

AN ABSTRACT OF THE THESIS OF

Henri J Sanville for the degree of Master of Science in Geology presented on December 10, 2015.

Title: The Hampton Tuff, High Lava Plains, Oregon:
Implications for Westward Migrating Silicic Volcanism

Abstract approved:

Anita L. Grunder

The Hampton Tuff is a $3.9 \pm .02$ Ma (2σ) ignimbrite sheet from the High Lava Plains of central Oregon. The majority of known outcrops exist to the north, within ~22 mi (~35 km) of the Frederick Butte Volcanic Center, the proposed source of the tuff. Thickness of the tuff is typically ~8 m (~25 ft), but varies from 6.5 m (20 ft) up to ~46 m (150 ft). In nearly all cases, these are minimum thicknesses as the bases of outcrops are rarely exposed and the tops are eroded. Assuming a constant thickness of 8 m and a defined area of 2418 km², the estimated eruption volume is ~20 km³, dense rock equivalent (DRE). Welding facies varies from nonwelded with pumice to densely welded with fiamme.

Westward migration of bimodal volcanism of the High Lava Plains consists mainly of rhyolitic domes, ignimbrites and ash-flow sheets, and is associated with widespread tholeiitic basalt. Ignimbrites represent the dominant volume of erupted high-silica rhyolite in this region and include the Devine Canyon Tuff (9.7 Ma), the Prater Creek Tuff (8.4 Ma), and the Rattlesnake Tuff (7.1 Ma); each of which represents 100–300 km³ of erupted material. A westward younging trend of rhyolitic volcanism of the High Lava Plains represents a coarse mirror of the northeast trending Yellowstone hotspot track from ~12 Ma to present. The Hampton Tuff is the youngest and westernmost tuff of the mapped ignimbrites within this westward younging trend. Although less voluminous than other High Lava Plains ignimbrites, the Hampton Tuff bears the high-iron signature (up to 3.9 wt% FeO*) that is characteristic of regional rhyolites and sparse dacites (up to 6.4 wt% FeO*). Microprobe analysis of glass shards from the Hampton Tuff indicates at least four compositional clusters with distinct ranges of silica that vary inversely with iron content. Although silica content of rhyolite compositions range from 73–77.5 wt% SiO₂ only ~25% of analyses are high-silica rhyolite (>75 wt% SiO₂), suggesting that the magma chamber is an example of “arrested development” of a magmatic system that could evolve more voluminous high-silica rhyolite like the Rattlesnake Tuff, given the opportunity to stage in the crust and enough thermal input.

Field mapping and new ⁴⁰Ar/³⁹Ar age dates correlate units previously mapped as the Tuff of Espeland Draw by Johnson (1998), the ash-flow tuff west of Hampton Butte (Walker, 1970) and the Hampton Tuff of Iademarco (2009); also included are outcrops previously considered to be the Buckaroo Lake tuff by Streck (unpublished

data). Field mapping also leads to the exclusion of several outcrops near Wagontire Mountain thought to be the Hampton Tuff and (or) the Tuff of Buckaroo Lake (MacLean, 1994). Major element analysis of the Buckaroo Lake tuff (6.85 Ma), sample HP-91-9, (Jordan, et al., 2004), confirms that the Buckaroo Lake tuff and the Hampton Tuff have distinct geochemical compositions.

Presented herein is the discovery of a previously unknown ignimbrite of the High Lava Plains. The ignimbrite is informally named the Potato Lake tuff. It has an age of 5.13 ± 0.02 Ma (2σ) and has a chemical composition that is distinct from the Hampton Tuff, as well as the Buckaroo Lake tuff. Chemical analysis, outcrop descriptions, and age data are presented.

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The Hampton Tuff, High Lava Plains, Oregon:
Implications for Westward Migrating Silicic Volcanism

by
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I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Henri J Sanville, Author

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Photographs, figures, and tables are my own work unless otherwise noted.

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The Hampton Tuff, High Lava Plains, Oregon:
Implications for Westward Migrating Silicic Volcanism

Chapter 1 Introduction

1.1 The Hampton Tuff - overview

The Hampton tuff is a 3.9 ± 0.02 m.y. (2σ) ignimbrite that is associated with the westward migration of silicic magmatism across central Oregon (Fig. 1) (Jordan, et al., 2004). Ignimbrites represent the dominant volume of erupted high silica rhyolite along the High Lava Plains of central Oregon, and include several ash-flow tuffs that vary from less than 100 km^3 to about 300 km^3 of erupted material. The Hampton Tuff lies at the northern limit of regional extension of the Northwest Basin and Range Province where N-NE striking normal faults diminish to the north merge into NW striking normal faults of low relief across the High Lava Plains. Late Tertiary and Quaternary basaltic lava flows cover much of the topography surrounding the Frederick Butte Volcanic Center, the inferred source of the Hampton Tuff (Figure 1.1) (Walker, 1981; Johnson, 1998). The low relief on fault blocks and younger volcanic cover make mapping a challenge.

The variably welded Hampton Tuff shares the high-iron ($0.38 - 6.4 \text{ FeO}^*$ wt %) signature that is characteristic of High Lava Plains rhyolites. However the tuff is smaller in volume and generally less evolved, having a lower component of high-silica rhyolite ($>75 \text{ wt\%}$). This suggests that the magma was on a trend capable of producing a high-silica rhyolite, but did not.

The Hampton Tuff includes the Tuff of Espeland Draw mapped by Johnson, 1998, the Hampton Tuff of Walker, 1981, and Iademarco, 2009, and possibly several smaller unnamed units described by Maclean, 1994, and MacLeod et al., 1975.

