characteristics. Basalt group B1 includes sample DM038, which has ~1% feldspar phenocrysts and is slightly more enriched than B3 samples. Basalt group B2, sample DM255A with ~5% feldspar phenocrysts, has greater enrichment than B1 or B3, except for Y-Lu. Group B3 includes samples DM255B and DM260 (~15-30% feldspar phenocrysts), and is the least enriched of the three basalt groups.

Comparison of the three basalt groups to geochemical data for Grande Ronde, Picture Gorge and Imnaha Basalts from Wolff et al. (2008) indicate that basalt B1 and B3 correlate best with Picture Gorge Basalt (Figure 96). Similarities between B1, B3 and the Picture Gorge Basalt include a pronounced enrichment of Ba compared to Rb and Th,

Figure 96: Plot of Ba vs. Ta and multi-element diagram of basalt units B1-B3 in comparison to average of Innaha basalts (dark gray triangle), Picture Gorge basalts (light gray squares) and Grande Ronde basalts (dark gray circles). B1: dark blue squares. B2: medium blue squares. B3: light blue squares. Point data and calculated average basalt used in multi-element diagram from Wolff et al. (2008)

Ba/Nb values greater than 4 (due to Ba enrichment rather than Nb depletion such as Grande Ronde Basalt) and less overall enrichment than Innaha or Grande Ronde Basalt.

Unit B2 appears to be geochemically related to groups B1 and B3 but is from a more evolved and enriched magma.

Discussion and Conclusions

The previously work done at the Dooley Mountain rhyolite complex by Gilluly (1937), Whitson (1988) and Evans (1992) left unanswered questions and interpretations in need of revision. The issues we address include:

- Are the geologic descriptions and interpretations of the rocks correct and are the rocks at the Dooley Mountain rhyolite complex predominantly of pyroclastic origin?
- Are the previously determined number of geochemical groups consistent with modern geochemical data?
- Is the Dooley Mountain rhyolite complex contemporaneous with the Columbia River Basalts or,
- Was the Dooley Mountain rhyolite complex emplaced over multiple eruptive periods before, during or after the eruption of the Columbia River Basalts?

Geologic descriptions and interpretations

Ten of the thirteen major unit divisions described by Evans (1992) include or are described as tuff. Although there are occurrences of tuff units throughout the quadrangle they do not appear to be neither dominant nor widespread units. Of over 100 hand samples (Appendix B-1) collected in the field, 11 samples from only six locations were identified as tuffs. There were however widespread breccias that may have been interpreted as ash-flow tuffs. At best, some of the breccia may be block-and-ash flow tuffs and not basal or top breccias of lava flows. Distinction between these two options

can be very difficult on small single outcrops. The vast majority of samples were massive or brecciated rhyolite.

Geochemical groups

Whitson (1988) concluded that there were four main geochemical groups of rhyolites within the Dooley mountain rhyolite. We confirm this assertion with modern XRF and ICP-MS data; however when comparing the distribution of samples within Whitson's groups to distribution there are differences. Whitson's group 1, 2 and 3 roughly correlate with our R3/R4, R1/R2 and R3/R4, respectively, and his group 4 is poorly defined and does not correlate well with our results.

Additionally, we have identified and correlated three rhyolitic tuff units to three distinct eruptive units of the Dinner Creek Tuff and three basalt units, two of which are Picture Gorge Basalt and the third geochemically related. By correlating the results of our geochemical groups with the geologic units previously mapped by Evans (1992) (Figure 97 and Table 12) we are able make revisions (Figure 99 and 100).

Figure 97: Geologic map showing locations of samples used for geochemical analysis and radiometric age dating. Unit R1: light blue; Unit R2s: yellow; Unit R3s: red; Unit R4: green; Unit T1: magenta; Unit T2: dark pink; Unit T3: light pink; Unit B1: dark blue square; Unit B2: medium blue square; Unit B3: light blue-gray square. Pyroclastic units identified with diamonds. Rhyolite flows and domes indicated with circles. Basalt flows indicated with squares. Map modified from Evans (1992). Ar-Ar age date from Hess (2014). K-Ar age date from Walker et al. (1974).

Table 12: Correlation of geochemical groups with units mapped by Evans (1992).

Sample Number	Group	Unit Mapped by Evans (1992)
DR4	1	Td3
EJ-23B	1	Td3
DM247	1	(Td12)
DM258	1	(Td1/Td2)
EJ-23A	2	Td2
DM234	2	Td2
DM235	2	Td1
DR2	3	Td11
DM202	3	Td11
DM220	3	(Td2)
DM240	3	Td13b
DM241	3	Td13a
DM250	3	(Td2)
MS-11-22DR	4	Unassigned
DM223	4	Td10
DM238	4	Td0
DM264	4	Td7
DM265A	4	Td6
DM265	4	Td6
DM265B	4	Td6
DM273A	4	Td9
DM246A	T1	(Td12c)
DM269	T2	(Tdt)
DM256	T3	(Td1)
DM260	B1	Tb1
DM255B	B1	Tb1
DM038	B2	Tb2
DM255A	B3	Unassigned

Figure 99: Geologic map showing extent of eruptive units determined by geochemical groups. Rhyolite Unit R1: light blue; Rhyolite unit R2: yellow; Rhyolite unit R3: red; Rhyolite unit R4: green. Basalt unit B1: dark blue; Basalt unit B2: light gray-blue. Tuff units T1-T3 are not shown on the map as there was no correlative unit mapped by Evans (1992). Map modified from Evans (1992).

Figure 100: Geologic cross sections with eruptive units determined by geochemical analysis. Rhyolite Unit R1: light blue; Rhyolite unit R2: yellow; Rhyolite unit R3: red; Rhyolite unit R4: green. Basalt unit B1: dark blue. Cross sections modified from Evan (1992).

Geologic timeline of the Dooley Mountain rhyolite complex

The Dooley Mountain rhyolite complex consists of multiple eruptive units that were emplaced probably during two distinct periods of activity. Geochemical analysis indicates that there are at least four distinct eruptive units, two from each period of activity, R1 & R2 being the earlier eruptive units and R3 & R4 the later ones.

The first eruptive period (units R1 and R2) occurred as early as ~16 Ma, post emplacement of the Dinner Creek Tuff unit 1 at 16.15-16.0 Ma (Streck, 2015) and a flow unit of the Picture Gorge Basalt member of the CRBG as early as ~16.4 Ma (Barry et al., 2013). One Ar-Ar age date of 15.59 ± 0.04 Ma from Hess (2014) from the stratigraphically younger unit of eruptive period 1 is consistent with this stratigraphy.

The second eruptive period (units R3 and R4) occurred after emplacement of Dinner Creek Tuff unit 2 (15.54-15.47 Ma) (Streck, 2015). One K-Ar age date from Walker et al. (1974) of 14.7 ± 0.4 is not consistent with the presence of at least one additional Picture Gorge Basalt unit overlying R3 in the south which is thought to be at the latest 15.2 ± 0.04 Ma (Barry et al., 2013).

The youngest stratigraphic unit identified is Dinner Creek Tuff unit 4 with an age of 14.99 Ma (Streck, 2015). This unit is located in the south of the study area, and in the field, appears to be directly overlying basalt unit B1 and B3 and underlying rhyolite unit R1. The field observed relationship is not congruent with the age dates that have been presented for all other units. The most likely cause of this incongruity is emplacement of Dinner Creek Tuff unit 4 as a valley fill deposit in the eroded rhyolite. The presence of

basalt B3 boulders alongside B1 in this location can also be attributed to transportation during erosion of the rhyolite.

The age of these eruptive events make the Dooley Mountain rhyolite complex an early eruptive center associated with the Yellowstone hotspot. This complex is the northernmost identified rhyolite center within the region of mid Miocene rhyolite initiation.

Conclusion

Mid-Miocene silicic volcanism in eastern Oregon is generally accepted to have initiated as early as 16.7-16.5 Ma near the Oregon-Idaho-Nevada border (e.g. McDermitt volcanic field). Whether or not there was a northward progression from this initiation point, as suggested by Coble and Mahood (2012), or widespread coeval volcanism without south to north progression, as suggested by Streck et al. (2015), is still under debate.

Evidence from this study show that both the Buchanan rhyolite complex and Dooley Mountain rhyolite complex were early (16.6-15.6 Ma) eruptive centers that do not fit the northward progressing model put forth by Coble and Mahood (2012). The Buchanan rhyolite complex eruptive period began from at least 16.13 ± 0.11 Ma (Hess, 2014) to as old as the Upper Steens $\sim 16.57 \pm 0.04$ Ma (Brueseke et al., 2007) and ended by the time the Wildcat Creek ash-flow tuff was emplaced ca. 15.9 ± 0.2 Ma (Hooper et al., 2002). The Dooley Rhyolite complex eruptive period began from at least 15.59 ± 0.04 Ma (Hess, 2014) to as old as 16.15-16.00 Ma just after emplacement of DIT 1 (Streck et al., 2015) and lasted until, at the latest, $\sim 15.2 \pm 0.04$ Ma (Barry et al., 2013) when the Picture Gorge basalt eruptions were winding down.

These data support the model that Streck et al. (2015) present that assert widespread silicic volcanism “popped up” throughout eastern Oregon coeval with main phase CRBG eruptions and are as old as the volcanic centers at the southern periphery (e.g. McDermitt volcanic field).