Frederick Butte, a dacitic to rhyolitic dome complex, is the inferred origin of the

Hampton Tuff (Walker, 1981; Johnson, 1998), but it is largely covered by younger basaltic-andesite of the High Lava Plains. The smaller volume (a few 10s of km³) of the Hampton Tuff suggests that the intensity of magmatism is waning in time along the trend of westward-younging volcanism of the High Lava Plains.

G.W. Walker published an age obtained from plagioclase using the K-Ar method in 1974, which was later recalculated and published by Fiebelkorn in 1982 and yielded an age of 3.7 ± 0.2 m.y. Walker's sample was collected ~13.5 miles NE (~N30°E), respectively, of the Frederick Butte Volcanic Center (Figure 2.3). A sample collected and dated by Mike Iademarco (2009) was obtained ~14.5 miles NE (~N55°W) of Frederick Butte and yielded an age of 3.8 ± 0.16 Ma, leading him to correlate that outcrop with the Hampton Tuff.

Although relatively crystal-poor, phenocrysts of the Hampton Tuff include plagioclase, quartz, orthopyroxene, clinopyroxene and Fe-Ti oxides (Johnson, 1998; Iademarco, 2009). Conflicting reports of mineral content also include fayalite olivine (Tucker et al. 2011) and sanidine (MacLean, 1994; Iademarco, 2009).

Table 1 Table of phenocrysts reported by previous workers. Plagioclase feldspar is the only mineral consistently documented.

Author	Plagioclase	Sanidine	Quartz	Orthopyroxene	Clinopyroxene	Olivine
Ford, 2012	x					
Iademarco, 2009	x	x	x	x (enstatite)		
Johnson, 1998	x		x		x	x
MacLean, 1994	x	x				
Tucker, 2011	x	x	x	x (ferrosilite)	x (hedenbergite)	x (fayalite)

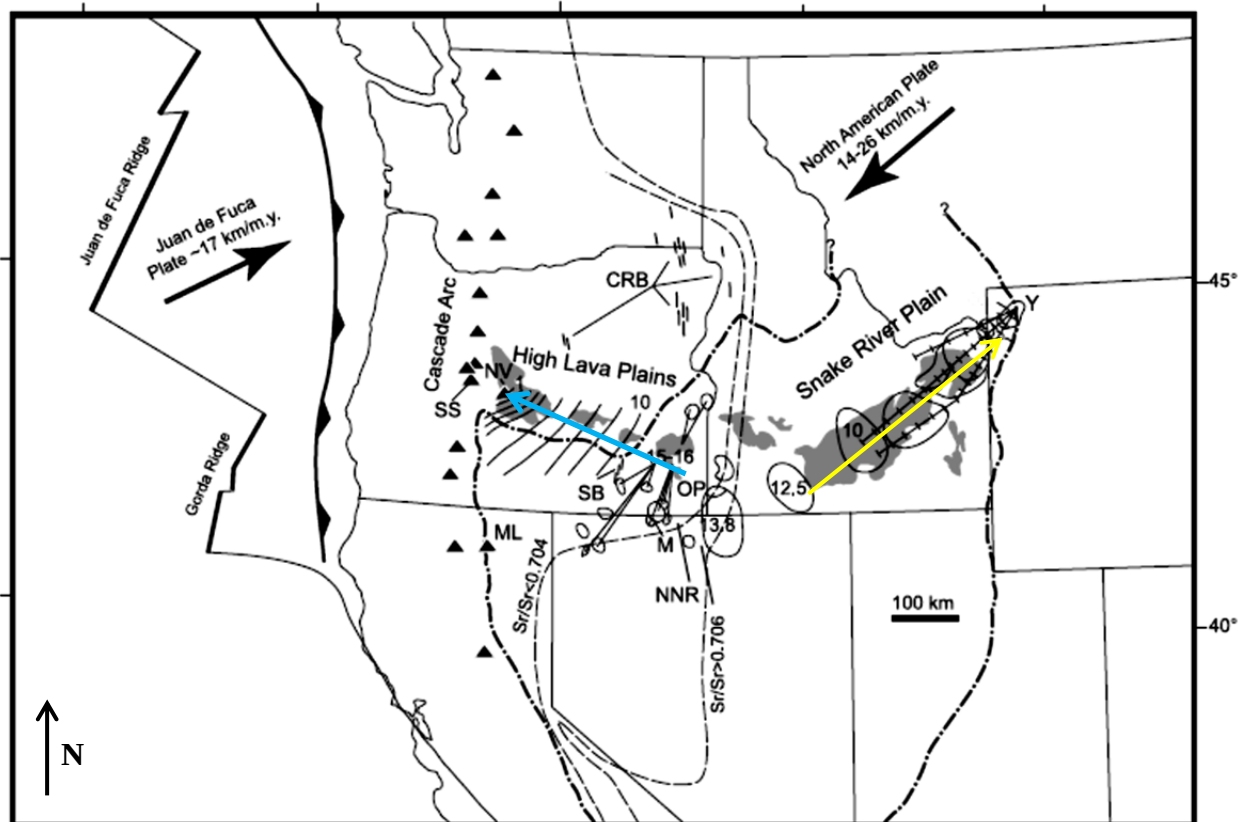


Figure 1.1 Tectonic setting of the Oregon High Lava Plains (HLP) and Snake River Plain. Y, Yellowstone; M, McDermitt volcanic field; OP, Owyhee Plateau; NV, Newberry volcano; SS, South Sister; ML, Medicine Lake volcano. Pliocene and younger basalts of the HLP and YSRP are shaded. The bold dash-dotted line shows the limit of Basin and Range extension. The lighter dashed lines represent the approximate positions of the Sr isotope discontinuities. The $\text{Sr}/\text{Sr} > 0.706$ line is thought to delineate the craton margin of North America. Figure modified from Jordan et al., 2004.