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Appendix A : Buchanan Rhyolite Complex

Appendix A-1 : Petrographic Data

Total Phenocryst Abundance									
Unit	Sample	Abundance (%)	Major Phases	Minor phases	Size (µm)	Phase Abundance (%)	Phase characteristics		General Texture
1A	B005(p)	10	Qz		250-1000	3	Sub-euhedral, simple twinning		
			Afs		150-2000	7	Eu-subhedral, simple twinning, perfect cleavage, minor amount of broken shards		
1B	B010(p)	15	Plag		200-2000	14	Eu-subhedral, polysynthetic and simple twinning, undulatory extinction, minor amount of broken shards, glomerocrysts		
3B	B155(p)	10	Cpx		100-500	1	Bright green to brown depending on degree of weathering		
					100-200	<1			
3C	B159(p)	1	Plag		100-2000	8	Eu-subhedral, polysynthetic and simple twinning, undulatory extinction, few small glomerocrysts		
					100-200	2	Eu-subhedral, minor amount of broken shards		
					50-100	<1			
3D	B165(p)	5	Plag		100-200	1	Polysynthetic and simple twinning		mafic inclusions of similar material
3D	B165(p)	5	Plag		25-50	<<1	Eu-subhedral, polysynthetic and simple twinning, undulatory extinction, few small glomerocrysts, few shards		
					25-50	<<<1			
3D	B165(p)	5	Plag		50-1500	5			
3D	B165(p)	5	Plag		25-50	<1			
					25-50	<1			
					50-100	<<1			

Unit	Sample	Total Phenocryst Abundance (%)		Major Phases	Minor phases	Size (µm)	Phase Abundance (%)	Phase characteristics	General Texture
		(%)							
3E	B172(p)	5	Plag			100-1000	5	Polysynthetic and simple twinning, skeletal, some shards	Devitrified, minor flow banding, porphyritic
							<1		
							<1		
							<<1		
4A	B114(p)	10	Plag			100-1000	10	Eu-subhedral, polysynthetic and simple twinning, minor pitting, many glomerocrysts	Devitrified, no flow banding, porphyritic
							<1		
							<1		
							<<1		
1A	B005	10	Qz			250-2000	3	Sub-euhedral, some shards	Devitrified microlite groundmass, porphyritic
							7		
							<1		
							<1		
1B	B010	15	Plag			100-2000	12	Eu-subhedral, polysynthetic and simple twinning, undulatory extinction, some glomerocrysts, some shards	Devitrified microlite groundmass, porphyritic
							1		
							1		
							1		
5B	B025b	3	Plag			50-1000	3	Euhedral, polysynthetic and simple twinning	Devitrified felty groundmass, porphyritic
							<1		
							<1		
							<<1		
4A	B108	1	Plag			100-500	3	Sub-euhedral, polysynthetic and simple twinning	Devitrified, felty groundmass, porphyritic
							<<1		
							<<1		
							<<1		

Unit		Total Phenocryst Abundance (%)		Major Phases	Minor phases	Size (µm)	Phase Abundance (%)	Phase characteristics	General Texture
4A	B109	1		Plag	Oxide	50-200	1 <		

		Total Phenocryst Abundance (%)		Major Phases		Minor phases	Size (µm)	Phase Abundance (%)	Phase characteristics		General Texture
Unit	Sample										
3E	B144	1		Plag		Oxide	50-200	1	Sub-euhedral, poly-synthetic and simple twinning		Devitrified, no flow banding, porphyritic. Contains mafic lithic fragments with thick reaction rims.
3C	B153	0		Plag		Oxide	50	<<<1	Anhedra, undulatory extinction, shard		Vitric, no flow banding, only one very small phenocryst, aphyric
3B	B155	8		Plag			500-2000	6	Euhedral, poly-synthetic and simple twinning. Mostly tabular habit.		Devitrified, no flow banding, porphyritic
				Afs			500-1000	2	Euhedral, no twinning, mostly equant habit		
						Oxide		<<1			
3E	B163	2		Plag			50-2000	2	An-subhedral, poly synthetic and simple twinning, undulatory extinction in large phenocrysts		Devitrified, no flow banding, porphyritic
3D	B165	8		Plag		Oxide	100-1000	8	Eu-subhedral, poly synthetic and simple twinning		Devitrified, flow banded, porphyritic
						Oxide		<1			
3D	B168	2		Plag			100-1000	2	Euhedral, poly synthetic and simple twinning		Devitrified, minor flow banding, very small vesicles along flow bands, porphyritic
						Oxide		<1			

Unit	Sample	Total Phenocryst Abundance (%)		Major Phases	Minor phases	Size (µm)	Phase Abundance (%)	Phase characteristics	General Texture
3E	B171	2		Plag	Oxide	100-1000	2	Sub-Euhedral, poly synthetic and simple twinning, most phenocrysts are broken	Devitrified, no flow banding, contains deformed glass shards, porphyritic
2A	B175	1		Plag		100-500	1	Sub-anhedral, poly synthetic and simple twinning, most phenocrysts are broken	Devitrified, strongly flow banded, irregular shaped vesicles along banding, porphyritic
2B	B178	1		Plag		100-500	1	Sub-euhedral, poly synthetic and simple twinning, most phenocrysts are broken, large crystals are shattered and spread in close proximity to original position	Vitric, no flow banding, porphyritic
3A	B185	0		N/A	N/A	N/A	N/A	N/A	Vitric, no flow banding, slight perlitic texture, aphyric
3F	B191	3		Afs		50-1000	3	Euhedral, undulatory extinction, simple twinning, perfect cleavage, many broken shards	Contains approximately 20% pumice by volume, possibly two populations of pumice-mafic and felsic, tuffaceous texture
b4A	B110b	1		Plag		100-2000	1	Sub-euhedral, poly-synthetic and simple twinning, undulatory extinction, larger phenocrysts are pitted	Groundmass is microlite plagioclase, porphyritic

Appendix A-2 : Geochemical Data

A-2a : XRF results

Samples with unit designation in parentheses (e.g. Samples ID: B153, Unit (R5))

were not used in the analysis of data but are stratigraphically within the listed unit.

Sample ID	B001C	B005	B010	B013	B014	B015	B022	B025B
Unit	R1	R1	R3	RT	R8	R8	R3	R5
This Study								
XRF - wt% (normalized)								
SiO ₂	84.61	80.64	70.07	71.47	75.33	75.32	76.83	77.56
TiO ₂	0.076	0.084	0.648	0.228	0.203	0.204	0.473	0.188
Al ₂ O ₃	8.10	10.29	14.76	12.84	13.25	13.36	11.15	12.37
FeO*	0.67	1.02	4.17	2.79	1.47	1.44	3.51	0.82
MnO	0.002	0.030	0.061	0.045	0.043	0.041	0.053	0.011
MgO	0.00	0.00	0.27	1.12	0.24	0.28	0.18	0.06
CaO	0.04	0.06	2.31	1.90	1.17	1.22	1.56	1.02
Na ₂ O	1.65	3.16	3.98	2.98	3.83	3.12	3.15	3.83
K ₂ O	4.83	4.71	3.53	6.60	4.43	4.99	2.94	4.10
P ₂ O ₅	0.011	0.009	0.179	0.041	0.035	0.031	0.142	0.033
XRF - ppm (unnormalized):								
Ni	0	0	1	2	1	2	1	0
Cr	3	3	3	3	3	3	2	3
Sc	1	3	12	4	5	4	10	4
V	3	2	23	6	10	12	18	5
Ba	101	96	1736	1312	1466	1581	1091	1442
Rb	129	134	51	75	111	108	72	87
Sr	7	5	256	142	94	95	143	82
Zr	204	256	252	359	162	156	209	199
Y	40	36	36	70	29	30	38	25
Nb	12	14	11	20	10	9	10	11
Ga	12	15	19	21	15	14	14	13
Cu	7	2	13	4	7	4	9	4
Zn	19	62	86	130	34	32	74	23
Pb	38	9	14	15	16	15	12	13
La	16	22	26	38	26	26	21	23
Ce	45	54	59	82	50	48	42	49
Th	10	11	9	6	12	11	8	8
Nd	18	25	24	42	21	19	22	19
U	4	5	3	2	5	4	3	4

Sample ID	B026	B108	B109	B110A	B110B	B111	B112	B116
Unit	R5	R6	R6	R2	Ba1	Ba2	R3	R6
This Study								
XRF - wt% (normalized)								
SiO2	72.31	75.34	76.36	77.02	55.92	56.68	69.01	75.77
TiO2	0.376	0.200	0.182	0.123	0.731	1.130	0.588	0.187
Al2O3	14.44	13.58	13.11	12.60	16.73	17.41	14.83	13.18
FeO*	2.29	1.39	1.23	1.04	7.40	8.13	4.10	1.50
MnO	0.046	0.020	0.008	0.037	0.125	0.153	0.091	0.009
MgO	0.38	0.12	0.12	0.10	6.12	3.65	0.96	0.11
CaO	1.75	0.84	0.83	0.74	8.86	7.27	3.18	0.90
Na2O	3.63	3.98	3.91	3.52	2.73	3.39	3.70	3.99
K2O	4.71	4.51	4.22	4.81	1.26	1.69	3.36	4.33
P2O5	0.076	0.016	0.016	0.011	0.135	0.493	0.175	0.016
XRF - ppm (unnormalized):								
Ni	1	4	1	3	117	41	5	2
Cr	2	6	5	4	203	57	4	3
Sc	6	5	5	4	29	21	10	4
V	22	7	14	3	172	177	56	11
Ba	1489	1537	1389	1071	584	1440	1297	1502
Rb	81	100	91	128	26	28	78	97
Sr	162	86	77	54	231	546	239	86
Zr	285	208	188	121	102	135	208	207
Y	31	21	15	30	24	26	33	25
Nb	12	11	10	11	5	8	10	11
Ga	15	14	14	14	16	18	15	14
Cu	7	5	4	6	78	36	17	4
Zn	40	31	25	27	59	83	54	32
Pb	15	16	14	18	4	6	12	15
La	27	23	17	27	12	21	25	26
Ce	49	45	29	53	25	42	48	50
Th	7	9	8	12	2	2	7	9
Nd	21	19	11	21	14	22	21	21
U	2	4	2	6	2	1	3	4