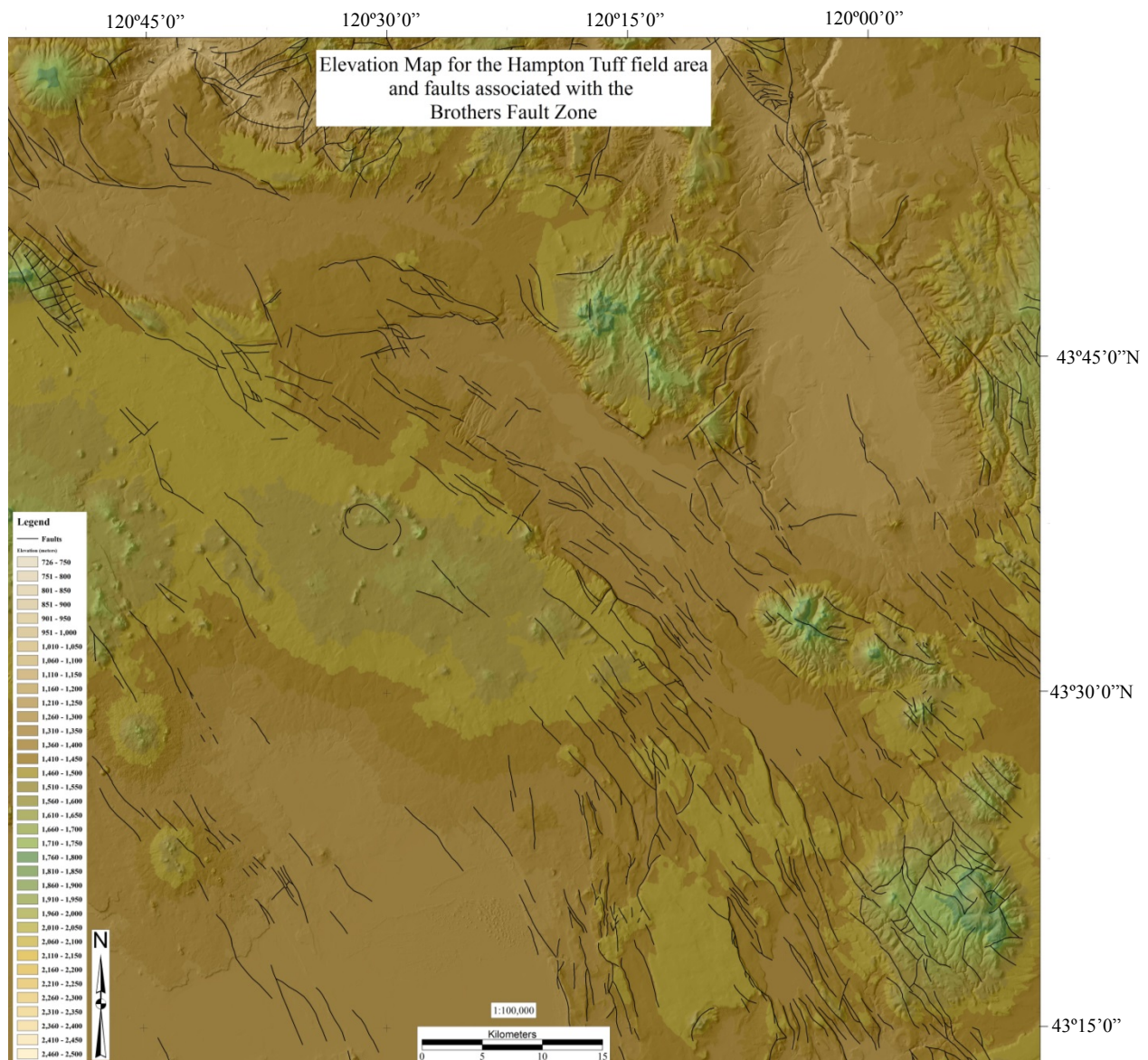


Figure 1.2 Elevation map for the Hampton Tuff field area and faults associated with the NW striking Brothers Fault Zone. The ring-fault structure of the Frederick Butte Volcanic Center (FBVC) is evident by the roughly circular feature in the left-center of the map. The FBVC is the proposed source of the Hampton Tuff based on the pattern of modern Hampton Tuff outcrops and the circular pattern of eroded volcanic edifices. The FBVC is on a topographic high (horst) bounded by sub-parallel grabens associated with basin and range style faulting along the Brothers Fault Zone. The gently sloping surface to the south and southeast of the FBVC has the aspect of a low, broad shield volcano. The area is covered by thin basalt flows that are younger than the 3.91 Ma Hampton Tuff, which crops out mainly to the north of the FBVC. Fault lines were generated from the OGDC-v5 database. The DEM consists of a 10 m ASTER derived Hillshade model and a filled contour raster created with TerrainTools for and rendered in ArcMap 10.1.

1.2 Geologic Setting

The High Lava Plains province of central Oregon is characterized by bimodal volcanism and consists mainly of rhyolitic domes, ignimbrite and ash-flow sheets, and widespread basaltic lava flows (Streck and Grunder, 2008), that crop out as low mesas. Westward younging of rhyolitic volcanism of the High Lava Plains represents a coarse mirror of the NE trending Yellowstone hotspot track with a time span from ~12 Ma to the present (Jordan, et al., 2004; Streck and Grunder, 2008). The High Lava Plains separates the Basin and Range extensional province to the south and the less extended region of the Blue Mountains to the north. Termination of the Basin and Range is exhibited by a decrease in relief on “fault-bounded range fronts” (Scarberry, et al., 2010) from southern Oregon into a transitional zone of NW striking faults called the Brothers Fault Zone (Walker, 1969). The Brothers Fault Zone is a system of en echelon normal faults that vary in offset from tens of meters to > 100 m (Figure 1.2) (Jordan et al., 2004)

Ongoing investigation of the processes responsible for magmatic evolution of the High Lava Plains indicate that it is a long lived system of volcanic activity and related tectonic deformation (Jordan et al., 2004; Scarberry, 2010; Long et al., 2012). Propagation of the Basin and Range extensional province into southern Oregon began ~ 22 Ma followed by magmatic input associated with the initiation of rollback of the subducted Farallon plate beneath North America beginning ~17 Ma (Long et al., 2012) and subsequent outpouring of the Steens Basalts ~16.7 Ma (Camp et al., 2013). The youngest of the Columbia River Flood Basalt Group, the Steens Basalt has an estimated volume of ~ 31, 800 km³ and is coincident with large extrusive eruptions of

rhyolitic composition (Camp et al., 2013). The average thickness of the Steens basalt is 600 m across an area of $\sim 53,000 \text{ km}^2$ (Camp et al., 2013). The large range-front normal fault at the base of the Steens Mountain exposes the youngest of the Steens basalt flows near the southern end of the segment. These lavas unconformably overly volcanic material that is tilted $\sim 20^\circ$ (Scarberry et al., 2010). To the north, the 9.7 Ma Devine Canyon Tuff is cut and ponded against a NW striking fault (Scarberry et al., 2010). Holocene fault scarps are also preserved at Steens Mountain. Tilting of the underlying volcanic units indicate tectonic activity prior to 16.7 Ma. Faulting of the Devine Canyon Tuff indicates that volcanic activity was syntectonic at $\sim 10 \text{ Ma}$ with motion along the Steens fault remaining active into the Holocene (Scarberry et al., 2010).

Studies from various researchers have reported varying degrees of extension along the Northwestern Basin and Range. Based on GPS data collected from 1999-2003, Hammond and Thatcher (2005) reported 2-5 mm/yr of E-W extension in northern Nevada, but no extension in Oregon. In contrast, Scarberry et al. (2010) report extension in the Northwest Basin and Range from 0.01~1.0 mm/yr. Correlation of volcanic units and restoration of cross sections along multiple segments of large north-northwest striking normal faults accounts for the variation in the rates presented Scarberry et al. (2010). Trench et al. (2012) propose an extension of 0.01 mm/yr since 5.68 Ma.

Displacement on N-NE striking normal faults decreases northward in Central Oregon and transitions into a NW striking fault zone, the Brothers Fault Zone.

Extension rates calculated from GPS data are dependent upon the rotation around a

fixed point, Euler pole. Extension rates decrease with distance from the pole (Trench, et al., 2012). Implications of geodetic analyses of the Northwest Basin and Range may require local rather than regional application. Syntectonic volcanic activity may also cloud calculated rates of extension as dike injection and magmatic input accommodate extension (Scarberry et al., 2010; Trench et al., 2012). Scarberry (2010) also argues that discrepancies in extension rates could be reconciled by allowing for episodic, rather than continuous deformation.