Sample ID	B121A	B121B	B126	B129	B138	B144	B146	B147
Unit	R8	R8	RT	R8	R6	R8	R5	R2
This Study								
XRF - wt% (normalized)								
SiO2	76.16	75.71	72.64	75.63	76.30	75.81	74.53	77.04
TiO2	0.198	0.190	0.477	0.198	0.178	0.327	0.280	0.122
Al2O3	13.18	13.17	13.25	13.30	13.09	12.61	13.07	12.57
FeO*	1.00	1.33	4.02	1.37	0.69	2.08	2.50	1.01
MnO	0.012	0.040	0.022	0.040	0.012	0.031	0.023	0.034
MgO	0.10	0.20	0.34	0.22	0.18	0.22	0.29	0.11
CaO	1.07	1.06	0.74	1.10	1.09	1.78	1.46	0.74
Na2O	3.65	3.78	4.76	3.23	3.93	3.31	3.48	3.53
K2O	4.60	4.49	3.60	4.89	4.51	3.76	4.31	4.82
P2O5	0.032	0.023	0.144	0.025	0.018	0.072	0.054	0.012
XRF - ppm (unnormalized):								
Ni	3	2	4	2	2	14	5	2
Cr	5	3	4	3	3	16	10	4
Sc	5	4	7	3	5	7	6	3
V	10	8	26	8	8	29	25	4
Ba	1433	1445	1531	1375	1511	1356	1333	1095
Rb	117	118	63	111	102	91	120	128
Sr	91	89	108	87	85	147	112	55
Zr	155	153	363	147	190	140	149	123
Y	27	29	66	27	24	27	27	30
Nb	10	10	22	9	10	8	9	11
Ga	13	14	21	13	15	14	14	14
Cu	8	5	3	4	3	12	6	4
Zn	23	29	138	28	17	30	28	27
Pb	16	16	14	14	17	11	13	17
La	24	26	56	26	25	20	22	25
Ce	47	48	89	42	47	37	42	51
Th	11	10	7	10	9	9	10	13
Nd	20	20	50	16	18	17	20	19
U	4	7	4	5	3	4	6	5

Sample ID	B148	B153	B155	B156	B158	B159	B160	B161
Unit	R2	(R5)	R4	R4	R4	R5	R5	R5
This Study								
XRF - wt% (normalized)								
SiO2	82.03	83.98	78.22	73.19	76.65	71.16	71.37	77.57
TiO2	0.150	0.152	0.229	0.303	0.252	0.489	0.442	0.213
Al2O3	9.71	9.90	11.76	13.63	12.55	14.33	14.03	12.19
FeO*	0.91	0.25	1.17	2.57	1.39	3.45	3.02	1.15
MnO	0.006	0.010	0.011	0.027	0.016	0.031	0.079	0.014
MgO	0.05	0.86	0.02	0.18	0.02	0.40	0.98	0.14
CaO	1.01	2.66	0.78	0.94	0.81	2.37	2.48	1.18
Na2O	2.58	0.17	3.30	3.90	3.67	3.55	3.57	3.28
K2O	3.53	2.01	4.48	5.22	4.61	4.12	3.92	4.22
P2O5	0.028	0.006	0.026	0.048	0.036	0.115	0.099	0.039
XRF - ppm (unnormalized):								
Ni	0	3	3	4	3	26	24	3
Cr	4	4	7	11	3	28	23	5
Sc	3	3	5	7	6	11	10	5
V	9	5	11	14	7	69	56	15
Ba	1071	1879	1318	1465	1444	1224	1252	1313
Rb	87	73	101	147	126	126	99	109
Sr	77	444	69	75	74	159	154	99
Zr	118	107	266	309	296	148	149	146
Y	18	13	32	33	27	28	24	25
Nb	7	6	11	13	13	9	9	8
Ga	11	7	13	15	15	15	14	13
Cu	5	1	7	9	8	21	12	9
Zn	13	10	21	37	29	52	39	20
Pb	11	7	19	12	13	13	12	12
La	16	20	29	28	21	23	22	23
Ce	35	29	45	53	45	41	39	42
Th	8	7	11	12	10	8	9	10
Nd	15	15	24	28	20	17	18	18
U	4	1	5	5	4	3	4	3

Sample ID	B162	B163	B165	B168	B171	B175	B178	B185
Unit	R6	R6	(R6)	(R6)	R6	R6	R7	R2
This Study								
XRF - wt% (normalized)								
SiO2	76.26	75.82	72.30	83.79	76.89	76.73	86.86	75.73
TiO2	0.178	0.183	0.538	0.364	0.180	0.214	0.129	0.113
Al2O3	13.12	13.27	14.82	9.49	12.83	12.64	7.80	12.62
FeO*	1.16	1.22	2.22	0.81	0.99	1.02	0.61	0.99
MnO	0.011	0.015	0.023	0.008	0.015	0.027	0.011	0.043
MgO	0.06	0.09	0.11	0.46	0.06	0.06	0.59	0.31
CaO	0.84	0.89	1.66	1.78	0.90	0.71	1.13	2.75
Na2O	3.88	3.94	4.47	0.46	3.90	3.54	0.55	2.29
K2O	4.47	4.56	3.75	2.81	4.21	5.03	2.30	5.14
P2O5	0.024	0.022	0.094	0.027	0.019	0.025	0.016	0.017
XRF - ppm (unnormalized):								
Ni	2	2	3	1	3	3	2	2
Cr	3	3	2	2	4	4	4	2
Sc	4	5	10	5	6	8	5	3
V	9	10	13	7	7	6	7	3
Ba	1538	1512	1437	3735	1467	1403	1668	1034
Rb	102	103	79	48	94	130	67	112
Sr	83	88	182	620	89	57	193	188
Zr	192	194	256	161	191	234	168	112
Y	28	33	39	19	31	56	28	29
Nb	12	11	14	9	10	11	6	10
Ga	14	15	17	10	14	15	10	13
Cu	5	5	6	1	3	5	1	5
Zn	24	32	102	15	18	49	33	25
Pb	15	15	13	5	17	14	5	15
La	29	28	32	17	29	34	19	28
Ce	51	50	56	29	44	53	35	44
Th	10	9	8	5	9	10	5	12
Nd	25	20	28	13	22	36	17	19
U	3	3	4	2	3	5	0	4

Sample ID	B191	B352	B354	B355	B356	EJ-03	EJ-04
Unit	RT	R6	R7	R6	Ba1	R1	R6
	This Study					Hess, 2014	
XRF - wt% (normalized)							
SiO2	68.82	75.53	81.16	75.50	57.16	78.81	84.35
TiO2	0.984	0.184	0.246	0.234	1.098	0.089	0.102
Al2O3	14.19	13.42	11.04	13.38	16.61	11.22	8.20
FeO*	4.64	1.39	1.11	1.52	8.36	0.80	1.02
MnO	0.110	0.03	0.05	0.07	0.09	0.019	0.013
MgO	0.42	0.12	0.62	0.16	4.65	0.00	0.00
CaO	2.20	0.92	2.59	0.83	7.53	0.05	0.11
Na2O	4.56	3.40	0.48	3.19	2.95	2.36	1.92
K2O	3.55	4.97	2.68	5.09	1.34	6.65	4.25
P2O5	0.531	0.027	0.012	0.030	0.207	0.009	0.035
XRF - ppm (unnormalized):							
Ni	4	1	2	2	86	2	1
Cr	2	2	4	2	145	4	3
Sc	14	5	8	6	26	4	5
V	54	6	7	6	188	6	3
Ba	1314	1526	981	1420	729	149	611
Rb	57	105	45	216	14	174	97
Sr	216	88	222	60	270	6	21
Zr	302	191	240	239	121	272	204
Y	55	31	16	44	25	36	39
Nb	19	11	11	12	6	16	11
Ga	21	14	10	15	16	15	10
Cu	5	5	4	11	76	6	10
Zn	143	35	51	56	66	69	34
Pb	11	16	15	17	6	46	12
La	37	28	17	33	11	34	28
Ce	71	54	35	55	31	49	48
Th	6	9	5	11	3	16	7
Nd	38	23	16	25	17	33	28
U	4	3	1	4	2	3	1

A-2b : ICP-MS results

Sample ID	B001C	B005	B010	B013	B014	B015	B022	B025B
Unit	R1	R1	R3	RT	R8	R8	R3	R5
This Study								
ICP-MS data (ppm)								
La	17.71	22.82	25.65	40.68	26.27	26.46	22.59	24.36
Ce	52.60	56.88	56.43	83.11	49.68	47.58	45.36	52.64
Pr	4.77	6.68	6.41	10.79	5.61	5.59	5.65	5.16
Nd	19.54	26.07	25.83	43.39	20.53	20.23	22.83	18.52
Sm	5.00	6.20	6.21	10.26	4.18	4.33	5.54	3.95
Eu	0.31	0.36	1.77	2.07	0.67	0.67	1.31	0.76
Gd	5.45	5.35	5.93	10.40	4.06	4.03	5.61	3.68
Tb	1.07	1.00	1.06	1.86	0.73	0.70	0.98	0.66
Dy	7.52	6.61	6.75	12.45	4.65	4.65	6.36	4.33
Ho	1.74	1.44	1.38	2.62	0.99	0.97	1.34	0.90
Er	5.20	4.21	3.86	7.41	2.92	2.86	3.84	2.64
Tm	0.84	0.70	0.58	1.16	0.47	0.46	0.59	0.42
Yb	5.51	4.71	3.74	7.53	3.14	3.07	3.78	2.78
Lu	0.87	0.74	0.59	1.23	0.50	0.49	0.62	0.43
Ba	103	98	1763	1315	1509	1612	1107	1477
Th	9.69	11.83	8.38	6.34	10.76	10.33	6.57	7.82
Nb	10.79	13.41	11.29	19.03	9.49	9.10	9.39	10.75
Y	37.68	33.21	34.69	66.95	27.70	27.37	35.59	23.84
Hf	6.70	8.28	7.16	9.19	5.17	4.98	5.74	5.78
Ta	0.80	1.03	0.87	1.21	0.91	0.88	0.70	0.90
U	3.68	4.91	2.71	2.56	4.78	4.55	2.88	3.36
Pb	37.02	8.51	13.98	14.13	15.05	14.46	11.67	12.80
Rb	129.8	134.1	51.0	73.6	112.4	107.7	70.9	88.0
Cs	3.29	3.38	1.39	2.79	5.27	5.21	2.59	2.73
Sr	8	6	258	143	98	98	146	85
Sc	1.5	2.2	12.2	3.3	4.1	4.1	9.5	3.1
Zr	210	262	253	357	166	160	212	205