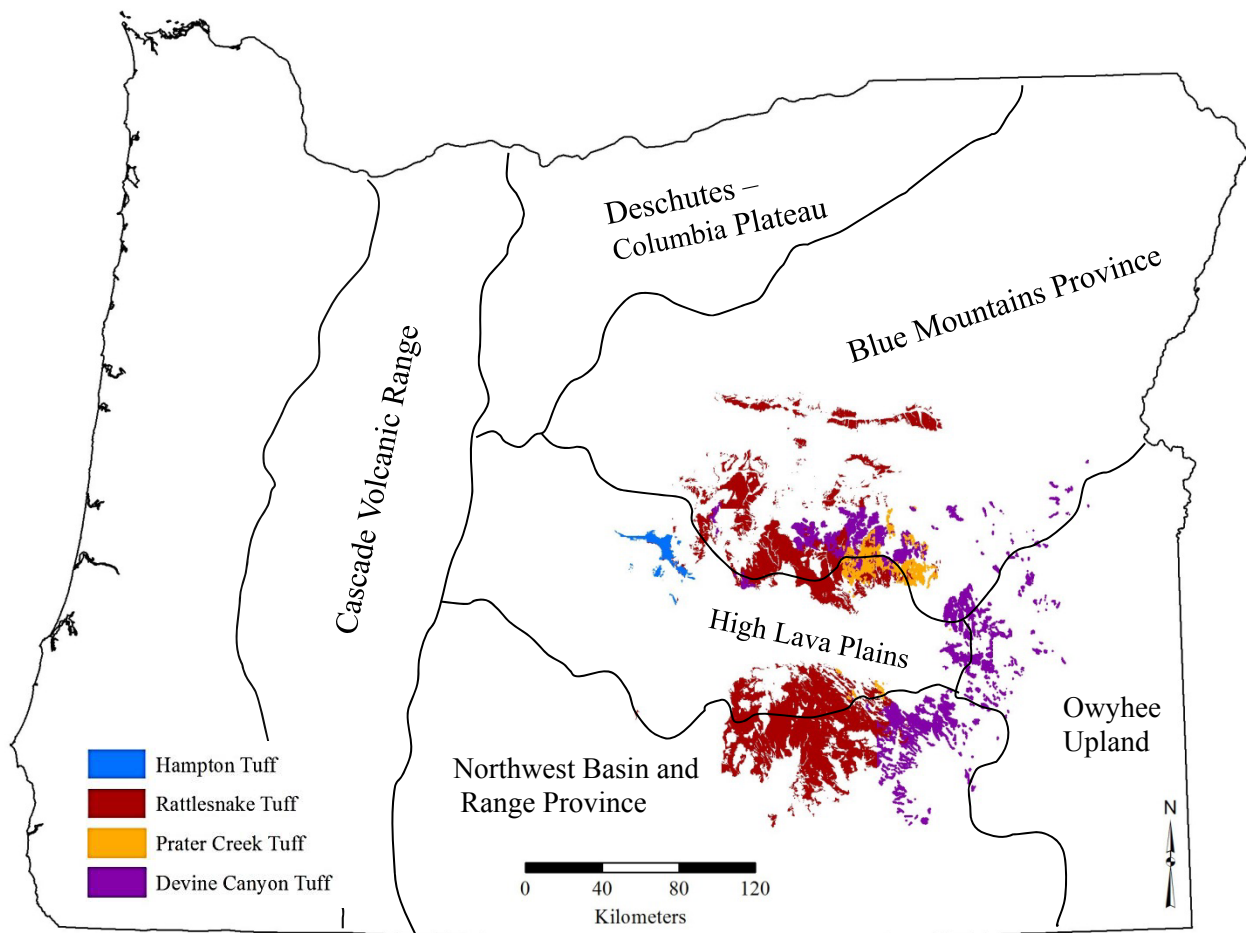


Figure 1.3 Map of Oregon with geologic provinces east of the Cascades. The three main ignimbrites of the High Lava Plains are the Devine Canyon Tuff (9.7 Ma, purple), Prater Creek Tuff (8.4 Ma, orange), and the Rattlesnake Tuff (7.01 Ma, red). Outcrops of the Prater Creek and Devine Canyon tuffs have been exaggerated because the Rattlesnake Tuff overlays both and obscures map details. The Hampton Tuff (3.9) Ma, blue), is the smallest and the youngest of the known High Lava Plains Ignimbrites. Geologic provinces after Walker and MacLeod (1991). Geologic layer rendered from the Oregon Geologic Digital Compilation, release 5 (OGDC 5) in ArcMap 10.1.

1.3 Ignimbrites of the High Lava Plains

The High Lava Plains of Central Oregon are punctuated by domes, dome complexes, and ash-flow tuffs of silicic composition that become progressively younger along a westward trend. Three large ignimbrite sheets dominate this progression from 10 – 7 Ma stemming from the Harney Basin near Burns, Oregon (Figure 1.1, 1.3): the Devine Canyon Tuff, the Prater Creek Tuff, and the Rattlesnake Tuff. Originally designated as the Danforth Formation by Piper, Robinson, and Park, (1939) these ignimbrites were later defined as individual formations and formally renamed by G.W. Walker (1979). All three ignimbrite sheets crop out along HWY 395 north of Burns, Oregon, where each has a designated type locality.

The Devine Canyon Ash-flow Tuff, herein referred to as the Devine Canyon Tuff, is the oldest of the three ignimbrites, 9.7 Ma (Jordan et al., 2004; Ford et al., 2013). The tuff is crystal rich near the source containing ~ 7 – 30% phenocrysts of sanidine, quartz, and minor hedenbergite and fayalite olivine (Davenport, 1971; Greene, 1973; Streck et al., 2015). A simple cooling unit that is typically 10 – 20 m in thickness, the Devine Canyon Tuff is non-welded to densely welded, may be vitric to devitrified, is occasionally pumiceous, and may display vapor phase alteration (Greene, 1973; Streck et al., 2015). Initial investigation by R.C. Greene (1973) indicated an aerial extent ~18,600km² and a volume of 195 km³. However, recent research by Wacaster et al. (2011) and Streck (2014) estimate an aerial extent >20,000 km² and a volume of 300 – 400 km³ (not including intra-caldera fill or distal air-fall deposits), making the Devine Canyon Tuff volumetrically the largest of the High Lava Plains ignimbrites.

The Prater Creek Ash-flow Tuff, herein referred to as the Prater Creek Tuff, is the smallest, but also least studied of these three High Lava Plains ignimbrites. A minimum estimate for the Prater Creek Tuff is $\sim 200 \text{ km}^3$ of erupted material (Parker, 1974). The type section for the Prater Creek Tuff is located $\sim 7 \text{ km}$ north of Burns, Oregon along HWY 395 where the tuff is described as a completely devitrified greyish-red or pinkish-grey ash-flow that is crystal poor with abundant lithophysae up to 7 cm in diameter (Davenport, 1971; Parker, 1974, Walker, 1979). Petrographic analysis by Davenport (1971) indicated fractured and anhedral microphenocrysts of alkali-feldspar (most likely sanidine) and quartz that are less than 1% of the ignimbrite. Age dating by Parker (1974) and Jordan et al. (2004) both produced a date of 8.4 Ma.

The Rattlesnake Tuff is a widespread low-aspect ignimbrite sheet that once covered up to $\sim 40,000 \text{ km}^2$ and traveled distances $> 150 \text{ km}$ from the source (Parker, 1974; Walker, 1979; Streck and Grunder, 1995; Streck and Ferns, 2004). The type locality, designated by G.W. Walker, 1979 is $\sim 10 \text{ km}$ north of Burns on HWY 395 where it is 22 m thick and consists of a densely welded basal vitrophyre that grades upward into a non-welded lithophysal zone capped by 2 m of pervasively devitrified tuff (Walker, 1979; Streck and Ferns, 2004). The Rattlesnake Tuff is crystal poor ($< 1 \%$) and is represented by 99% high-silica rhyolite ($75 - 77.5 \text{ wt\% SiO}_2$) with minor black dacitic pumices. Multiple dating analyses determined an age of 7.1 Ma (Streck and Grunder, 1995; Jordan et al., 2004).

An ash-flow tuff that overlies the Rattlesnake Tuff south of Wagontire Mountain on HWY 395 is informally known as the tuff of Buckaroo Lake, or the

Buckaroo Lake tuff. The Hampton Tuff has been previously associated with the Buckaroo Lake tuff because they have a similar appearance in outcrop, but also because they were thought to be chemically similar (MacLean, 1994). Chemical analysis of the Buckaroo Lake tuff was presented graphically by MacLean (1994). These same samples (BL-46a, BL-46b, BL-46d, BL-46e, and BL-46f), herein called the BL-samples, were later published, and correlated to the Hampton Tuff (Johnson, 1998). The BL-samples were collected by Dr. Martin Streck in an area north of Brothers, Oregon (Martin Streck, personal communication) that is now known to be pumiceous outcroppings of the Hampton Tuff. A sample collected from an area south of Wagontire Mountain (Figure 1.4), HP-91-9, has been previously dated, and is 6.85 Ma (Jordan et al., 2004). It is this sample and age that are attributed to the Buckaroo Lake tuff. An exhaustive search of the literature returned no chemical analysis for this sample or any other sample known to be the Buckaroo Lake tuff. Chemical analysis of sample HP-91-9 (section 3.6) is included herein for comparison with other High Lava Plains ignimbrites and the Hampton Tuff; as well as possible correlation to a previously unknown tuff initially thought to be the Hampton Tuff.

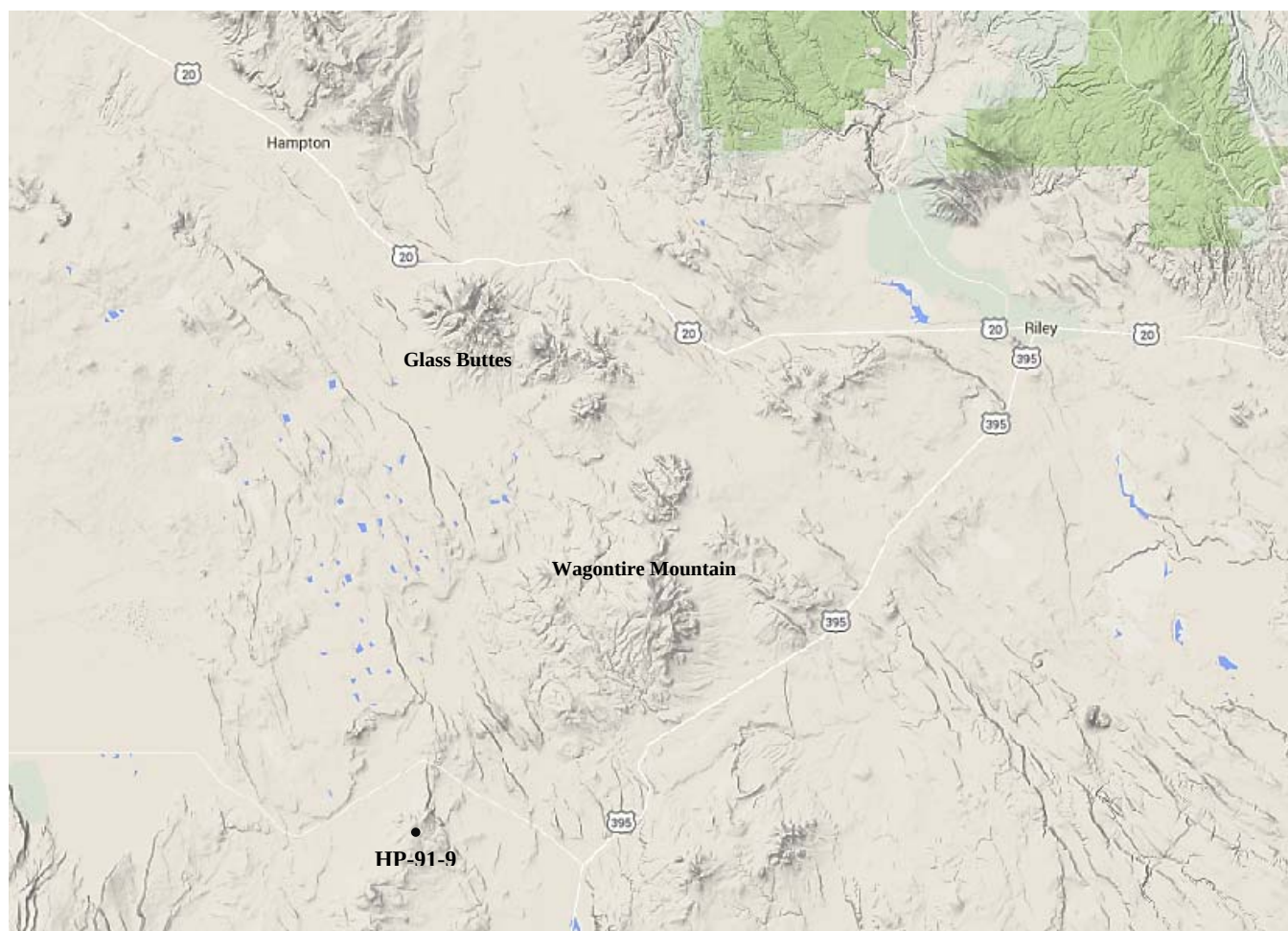


Figure 1.4 Terrain map showing Wagontire Mountain and location where sample HP-91-9 was collected. The Buckaroo Lake tuff overlies the Rattlesnake Tuff on mesas along Hwy 395. ([Google maps](#), last accessed December, 2015).