Sample ID	B026	B108	B109	B110A	B110B	B111	B112	B116
Unit	R5	R6	R6	R2	Ba1	Ba2	R3	R6
This Study								
ICP-MS data (ppm)								
La	27.33	25.91	21.21	28.97	11.18	20.70	24.83	27.98
Ce	51.71	45.01	35.61	53.86	21.16	41.66	45.45	52.49
Pr	6.01	5.35	3.72	6.02	3.00	5.54	5.67	6.39
Nd	22.18	19.06	12.91	21.18	12.44	22.70	22.34	23.73
Sm	4.73	3.99	2.52	4.40	3.25	5.07	4.96	5.11
Eu	1.07	0.83	0.72	0.52	0.98	1.60	1.15	0.82
Gd	4.54	3.46	2.20	4.12	3.59	5.00	4.98	4.49
Tb	0.78	0.60	0.40	0.74	0.64	0.78	0.86	0.80
Dy	4.96	3.88	2.64	4.89	4.09	4.82	5.46	4.84
Ho	1.07	0.79	0.56	1.05	0.90	0.96	1.17	0.98
Er	3.07	2.25	1.73	3.03	2.60	2.60	3.36	2.78
Tm	0.49	0.37	0.28	0.50	0.37	0.38	0.51	0.44
Yb	3.27	2.43	1.86	3.29	2.47	2.40	3.33	2.87
Lu	0.52	0.39	0.30	0.53	0.40	0.38	0.53	0.44
Ba	1507	1580	1536	1122	582	1456	1323	1555
Th	6.71	8.96	8.63	12.49	2.67	2.13	6.84	8.72
Nb	11.32	11.46	10.85	10.76	4.62	8.28	9.55	11.20
Y	29.02	20.09	15.57	29.58	23.01	25.60	32.78	24.87
Hf	7.20	5.96	5.93	4.31	2.77	3.45	5.47	5.86
Ta	0.85	1.02	0.93	1.15	0.39	0.52	0.76	0.96
U	2.91	3.33	3.02	5.50	1.02	0.89	3.06	3.32
Pb	14.46	14.75	14.77	16.73	4.42	6.60	11.91	15.05
Rb	80.6	95.7	93.0	124.8	24.3	25.3	76.6	94.5
Cs	2.98	2.62	2.92	5.88	0.98	0.97	3.27	2.33
Sr	163	85	83	55	230	548	240	87
Sc	6.3	5.0	4.9	3.3	28.6	19.7	9.9	4.8
Zr	284	216	208	127	105	141	211	210

Sample ID	B121A	B121B	B126	B129	B138	B144	B146	B147
Unit	R8	R8	RT	R8	R6	R8	R5	R2
This Study								
ICP-MS data (ppm)								
La	25.89	25.97	54.29	25.45	26.52	21.42	25.79	28.73
Ce	48.50	49.31	90.78	47.77	50.95	41.01	44.50	53.52
Pr	5.59	5.55	12.96	5.52	5.47	4.76	5.70	6.00
Nd	19.87	20.18	50.39	19.78	19.74	17.87	20.46	21.23
Sm	3.96	4.22	10.86	4.12	4.13	3.89	4.24	4.45
Eu	0.63	0.63	2.36	0.62	0.80	0.74	0.83	0.52
Gd	3.80	3.90	10.53	3.78	3.70	3.80	4.08	4.12
Tb	0.70	0.71	1.82	0.69	0.67	0.69	0.72	0.74
Dy	4.51	4.43	11.44	4.48	4.11	4.43	4.58	4.82
Ho	0.97	0.98	2.38	0.95	0.87	0.93	0.95	1.04
Er	2.87	2.93	6.79	2.83	2.61	2.82	2.80	3.09
Tm	0.46	0.46	1.01	0.46	0.40	0.44	0.43	0.50
Yb	3.17	3.13	6.36	3.01	2.75	2.90	2.86	3.28
Lu	0.52	0.50	0.99	0.49	0.44	0.47	0.45	0.52
Ba	1479	1482	1572	1436	1552	1406	1394	1138
Th	10.91	11.02	6.88	10.72	8.86	8.48	9.62	12.51
Nb	9.64	9.59	22.22	9.46	10.81	8.32	8.76	10.64
Y	26.81	27.39	63.79	26.85	22.50	26.58	25.75	29.18
Hf	4.91	4.83	9.47	4.79	5.63	4.32	4.66	4.31
Ta	0.92	0.92	1.38	0.91	0.94	0.79	0.84	1.13
U	4.36	4.76	3.18	4.61	3.50	3.58	4.11	5.37
Pb	14.77	14.98	12.89	14.65	15.20	11.44	12.62	16.65
Rb	113.5	113.0	60.6	111.3	98.4	89.9	117.9	125.0
Cs	3.61	5.31	1.54	5.16	3.11	4.82	5.50	5.81
Sr	92	88	108	90	85	148	113	55
Sc	4.0	3.9	6.0	3.6	4.7	6.8	5.9	3.1
Zr	157	156	371	153	192	145	152	126

Sample ID	B148	B153	B155	B156	B158	B159	B160	B161
Unit	R2	(R5)	R4	R4	R4	R5	R5	R5
This Study								
ICP-MS data (ppm)								
La	19.65	21.19	26.86	29.02	21.23	23.97	22.76	23.68
Ce	36.35	32.51	48.12	52.90	46.32	46.86	43.90	43.79
Pr	4.19	4.48	6.17	7.15	4.64	5.58	5.16	5.00
Nd	14.90	16.27	23.21	27.46	17.82	20.54	18.73	18.05
Sm	3.29	3.30	5.19	6.16	4.07	4.30	4.03	3.82
Eu	0.54	0.46	0.93	1.04	0.99	0.92	0.83	0.68
Gd	2.78	2.69	4.75	5.73	3.97	4.04	3.82	3.51
Tb	0.49	0.44	0.86	1.00	0.74	0.72	0.66	0.63
Dy	3.02	2.61	5.49	6.22	4.84	4.57	4.18	4.05
Ho	0.66	0.51	1.17	1.29	1.05	0.98	0.87	0.87
Er	1.84	1.45	3.48	3.63	3.14	2.85	2.48	2.59
Tm	0.30	0.24	0.55	0.55	0.49	0.45	0.39	0.41
Yb	1.88	1.68	3.56	3.56	3.25	2.97	2.58	2.71
Lu	0.31	0.26	0.58	0.54	0.52	0.49	0.42	0.46
Ba	1110	1954	1373	1509	1505	1265	1291	1361
Th	7.94	7.16	11.38	12.81	11.33	8.39	8.66	9.37
Nb	6.95	5.23	11.43	13.04	12.14	8.70	8.03	7.22
Y	17.71	12.54	31.22	32.30	27.53	26.60	23.46	24.31
Hf	3.70	3.23	7.22	8.29	7.83	4.60	4.59	4.66
Ta	0.67	0.59	0.91	1.03	0.95	0.80	0.71	0.67
U	2.89	1.05	4.15	5.13	4.68	3.60	3.58	3.33
Pb	11.83	6.39	17.70	12.90	11.87	12.80	11.03	12.01
Rb	84.8	71.5	99.1	143.0	122.2	122.9	95.9	105.0
Cs	2.82	7.67	4.18	4.50	5.64	12.27	4.00	5.26
Sr	76	451	69	75	75	158	153	98
Sc	2.7	2.6	4.8	6.6	5.9	11.2	10.1	4.6
Zr	121	108	272	311	298	152	153	147

Sample ID	B162	B163	B165	B168	B171	B175	B178	B185
Unit	R6	R6	(R6)	(R6)	R6	R6	R7	R2
This Study								
ICP-MS data (ppm)								
La	30.00	29.93	33.30	16.47	29.14	36.04	17.55	26.01
Ce	53.77	55.15	61.39	32.39	54.94	62.24	38.32	47.53
Pr	6.69	6.36	7.70	4.04	6.45	9.58	4.41	5.47
Nd	24.37	22.95	29.86	15.15	23.71	37.29	17.63	19.36
Sm	5.16	4.84	6.52	3.24	4.94	8.52	4.28	4.18
Eu	0.79	0.81	1.69	0.91	0.92	1.28	0.84	0.46
Gd	4.55	4.53	6.43	3.02	4.57	8.75	4.29	3.78
Tb	0.80	0.83	1.09	0.51	0.81	1.53	0.74	0.69
Dy	5.14	5.41	7.02	3.31	5.34	9.81	4.91	4.60
Ho	1.07	1.15	1.44	0.69	1.13	2.08	1.03	0.98
Er	3.02	3.35	4.04	1.97	3.15	5.84	2.92	2.90
Tm	0.47	0.52	0.62	0.31	0.50	0.90	0.46	0.47
Yb	3.03	3.45	4.04	2.04	3.31	5.76	2.93	3.07
Lu	0.47	0.54	0.64	0.33	0.53	0.90	0.45	0.50
Ba	1603	1567	1476	3876	1530	1466	1709	1051
Th	8.81	9.03	7.08	4.50	8.70	10.93	4.97	11.72
Nb	11.16	10.93	14.09	9.19	9.83	9.11	6.30	9.46
Y	28.69	31.57	38.70	18.72	29.89	55.33	27.38	27.66
Hf	5.75	5.84	6.98	4.38	5.73	6.78	4.57	3.87
Ta	0.95	0.94	1.03	0.67	0.85	0.69	0.49	1.07
U	3.22	3.35	2.78	1.14	3.34	4.76	0.76	4.37
Pb	14.43	14.32	12.97	4.52	14.81	14.29	4.22	15.17
Rb	99.6	99.6	75.3	46.0	91.1	125.2	64.0	106.8
Cs	3.61	3.20	1.67	31.45	2.93	3.55	9.85	5.77
Sr	84	87	181	612	89	57	189	188
Sc	5.2	5.1	9.5	5.0	4.8	6.8	4.9	2.9
Zr	195	198	259	165	193	235	168	111