The Big Three (Devine Canyon, Prater Creek, and Rattlesnake) ignimbrites of the High Lava Plains cover a vast extent of Central Oregon recording the westward migration of silicic volcanism across Oregon spanning three million years. Following lightly in their footsteps are the younger and less voluminous ignimbrites such as the Hampton Tuff, Buckaroo Lake tuff, and a newly discovered tuff, described in section 3.6. Magmatic output appears to be waning in time as the migration approaches the High Cascades volcanic system. While younger tuffs share characteristics that define the Big Three, they are greatly reduced in volume and are generally less evolved suggesting that some process or a combination of processes are hindering the development of large silicic magma chambers along the westward journey in time.

Chapter 2 - Methods

2.1 Field Work

Geologic mapping was done in the field in an area within 70 km of the Frederick Butte Volcanic Center, the proposed source of the Hampton Tuff (Walker, 1981; Johnson, 1998). Mapping was done directly onto 7.5 minute quadrangle topographic maps at a scale of 1:24,000. Outcrops of the Hampton Tuff previously mapped by Walker (1967); Greene (1972); MacLean (1994); Johnson (1998) and Iademarco (2009) were field checked for identification and accuracy.

Outcrops of the Hampton Tuff were measured for thickness and visually identifiable characteristics were noted for correlation across the mapping area. These characteristics included degree of welding, color and size of pumice distribution (if applicable), vapor phase alteration, weathering patterns, phenocryst populations and jointing. Visual inspection of pumice for size and color were conducted at outcrops where pumice structure was maintained. Analysis of largest pumice (e.g. largest pumice counts) was conducted in the Camp Creek area as well as the Coyote Rock area.

A total of 46 samples were collected from a variety of outcrop locations. Whole rock samples were collected in areas where the tuff was densely welded or consisted of densely welded vitrophyre. Whole rock and pumice samples were collected at outcrops where welding and subsequent pumice deformation was minimal. Where applicable, pumice samples were collected to include the range of variations in pumice populations (e.g. pink, tan, black, or banded pumice).

Samples were also collected along a vertical transect from the Lizard Creek Quarry area to characterize variations throughout the section (figure 2.2). This outcrop was previously described in detail by Iademarco (2009).



Figure 2.1 **A** Outcrop of the Hampton Tuff that grades vertically from densely welded vitrophyre to densely welded with fiamme. **B** Further grading upward to densely welded with deformed pumice. Hammer is ~ 33 cm (13 in).



Figure 2.2 Photograph of outcrop at the Lizard Creek Quarry. Outcrop height is 12 m (~ 39 ft). Hammer is ~ 42 cm (16.5 in).

2.2 $^{40}\text{Ar}/^{39}\text{Ar}$ dating – methods

2.2.1 The Hampton Tuff dating methods

Two samples of the Hampton Tuff were chosen for dating using the $^{40}\text{Ar}/^{39}\text{Ar}$ method. Samples were chosen for dating based on sample freshness and location (Figure 3.1). A sample from the densely welded section of Rimrock Draw (HJS-HTP-006-2012), ~8 miles NE (~N35°E) from the Frederick Butte Volcanic Center, was chosen for the purpose of correlating a tuff informally named the Tuff of Espeland Draw (Johnson, 1998) to the Hampton Tuff. Figure 2.3 is a map indicating the location of samples dated. Sample number HJS-HTP-0020-0913, a large, grey banded pumice measuring ~23 x 3 x 10 inches, was collected from the Camp Creek Rd. area. This sample was collected from an incipiently welded section ~18 miles NE (~N10°E) of Frederick Butte.

Densely welded sample HJS-HTP-006-2012, hereafter referred to as 006, was hand crushed with a hammer on a clean iron plate and then fed into a chipmunk mini jaw crusher. The sample was then sieved to $>350\text{ }\mu\text{m}$ and $<550\text{ }\mu\text{m}$ and underwent magnetic separation with a Frantz magnetic separator to eliminate magnetic glass shards and phenocrysts. The sample was then cleaned in a ~5% hydrofluoric acid (HF) bath for approximately five minutes. The cleaned sample was then placed in a heavy liquid separation apparatus in an attempt to separate any sanidine from plagioclase feldspar and quartz. No sanidine was found at this scale. A sample consisting of 40 mg of inclusion-free plagioclase $> 350\text{ }\mu\text{m}$ was handpicked under a binocular microscope and submitted for analysis.

The grey banded pumice, sample HJS-HTP-0020-0913, hereafter referred to as 0020, was hand crushed with a clean mortar and pestle. Samples were washed with de-ionized water and allowed to dry overnight in a 55° C drying oven. Pumice fragments were sieved and fragments $>300\text{ }\mu\text{m}$ and $<500\text{ }\mu\text{m}$ were separated on the Frantz magnetic separator at 0.10 magnetic power with a 20° tilt followed by handpicking of glass shards under a binocular microscope. Inclusion-free plagioclase was further subjected to a ~5% HF bath for ~5 minutes and then handpicked under a binocular microscope. A 50 mg sample of clean vitric glass (Figure 3.14) and a 40 mg sample of inclusion-free plagioclase $>350\text{ }\mu\text{m}$ were submitted for analysis.