Sample ID	B191	B352	B354	B355	B356	EJ-03	EJ-04
Unit	RT	R6	R7	R6	Ba1	R1	R6
	This Study					Hess, 2014	
ICP-MS data (ppm)							
La	36.28	28.51	17.61	28.86	13.56	32.04	28.32
Ce	76.71	52.95	36.33	57.23	27.72	47.37	45.70
Pr	9.92	6.20	4.55	6.99	3.59	8.93	7.41
Nd	40.28	22.73	17.88	27.41	15.17	33.59	29.04
Sm	9.42	4.98	4.14	6.25	3.69	7.32	6.68
Eu	2.47	0.75	0.88	1.20	1.20	0.43	1.25
Gd	9.15	4.47	3.54	6.23	4.13	6.03	6.10
Tb	1.55	0.80	0.58	1.14	0.71	1.11	1.12
Dy	9.73	5.32	3.35	7.29	4.45	7.14	7.31
Ho	2.05	1.12	0.64	1.58	0.95	1.51	1.58
Er	5.60	3.29	1.71	4.66	2.62	4.39	4.53
Tm	0.83	0.51	0.24	0.73	0.40	0.68	0.69
Yb	5.40	3.37	1.57	4.72	2.49	4.62	4.42
Lu	0.84	0.55	0.24	0.82	0.39	0.72	0.69
Ba	1340	1555	1011	1434	733	153	627
Th	5.76	8.96	7.25	10.95	3.58	13.00	7.72
Nb	18.98	11.11	10.38	11.46	6.54	9.28	7.60
Y	53.19	30.74	15.14	42.60	24.31	34.19	37.18
Hf	7.86	5.85	6.82	6.95	3.34	8.87	6.14
Ta	1.21	0.97	0.79	0.93	0.52	0.47	0.46
U	2.43	3.88	1.14	5.04	1.27	4.41	2.83
Pb	11.02	15.36	12.65	14.96	5.58	43.86	11.97
Rb	54.8	103.4	43.6	208.8	12.9	178.5	100.6
Cs	2.48	4.54	5.48	5.51	0.92	2.77	3.96
Sr	216	92	232	61	271	8	24
Sc	14.1	5.0	6.2	6.7	25.9	2.6	4.4
Zr	311	196	244	241	123	282	215

A-2c : Analytical error

	B109	B109 replicate	Standard Deviation	Percent Error
XRF- wt% (normalized)				
SiO2	76.36	76.38	0.01	0.03
TiO2	0.182	0.184	0.00	1.22
Al2O3	13.11	13.09	0.02	0.19
FeO*	1.23	1.24	0.01	0.88
MnO	0.008	0.008	0.00	0.69
MgO	0.12	0.11	0.01	11.11
CaO	0.83	0.84	0.00	0.82
Na2O	3.91	3.87	0.03	1.00
K2O	4.22	4.26	0.03	0.85
P2O5	0.016	0.017	0.00	7.58
XRF- ppm (unnormalized):				
Ni	1.1904	1.984	0.56	66.67
Cr	4.7616	3.7696	0.70	20.83
Sc	5.456	5.6544	0.14	3.64
V	13.9872	12.9952	0.70	7.09
Ba	1388.8	1484.2304	67.48	6.87
Rb	91.1648	96.8192	4.00	6.20
Sr	77.376	83.4272	4.28	7.82
Zr	188.2816	200.2848	8.49	6.38
Y	14.6816	16.1696	1.05	10.14
Nb	10.2176	10.7136	0.35	4.85
Ga	13.5904	14.5824	0.70	7.30
Cu	4.0672	4.464	0.28	9.76
Zn	24.8	27.0816	1.61	9.20
Pb	14.4832	16.9632	1.75	17.12
La	17.36	19.6416	1.61	13.14
Ce	29.3632	33.728	3.09	14.86
Th	7.5392	9.1264	1.12	21.05
Nd	10.7136	13.392	1.89	25.00
U	2.2816	2.6784	0.28	17.39

	B109	B109 replicate	Standard Deviation	Percent Error
ICP-MS data (ppm)				
La	21.21	21.50	0.20	1.34
Ce	35.61	36.04	0.30	1.20
Pr	3.72	3.79	0.05	1.87
Nd	12.91	12.93	0.01	0.13
Sm	2.52	2.45	0.05	3.08
Eu	0.72	0.71	0.01	1.67
Gd	2.20	2.26	0.04	2.69
Tb	0.40	0.41	0.01	3.37
Dy	2.64	2.74	0.07	3.83
Ho	0.56	0.58	0.01	2.05
Er	1.73	1.73	0.00	0.06
Tm	0.28	0.28	0.00	0.83
Yb	1.86	1.90	0.03	2.35
Lu	0.30	0.31	0.01	5.04
Ba	1536.09	1534.89	0.84	0.08
Th	8.63	8.63	0.00	0.02
Nb	10.85	10.98	0.09	1.20
Y	15.57	15.55	0.01	0.12
Hf	5.93	6.01	0.06	1.40
Ta	0.93	0.95	0.01	1.60
U	3.02	2.92	0.07	3.10
Pb	14.77	14.66	0.08	0.75
Rb	92.97	93.07	0.07	0.10
Cs	2.92	2.94	0.02	0.74
Sr	82.54	82.53	0.01	0.01
Sc	4.90	5.12	0.16	4.50
Zr	208.27	205.55	1.92	1.30

	B163	B163 replicate	Standard Deviation	Percent Error
XRF- wt% (normalized)				
SiO2	75.82	75.83	0.00	0.00
TiO2	0.183	0.182	0.00	0.68
Al2O3	13.27	13.29	0.02	0.21
FeO*	1.22	1.24	0.01	1.53
MnO	0.015	0.016	0.00	2.36
MgO	0.09	0.08	0.00	3.58
CaO	0.89	0.88	0.00	0.30
Na2O	3.94	3.91	0.02	0.87
K2O	4.56	4.55	0.00	0.12
P2O5	0.022	0.019	0.00	12.69
XRF- ppm (unnormalized):				
Ni	2.1824	3.0752	0.63	40.91
Cr	3.1744	4.5632	0.98	43.75
Sc	5.456	5.2576	0.14	3.64
V	10.2176	10.0192	0.14	1.94
Ba	1511.907	1507.5424	3.09	0.29
Rb	102.8704	104.0608	0.84	1.16
Sr	87.6928	87.792	0.07	0.11
Zr	194.1344	195.1264	0.70	0.51
Y	32.5376	31.6448	0.63	2.74
Nb	11.0112	11.7056	0.49	6.31
Ga	14.7808	14.0864	0.49	4.70
Cu	5.0592	5.0592	0.00	0.00
Zn	31.8432	32.0416	0.14	0.62
Pb	14.5824	14.7808	0.14	1.36
La	28.272	27.6768	0.42	2.11
Ce	49.9968	48.9056	0.77	2.18
Th	9.424	9.5232	0.07	1.05
Nd	20.4352	22.0224	1.12	7.77
U	3.2736	4.464	0.84	36.36

	B163	B163 replicate	Standard Deviation	Percent Error
ICP-MS data (ppm)				
La	29.93	29.32	0.43	2.03
Ce	55.15	54.36	0.56	1.44
Pr	6.36	6.30	0.05	1.02
Nd	22.95	22.76	0.14	0.84
Sm	4.84	4.80	0.02	0.71
Eu	0.81	0.84	0.02	3.91
Gd	4.53	4.43	0.07	2.10
Tb	0.83	0.83	0.01	0.85
Dy	5.41	5.30	0.07	1.96
Ho	1.15	1.15	0.00	0.43
Er	3.35	3.26	0.06	2.68
Tm	0.52	0.51	0.01	1.52
Yb	3.45	3.41	0.03	1.28
Lu	0.54	0.53	0.01	1.56
Ba	1567.25	1550.96	11.51	1.04
Th	9.03	9.03	0.00	0.05
Nb	10.93	10.92	0.01	0.08
Y	31.57	31.27	0.21	0.93
Hf	5.84	5.69	0.10	2.46
Ta	0.94	0.93	0.01	1.26
U	3.35	3.49	0.10	4.35
Pb	14.32	14.29	0.02	0.24
Rb	99.64	99.74	0.07	0.10
Cs	3.20	3.12	0.06	2.53
Sr	87.17	87.27	0.07	0.12
Sc	5.11	5.01	0.07	1.91
Zr	197.67	196.16	1.07	0.77

Appendix A-3 : Sample Locations

Sample ID	Geographic Unit	Unit	Latitude	Longitude	Thinsection	XRF/ICP-MS
B001C	1A	R1	43.645	-118.63		X
B005	1A	R1	43.64	-118.62	X	X
B010	1B	R3	43.639	-118.62	X	X
B013	3F	RT	43.637	-118.61		X
B014	5A	R8	43.637	-118.61		X
B015	5A	R8	43.633	-118.61		X
B022	1B	R3	43.624	-118.62		X
B025B	5B	R5	43.651	-118.53	X	X
B026	5B	R5	43.652	-118.53		X
B108	4A	R6	43.565	-118.52	X	X
B109	4A	R6	43.565	-118.53	X	X
B110A	4B	R2	43.565	-118.53		X
B110B	b4A	Ba1	43.565	-118.53	X	X
B111	b4B	Ba2	43.563	-118.53		X
B112	4C	R3	43.558	-118.53	X	X
B114	4C	R3	43.556	-118.53	X	
B116	4A	R6	43.574	-118.52		X
B121A	3E	R8	43.649	-118.55	X	X
B121B	3E	R8	43.649	-118.55		X
B126	3F	RT	43.645	-118.57		X
B129	3E	R6	43.642	-118.56		X
B131	3E	R8	43.639	-118.56	X	
B138	3D	R6	43.629	-118.56	X	X
B144	3E	R8	43.617	-118.59	X	X
B146	3C	R5	43.615	-118.59		X
B147	3A	R2	43.613	-118.59		X
B148	3A	R2	43.614	-118.59		X

Sample ID	Geographic Unit	Unit	Latitude	Longitude	Thinsection	XRF/ICP-MS
B153	3C	(R5)	43.613	-118.56	X	X
B155	3B	R4	43.614	-118.56	X	X
B156	3B	R4	43.615	-118.57		X
B158	3B	R4	43.616	-118.56		X
B159	3C	R5	43.616	-118.56	X	X
B160	3C	R5	43.617	-118.56		X
B161	3C	R5	43.617	-118.56		X
B162	3D	R6	43.619	-118.56		X
B163	3D	R6	43.619	-118.56	X	X
B165	3D	(R6)	43.625	-118.55	X	X
B168	3D	(R6)	43.627	-118.55	X	X
B171	3D	R6	43.628	-118.55	X	X
B172	3E	R8	43.629	-118.55	X	
B175	3D	R6	43.602	-118.63	X	X
B178	3E	R7	43.606	-118.62	X	X
B185	3A	R2	43.597	-118.6	X	X
B191	3F	RT	43.599	-118.6	X	X
B352	3D	R6	43.619	-118.56		X
B354	2B	R7	43.607	-118.62		X
B355	2A	R6	43.602	-118.62		X
B356	b3B	Ba1	43.616	-118.56		X

Appendix B : Dooley Mountain Rhyolite Complex

Appendix B-1 : Hand Sample Data

Sample Number	Lat.	Long.	Color	Phenocrysts	Size (mm)	Abundance (%)	Other details
28	44.570	-117.83	white/ tan			0	includes medium gray clasts up to 15cm, and vitric white clasts
31	44.569	-117.839	pink	feldspar, quartz	1	1	flow banded
32	44.567	-117.846	white			0	
34A	44.564	-117.849	light gray/ pink			0	flow banded
34B	44.564	-117.849	light gray			0	breccia, white clasts <2cm
34C	44.564	-117.849	med gray			0	breccia, white clasts <1cm
35	44.562	-117.847	med gray	quartz	<1	<1	breccia, white clasts <10cm
36	44.562	-117.848	white	quartz	<1	<1	
37	44.561	-117.848	white			0	
38	44.506	-117.846	medium/ dark gray	feldspar	<1	<1	Basalt, vesiculated
39A	44.506	-117.846	black			0	Vitric
39B	44.506	-117.846	medium gray/ pink	feldspar, amphibole	<1, 1	1	altered red/brown phenocrysts likely amphibole
40	44.559	-117.847	light gray	quartz	<1	<1	
41	44.559	-117.847	white	feldspar, quartz	<1, <1	<1	
42	44.555	-117.851	white			0	
43	44.555	-117.851	white/ light gray	feldspar, quartz	<1, 1	1	breccia, white clasts
44A	44.551	-117.851	light gray			0	breccia, white clasts
44B	44.551	-117.851	white			0	
45	44.549	-117.850	white			0	
46	44.549	-117.849	white			0	
47	44.546	-117.851	white	feldspar, quartz	<1, 1	1	
48	44.547	-117.852	white	feldspar, quartz	<1, 1	1	white clasts
49	44.539	-117.844	white	feldspar, quartz	<1, 1	1	
50	44.533	-117.842	black			0	vitric
51A	44.529	-117.840	black			0	vitric, flow banded glass

Sample Number	Lat.	Long.	Color	Phenocrysts	Size (mm)	Abundance (%)	Other details
51B	44.529	-117.840	light/ medium gray			0	
52	44.522	-117.842	dark gray	feldspar	2	30	Basalt
53	44.516	-117.844	white/ pink	feldspar	1	1	
200	44.580	-117.839	white/ light gray			0	
201	44.585	-117.843	black	feldspar	3	10	
202	44.585	-117.845	light/ medium gray	feldspar	2	5	
204	44.585	-117.848	light gray			0	Tuff dike, pumaceous, white lithics
205	44.586	-117.850	medium/ dark gray	feldspar	2	3	
206	44.589	-117.846	black	feldspar	3	10	vitric
207	44.589	-117.850	white	feldspar, quartz	3, 1	5	
208A	44.612	-117.861	light gray	feldspar	<1	1	ashy, black speckles
208B	44.612	-117.861	light/ medium gray	feldspar	1	1	flow banded blocks within ashy matrix of 208A
209	44.507	-117.845	medium gray	feldspar	<1	<1	
210	44.508	-117.845	medium gray/ pink	feldspar	1	<1	
211	44.508	-117.845	light gray/ green			0	vitric, perlitic
212	44.510	-117.846	light/ medium gray	feldspar	3	5	vitric
213	44.510	-117.847	light gray	feldspar, quartz	2, 1	3	
214	44.512	-117.845	light gray			0	vitric
215	44.514	-117.846	light gray/ pink	feldspar	2	1	
216	44.515	-117.844	light gray/ pink	feldspar	1	1	
217	44.530	-117.838	light gray			0	
218	44.532	-117.837	light gray			0	vitric, black speckles
219	44.532	-117.837	light gray/ tan	feldspar	2	2	
220	44.533	-117.837	medium gray	feldspar	3	15	
221	44.560	-117.841	white			0	

Sample Number	Lat.	Long.	Color	Phenocrysts	Size (mm)	Abundance (%)	Other details
222	44.556	-117.828	white/ light gray			0	
223	44.575	-117.821	light gray/ pink			0	
224	44.578	-117.819	medium gray	feldspar, amphibole	3, 2	10	altered red/brown phenocrysts likely amphibole
225	44.576	-117.822	black			0	obsidian, weathering to shards
226	44.568	-117.849	medium/ dark gray	quartz	<1	1	spherulites to 2cm
227	44.562	-117.852	white			0	
228	44.563	-117.860	white			0	breccia, white clasts of similar material, dark gray clasts with 8% 3mm feldspar
229	44.560	-117.858	light/ medium gray	feldspar	3	3	
230	44.558	-117.849	light gray			0	white clasts
231	44.578	-117.860	light gray			0	white clasts and spherulites
232	44.540	-117.861	tan			0	microlite groundmass, vesiculated
233	44.535	-117.859	light gray/ lavender			0	flow banded clasts
234	44.533	-117.856	black	feldspar	3	5	vitric
235	44.547	-117.866	dark gray	feldspar, amphibole	2, 1	3	altered red/ brown phenocrysts likely amphibole
236A	44.525	-117.861	red/ brown			0	
236B	44.525	-117.861	tan/ orange			0	
237	44.527	-117.862	black			0	obsidian
238	44.575	-117.822	black			0	obsidian
239	44.579	-117.819	medium gray	feldspar, amphibole	2, 1	5	
240	44.580	-117.812	medium gray/pink	feldspar	3	10	
241	44.580	-117.811	black	feldspar	3	5	vitric

Sample Number	Lat.	Long.	Color	Phenocrysts	Size (mm)	Abundance (%)	Other details
244	44.607	-117.801	light gray			0	flow banded
246A	44.613	-117.799	light gray	feldspar	2	2	Tuff, 5% dark gray lithics <2mm
246B	44.613	-117.799	light tan	feldspar	2	1	Tuff, 5% dark gray lithics <2mm
247	44.585	-117.795	light gray			0	ashy
249	44.547	-117.831	white/ pink			0	
250	44.544	-117.821	black	feldspar	3	10	vitric
251	44.545	-117.820	white	feldspar, quartz	1, 1	1	
252	44.551	-117.818	black	feldspar	3	10	
253	44.573	-117.812	white/ pink	feldspar	3	3	
254	44.526	-117.802	medium gray			0	Burnt River schist
255A	44.527	-117.802	dark gray	feldspar, olivine	2, 1	3	Basalt
255B	44.527	-117.802	dark gray/ black	feldspar	10	15	Basalt
256	44.527	-117.802	Black/ dark gray	feldspar	2	2	Welded tuff, vitric, lithics 1cm, pumice/fiame upto 5cm
258	44.528	-117.802	medium gray			0	vitric
259	44.529	-117.802	light gray/ medium gray			0	
260	44.522	-117.842	dark gray	feldspar, olivine	4, 1	15	Basalt
261	44.504	-117.844	dark gray	feldspar, olivine	2, 3	5	Basalt, fragments of Burnt River schist
262	44.508	-117.808	light gray/ medium gray	feldspar	1	1	
263	44.510	-117.811	medium gray	feldspar, amphibole	3, 2	5	contains altered red/brown phenocrysts likely amphibole

Sample Number	Lat.	Long.	Color	Phenocrysts	Size (mm)	Abundance (%)	Other details
264	44.510	-117.811	light gray	feldspar, amphibole	3, 1	5	altered red/brown phenocrysts likely amphibole
265A	44.511	-117.813	black	feldspar, amphibole	3, 2	5	top breccia, contains altered red/brown phenocrysts likely amphibole
265Ash	44.511	-117.813	medium gray/brown	feldspar	1	1	ash fall, contains 2cm obsidian clasts
265Lapilli	44.511	-117.813	medium gray/brown	feldspar	1	1	lapilli fall, contains pumice to 2 cm and obsidian to 5mm
265B	44.511	-117.813	medium gray	feldspar	3	1	bottom breccia
266	44.511	-117.815	light gray/pink	feldspar	2	5	
267	44.525	-117.815	white			0	microlite groundmass
268	44.525	-117.815	medium gray			0	
269	44.525	-117.815	tan	feldspar	1	1	tuff, lithics up to 4mm
270	44.525	-117.815	dark gray	feldspar	2	1	tuff, lithics up to 5mm, fiamme up to 3cm
271	44.516	-117.821	dark gray	feldspar	3	10	vitric
272	44.556	-117.919	light gray	feldspar	1	1	
273A	44.557	-117.918	medium gray	feldspar	3	10	
273B	44.557	-117.918	brown gray			0	tuff, pumice up to 2cm and obsidian clasts up to 2cm
274	44.554	-117.916	dark gray	feldspar	2	5	tuff, pumice 2cm obsidian 2cm
276	44.506	-117.913	light gray	feldspar	1	2	tuff, lithics up to 1cm

Appendix B-2 : Petrographic Data

Unit	Sample	Total Phenocryst Abundance (%)	Major Phases	Size (µm)	Phase Abundance (%)	Phase characteristics	General Texture
3	DM047	1	Qz	50-400	<1	Sub-euhedral, fractured	Devitrified, porphyritic
			Afs	100-300	<1	Sub-euhedral, no twinning	
3	DM048	1	Qz	100-200	<1	Sub-euhedral, fractured	Devitrified, porphyritic, brecciated
			Afs	100-300	<1	Eu-subhedral, no twinning, perfect cleavage,	
4	DM202	8	Plag	200-2000	8	Euhedral-subhedral, poly-synthetic and simple twinning, undulatory extinction	Vitric groundmas, porphyritic
			Afs	200-500	<1	sub-anhedral, no twinning, perfect cleavage	
2	DM213	5	Plag	200-2000	5	Eu-subhedral, poly-synthetic and simple twinning, undulatory extinction	Devitrified, porphyritic
			Afs	200-500	<1	Sub-abhedral, no twinning, perfect cleavage	
2	DM215	3	Plag	200-1000	3	Eu-subhedral, poly-synthetic and simple twinning, undulatory extinction	Devitrified, porphyritic, thin flow bands
			Afs	200-500	<1		
4	DM220	3	Plag	200-2000	3	Euhedral, poly-synthetic and simple twinning. Mostly tabular habit.	Devitrified, porphyritic
3	DM223	<1	Qz	50-100	<1	Sub-euhedral, fractured	Devitrified, small spherulites, flow banded, aphanitic

Unit	Sample	Total Phenocryst Abundance (%)	Major Phases	Size (μm)	Phase Abundance (%)	Phase characteristics	General Texture
3	DM229	1	Qz	50-300	<1	An-subhedral, no twinning	Devitrified, porphyritic
			Afs	100-500	<1	An-subhedral, no twinning, perfect cleavage	
			Plag	500-2000	<1	Euhedral, poly-synthetic and simple twinning. Mostly tabular habit	
3	DM239	10	Plag	200-2000	8	Eu-subhedral, poly-synthetic and simple twinning, undulatory extinction	Devitrified, no flow banding, porphyritic, speckled groundmass
			Afs	200-2000	2	Sub-anhedral, no twinning, perfect cleavage	
4	DM240	10	Plag	200-2000	10	Eu-subhedral, poly-synthetic and simple twinning, undulatory extinction	Vitric, minor flow banding, porphyritic
4	DM244	0	N/A	N/A	N/A	N/A	Devitrified, aphanitic, secondary quartz
1	DM251	1	Plag		<1	Eu-subhedral, poly-synthetic and simple twinning	Devitrified, porphyritic
			Afs		<1	Sub-anhedral, no twinning, perfect cleavage	
			Qz		<1	Eu-subhedral, fractured	
6	DM256	5	Plag	200-2000	5	Euhedral, poly-synthetic and simple twinning, undulatory extinction, many broken shards	Tuffaceous, vitric, porphyritic, many fiamme, no lithic fragments

Unit	Sample	Total Phenocryst Abundance (%)	Major Phases	Size (µm)	Phase Abundance (%)	Phase characteristics	General Texture
1	DM258	0	N/A	N/A	N/A	N/A	Vitric, minor perlitic texture, aphanitic
1	DM259	0	N/A	N/A	N/A	N/A	Devitrified, spherulitic groundmass, flow banded, aphanitic
3	DM264	5	Plag	50-2000	4	Eu-subhedral, poly-synthetic and simple twinning, undulatory extinction	Devitrified, porphyritic, minor flow banding
			Amp	200-1000	1	Eu-subhedral, prismatic, dark brown	
5	DM269	3	Plag	50-1000		Eu-subhedral, poly-synthetic and simple twinning, some broken shards	Tuffaceous, glass shards, lithic fragments

Appendix B-3 : Geochemical Data

B-3a : XRF results

Sample ID	DM038	DM044 B	DM048	DM202	DM220	DM223	DM234	DM235
Unit	B2	R4	R4	R3	R3	R4	R2	R2
This Study								
XRF - wt% (normalized)								
SiO ₂	53.58	83.48	81.03	76.55	76.37	77.43	77.65	76.72
TiO ₂	0.87	0.14	0.19	0.34	0.28	0.16	0.12	0.11
Al ₂ O ₃	17.25	12.38	14.11	13.47	13.50	12.83	13.37	13.00
FeO*	7.56	0.64	0.50	0.62	1.42	1.23	1.08	1.33
MnO	0.135	0.008	0.003	0.004	0.009	0.008	0.032	0.031
MgO	6.70	0.08	0.04	0.01	0.03	0.01	0.03	0.05
CaO	10.38	0.03	0.03	1.32	1.40	0.80	1.21	0.92
Na ₂ O	2.80	0.01	0.20	3.87	3.28	3.78	2.38	3.66
K ₂ O	0.50	3.22	3.88	3.80	3.69	3.74	4.10	4.16
P ₂ O ₅	0.228	0.013	0.014	0.017	0.023	0.016	0.015	0.014
XRF - ppm (unnormalized):								
Ni	62	0	3	2	2	1	1	4
Cr	229	3	3	3	2	3	3	16
Sc	32	5	6	8	9	3	4	4
V	216	3	5	6	8	4	4	4
Ba	339	2725	1523	1840	1331	1516	1705	1677
Rb	8	86	101	97	89	95	116	98
Sr	386	9	27	169	137	108	123	96
Zr	85	222	326	382	346	284	173	180
Y	24	55	39	52	55	51	36	30
Nb	4.7	14.0	16.0	16.1	14.1	15.2	9.4	10.2
Ga	16	20	21	21	20	21	16	18
Cu	27	0	0	6	6	3	2	4
Zn	76	2	13	82	107	90	48	68
Pb	1	3	2	15	15	16	17	17
La	11	37	39	45	38	60	40	37
Ce	24	60	82	86	76	66	75	69
Th	1	10	9	9	7	8	8	9
Nd	13	31	38	46	39	65	30	31
U	1	3	3	3	2	3	3	2

Sample ID	DM238	DM240	DM241	DM246 A	DM247	DM250	DM255 A	DM255 B
	R4	R3	R3	T1	R1	R3	B3	B1
	This Study							
XRF - wt% (normalized)								
SiO2	76.52	75.09	74.13	80.23	76.02	74.62	49.89	50.02
TiO2	0.15	0.29	0.28	0.19	0.06	0.28	1.67	0.99
Al2O3	12.42	13.86	13.34	10.97	14.06	13.73	15.07	17.18
FeO*	2.00	1.33	2.73	1.26	0.83	2.10	8.77	9.97
MnO	0.037	0.018	0.045	0.007	0.036	0.023	0.174	0.173
MgO	0.04	0.04	0.19	0.10	0.09	0.07	8.27	7.53
CaO	1.12	1.50	1.59	0.45	0.70	1.49	9.60	11.00
Na2O	4.02	4.11	3.84	3.45	3.25	3.57	4.32	2.50
K2O	3.67	3.73	3.81	3.32	4.95	4.07	1.37	0.44
P2O5	0.013	0.046	0.047	0.021	0.015	0.036	0.869	0.178
XRF - ppm (unnormalized):								
Ni	1	3	2	2	2	3	188	57
Cr	3	8	3	5	3	3	285	88
Sc	4	8	7	4	4	7	21	32
V	3	13	12	15	3	10	210	241
Ba	1485	1343	1279	1201	667	1286	920	231
Rb	94	94	90	67	121	92	19	8
Sr	113	149	134	38	39	144	1626	314
Zr	274	319	297	378	85	298	172	60
Y	59	49	46	82	34	48	20	24
Nb	15.1	13.8	12.9	21.3	10.5	12.5	13.5	3.6
Ga	20	21	19	18	16	20	20	16
Cu	3	4	4	3	1	6	64	35
Zn	119	109	83	124	38	202	113	92
Pb	15	16	14	14	18	14	8	1
La	40	39	37	36	27	37	44	7
Ce	74	69	65	68	46	68	93	18
Th	7	8	8	7	10	8	5	1
Nd	40	33	33	38	20	33	48	11
U	4	3	3	4	4	3	3	0

Sample ID	DM256	DM258	DM260	DM264	DM265 A	DM265	DM265 B	DM269
	T3	R1	B1	R4	R4	R4	R4	T2
This Study								
XRF - wt% (normalized)								
SiO2	69.65	76.69	50.63	75.65	75.69	73.97	75.65	76.20
TiO2	0.57	0.05	0.95	0.19	0.19	0.21	0.17	0.28
Al2O3	14.18	13.59	17.68	13.15	12.78	13.25	12.71	12.48
FeO*	4.81	0.95	11.22	2.21	2.18	3.09	2.06	2.86
MnO	0.095	0.044	0.245	0.012	0.031	0.039	0.029	0.023
MgO	0.40	0.04	4.62	0.07	0.11	0.23	0.11	0.31
CaO	2.41	0.68	11.63	0.97	1.09	1.37	1.35	0.76
Na2O	3.30	3.12	2.58	3.72	3.26	3.19	3.35	3.05
K2O	4.41	4.83	0.29	3.99	4.65	4.61	4.56	4.00
P2O5	0.170	0.013	0.142	0.029	0.024	0.051	0.025	0.034
XRF - ppm (unnormalized):								
Ni	4	2	48	4	2	2	1	4
Cr	3	2	88	3	2	6	2	3
Sc	12	4	33	5	6	4	3	5
V	34	2	239	8	7	5	6	14
Ba	1063	591	173	1419	1354	1395	1508	1344
Rb	73	125	6	103	101	103	102	64
Sr	189	34	251	101	116	100	105	86
Zr	299	76	51	270	271	264	238	358
Y	71	36	23	38	51	47	51	61
Nb	13.1	9.8	2.9	13.7	14.0	13.2	13.3	20.8
Ga	20	17	17	19	20	19	19	20
Cu	3	0	35	4	6	4	3	2
Zn	162	40	86	72	101	83	74	120
Pb	12	17	2	15	14	14	14	15
La	32	23	9	35	40	37	37	39
Ce	62	44	16	54	75	73	74	70
Th	6	9	1	8	9	7	8	6
Nd	37	18	10	30	37	35	35	36
U	3	3	0	2	5	3	3	3

Sample ID	DM273A	DR2	DR4	MS-11-					
				22DR	EJ-23A	EJ-23B			
				R4	R3	R1	R4	R2	R1
				This Study	Streck			Hess (2014)	
XRF - wt% (normalized)									
SiO2	75.89	73.91	76.44	76.84	76.72	76.90			
TiO2	0.20	0.33	0.05	0.17	0.12	0.05			
Al2O3	13.76	14.11	13.46	13.90	13.03	13.34			
FeO*	1.27	2.08	0.84	1.31	1.38	1.17			
MnO	0.023	0.037	0.042	0.027	0.033	0.044			
MgO	0.01	0.03	0.03	0.06	0.03	0.03			
CaO	1.34	2.08	0.68	0.84	1.05	0.69			
Na2O	3.24	3.78	3.18	2.57	3.12	2.90			
K2O	4.26	3.62	5.26	4.26	4.50	4.86			
P2O5	0.012	0.032	0.016	0.020	0.013	0.015			
XRF - ppm (unnormalized):									
Ni	2	0	0	1	0	0			
Cr	3	2	1	2	4	3			
Sc	7	11	4	5	3	3			
V	5	6	2	6	5	1			
Ba	1577	1480	593	1281	1597	580			
Rb	91	77	130	96	93	122			
Sr	137	193	34	64	91	33			
Zr	320	363	72	210	170	73			
Y	53	46	35	49	37	35			
Nb	12.7	14.1	9.3	11.3	10.0	10.7			
Ga	20	20	16	19	17	16			
Cu	2	3	0	2	1	0			
Zn	71	84	38	66	61	40			
Pb	15	13	16	15	14	17			
La	38	36	22	37	33	21			
Ce	74	68	39	78	62	44			
Th	8	9	11	9	8	10			
Nd	38	33	17	38	28	19			
U	4	4	4	5	2	4			

B-3b : ICP-MS results

Sample ID	DM038	DM044 B	DM048	DM202	DM220	DM223	DM234	DM235
Unit	B2	R4	R4	R3	R3	R4	R2	R2
This Study								
ICP-MS - ppm								
La	11.87	33.92	42.25	45.38	41.83	61.22	40.40	40.36
Ce	24.74	64.53	87.46	89.53	81.12	74.31	78.94	75.52
Pr	3.45	8.19	10.83	11.72	10.48	17.30	9.22	8.72
Nd	14.81	31.51	42.33	45.97	41.08	67.67	33.32	32.21
Sm	3.75	7.05	9.28	10.57	9.32	14.83	7.03	6.57
Eu	1.16	0.69	1.24	1.62	1.36	1.91	0.85	0.83
Gd	3.78	7.18	8.29	9.63	8.76	11.58	6.26	5.51
Tb	0.64	1.30	1.33	1.61	1.55	1.93	1.09	0.94
Dy	4.15	8.40	7.61	9.99	9.79	11.10	6.77	5.78
Ho	0.86	1.83	1.55	2.03	2.05	2.12	1.36	1.18
Er	2.43	5.31	4.38	5.65	5.62	5.68	3.77	3.44
Tm	0.34	0.80	0.69	0.84	0.87	0.85	0.57	0.54
Yb	2.22	5.10	4.59	5.27	5.52	5.42	3.57	3.49
Lu	0.36	0.80	0.74	0.79	0.86	0.82	0.58	0.55
Ba	338	2798	1594	1906	1362	1556	1756	1733
Th	0.98	9.89	8.61	8.17	7.33	8.14	8.34	8.96
Nb	4.88	13.04	12.77	16.28	14.19	15.06	8.71	8.95
Y	22.39	52.35	38.17	52.04	53.19	50.30	35.28	30.57
Hf	2.26	6.79	8.78	9.73	8.66	7.89	5.18	5.41
Ta	0.29	1.01	0.95	1.11	0.98	1.05	0.73	0.78
U	0.36	3.58	3.21	3.10	2.97	3.29	3.03	3.22
Pb	2.68	1.92	2.04	14.35	13.43	15.47	16.28	14.98
Rb	7.20	81.80	96.93	93.47	85.61	92.45	111.27	93.96
Cs	0.27	1.35	2.37	4.37	4.33	2.88	6.15	2.42
Sr	385	10	27	170	135	106	123	95
Sc	31.22	4.70	5.77	8.28	8.89	3.68	3.37	3.59
Zr	88	223	331	389	352	288	175	184

Sample ID	DM238	DM240	DM241	DM246	DM247	DM250	DM255	DM255
	R4	R3	R3	A	R1	R3	A	B
	This Study							
ICP-MS - ppm								
La	39.61	39.29	37.14	37.17	24.65	35.85	45.35	6.91
Ce	82.71	75.05	73.79	76.82	48.68	70.05	97.56	15.89
Pr	10.46	9.89	9.23	9.92	5.49	8.68	12.60	2.30
Nd	40.82	37.90	35.26	39.62	19.72	33.36	49.60	10.20
Sm	9.51	8.22	7.93	9.76	4.60	7.09	8.73	2.86
Eu	1.36	1.22	1.12	1.50	0.26	1.11	2.29	0.96
Gd	9.01	7.81	7.24	10.07	4.68	7.07	6.27	3.37
Tb	1.62	1.36	1.25	1.95	0.87	1.24	0.81	0.61
Dy	10.41	8.47	8.07	13.27	5.64	7.90	4.30	4.14
Ho	2.21	1.76	1.69	3.00	1.17	1.71	0.79	0.90
Er	6.11	5.01	4.83	8.97	3.35	4.85	2.00	2.45
Tm	0.93	0.76	0.73	1.38	0.52	0.74	0.27	0.38
Yb	5.92	4.73	4.64	9.15	3.35	4.68	1.64	2.26
Lu	0.90	0.74	0.72	1.49	0.51	0.76	0.27	0.38
Ba	1518	1364	1327	1238	690	1325	922	231
Th	7.84	7.94	7.64	6.85	9.84	7.54	3.51	0.60
Nb	14.91	13.69	12.92	20.39	8.94	12.08	13.54	3.76
Y	57.38	47.27	45.55	80.25	33.47	47.78	20.86	22.53
Hf	7.71	8.15	7.71	10.08	3.48	7.81	4.14	1.63
Ta	1.10	0.98	0.95	1.25	1.03	0.87	0.72	0.23
U	3.10	3.20	3.02	3.01	3.93	3.03	1.15	0.21
Pb	14.43	14.10	13.67	12.54	17.35	13.65	8.65	1.34
Rb	89.47	89.66	86.67	64.10	115.45	87.50	16.45	6.67
Cs	4.10	2.93	4.22	2.38	4.77	4.60	0.95	0.16
Sr	111	146	135	38	40	145	1611	319
Sc	3.63	6.47	7.08	3.93	3.41	7.01	20.29	32.68
Zr	275	321	307	387	87	303	174	60

Sample ID	DM256	DM258	DM260	DM264	DM265	DM265	DM265	DM269
	T3	R1	B1	R4	A R4	R4	B R4	T2
	This Study							
ICP-MS - ppm								
La	35.17	23.01	5.11	36.72	38.58	40.85	39.74	39.37
Ce	66.20	45.36	12.04	59.03	77.14	81.33	80.49	74.93
Pr	9.23	5.32	1.77	8.83	9.30	9.96	9.67	9.96
Nd	38.58	19.09	8.44	33.69	35.87	38.40	37.04	38.90
Sm	9.21	4.55	2.46	7.23	7.74	8.50	8.01	8.82
Eu	2.04	0.23	0.92	1.06	0.88	1.07	0.90	1.97
Gd	10.28	4.78	3.25	6.85	7.60	8.02	7.76	8.83
Tb	1.80	0.90	0.60	1.16	1.31	1.43	1.38	1.61
Dy	11.84	5.93	4.10	7.25	8.30	8.93	8.87	10.41
Ho	2.61	1.24	0.89	1.51	1.76	1.90	1.89	2.25
Er	7.37	3.52	2.56	4.19	5.03	5.37	5.29	6.47
Tm	1.09	0.55	0.38	0.64	0.74	0.80	0.81	1.00
Yb	6.70	3.50	2.34	4.10	4.77	5.14	5.09	6.45
Lu	1.10	0.54	0.39	0.65	0.76	0.84	0.81	1.05
Ba	1093	614	171	1460	1443	1398	1559	1392
Th	6.13	9.57	0.44	8.79	8.59	8.83	8.71	6.72
Nb	13.75	10.01	3.20	13.24	13.08	13.42	12.88	19.75
Y	71.37	35.36	23.02	37.92	46.41	49.69	49.51	60.02
Hf	8.10	3.28	1.49	7.38	7.37	7.69	7.01	9.26
Ta	0.88	1.14	0.21	1.01	0.99	1.04	1.01	1.26
U	2.99	4.13	0.15	2.76	3.39	3.90	3.47	2.61
Pb	12.30	17.03	0.93	14.32	14.97	15.48	14.78	13.53
Rb	71.26	121.57	5.09	98.55	99.89	96.45	101.59	61.59
Cs	2.90	4.92	0.43	3.41	4.88	5.92	5.23	1.02
Sr	190	35	255	99	99	114	105	85
Sc	13.11	3.45	33.06	4.84	4.32	5.76	4.11	4.11
Zr	310	78	53	263	269	272	241	362

Sample ID	DM273A	DR2	DR4	MS-11- 22DR	EJ-23A	EJ-23B
	R4	R3	R1	R4	R2	R1
	This Study	Streck			Hess (2014)	
	ICP-MS - ppm					
La	39.71	35.07	23.08	40.20	36.35	22.69
Ce	76.76	70.32	44.84	83.81	69.29	44.39
Pr	9.62	8.77	5.27	10.54	8.06	5.19
Nd	37.12	34.54	19.07	39.94	29.18	18.85
Sm	8.21	7.79	4.59	8.67	5.98	4.53
Eu	1.46	1.58	0.24	0.83	0.79	0.23
Gd	8.27	7.51	4.72	8.02	5.61	4.66
Tb	1.46	1.29	0.88	1.40	0.98	0.87
Dy	9.17	8.23	5.71	8.82	6.14	5.69
Ho	1.96	1.71	1.21	1.84	1.29	1.20
Er	5.56	4.91	3.50	5.13	3.70	3.39
Tm	0.86	0.75	0.53	0.78	0.56	0.52
Yb	5.46	4.78	3.42	5.01	3.61	3.36
Lu	0.89	0.75	0.53	0.81	0.57	0.52
Ba	1644	1523	614	1323	1626	589
Th	8.01	6.83	9.28	8.98	8.52	9.43
Nb	11.98	13.76	9.50	10.91	9.61	9.49
Y	52.58	45.47	34.36	48.25	35.11	33.87
Hf	8.10	8.80	3.17	6.37	5.14	3.19
Ta	0.89	0.90	1.08	0.88	0.79	1.07
U	3.13	2.73	3.97	3.50	3.11	4.00
Pb	14.31	13.19	16.54	14.09	14.88	16.07
Rb	88.35	77.46	130.65	99.65	93.23	122.45
Cs	3.55	3.46	5.07	4.92	3.87	6.01
Sr	137	192	34	68	96	37
Sc	6.43	11.32	3.32	4.67	3.41	3.14
Zr	323	375	75	216	172	75

B-3c : Multi-element diagrams

Figure A1: Multi-element diagram of average geochemical group R1 (light blue) in comparison to within group samples (dark gray). Concentrations normalized to mantle values of Sun and McDonough (1989).

Figure A2: Multi-element diagram of average geochemical group R2 (yellow) in comparison to within group samples (dark gray). Concentrations normalized to mantle values of Sun and McDonough (1989).

Figure A3: Multi-element diagram of average geochemical group R3 (red) in comparison to within group samples (dark gray). Concentrations normalized to mantle values of Sun and McDonough (1989).

Figure A4: Multi-element diagram of average geochemical group R4 (green) in comparison to within group samples (dark gray). Outlying samples with depleted Sr and Pb are samples DM044B and DM048. Concentrations normalized to mantle values of Sun and McDonough (1989).