Plagioclase samples for both 006 and 0020, as well as the glass sample from 0020, were placed in quartz vials with the fluence monitor, FCT sanidine (28.201 ± 0.023) (Kuiper et al., 2008). The samples were irradiated for 6 hours in the Cadmium-Lined In-Core Irradiation Tube (CLICIT) TRIGA nuclear reactor at Oregon State University. Parabolic extrapolation of the irradiation height against the gradient of measured flux allows for the calculation of individual J-values for each sample. After being placed into Cu-planchettes in an ultrahigh vacuum, irradiated samples were then incrementally heated. In order to release argon evenly, a defocused 25 W CO₂ laser beam was used in a preset pattern across the samples. Gas fractions were purified using a SAES Zr-Al ST101 getter for ~ 10 minutes at 400° C followed by two SAES Fe-V-Zr ST172 getters at 200° C and then at room temperature (Miggins, D.P., personal communication, 2014). Incremental age determinations were performed on a Thermo Scientific Model ARGUS-VI mass spectrometer in the Argon Geochronology Lab at Oregon State University. The ARGUS-VI has five Faraday

collectors each fitted with 10^{12} Ohm resistors and one ion-counting CuBE electron multiplier. The ion-counting electron multiplier is mounted next to the lowest mass Faraday collector which allows for the simultaneous measurement of all argon isotopes, with ^{36}Ar measured on the multiplier and ^{37}Ar through ^{40}Ar on the adjacent Faraday collectors.

Three $^{40}\text{Ar}/^{39}\text{Ar}$ ages were calculated using the corrected decay constant of Steiger and Jäger, 1977, of $5.530 \pm 0.097 \times 10^{-10}$ (per year) as published by Min et al., 2000; all other constants as in Koppers, et al., 2003. Weighted plateau ages were calculated as the weighted mean of the age at each heat step using $1/\sigma^2$ as the weighting factor, as described by Duncan and Hogan, 1995. Isochron ages were calculated using the least squares fit of a straight line with correlated errors, YORK2, (York, 1969) as described by Koppers, 2002. Plateau and Isochron ages were calculated and plots rendered using ArArCALC v2.6.2 software from Koppers, 2002, which is available from the <http://earthref.org/ArArCALC/> website.

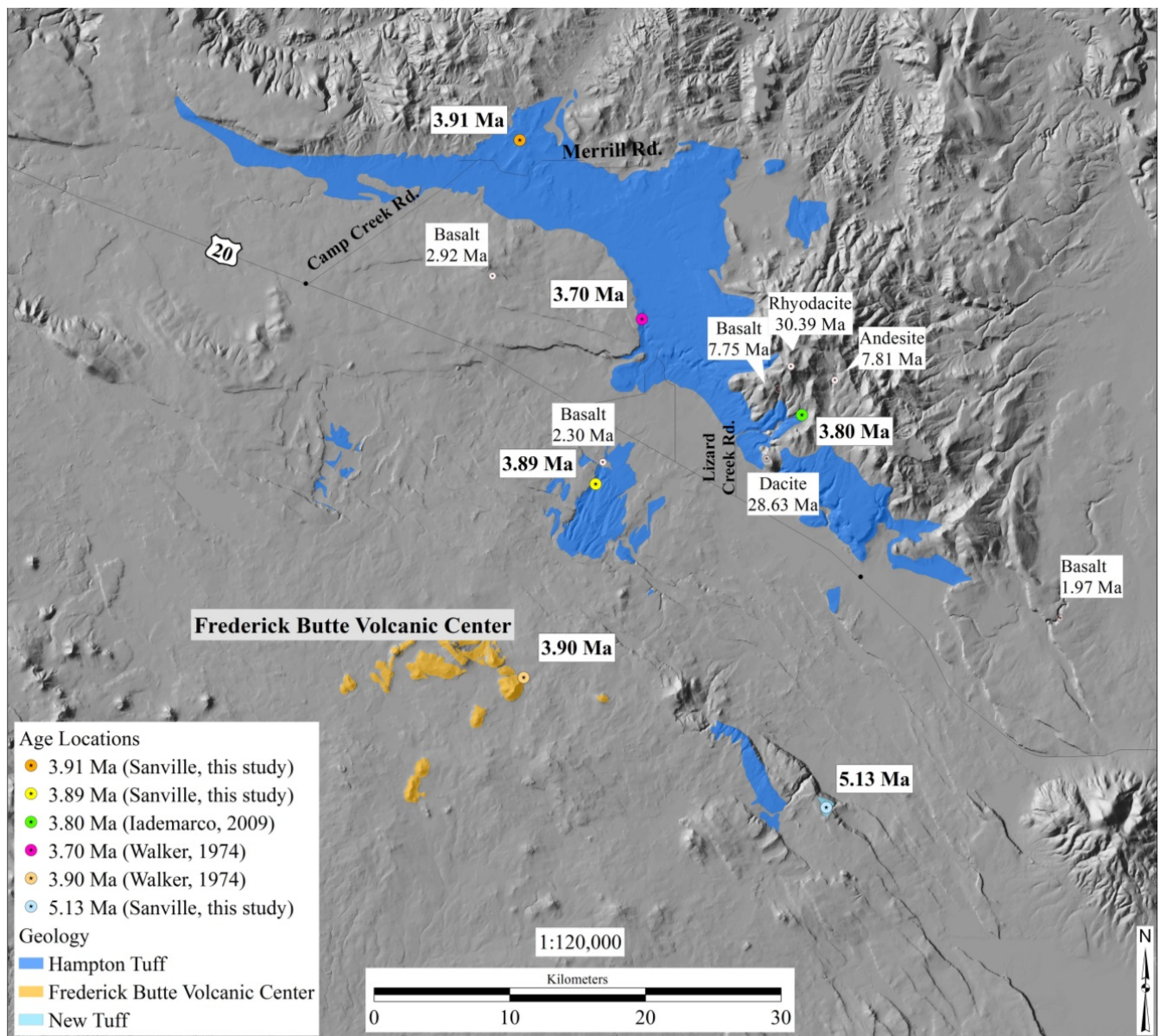


Figure 2.3 Map showing locations of samples that have ages and are correlated with the Hampton Tuff. The newly discovered Potato Lake tuff (5.13 Ma) is also included on this map. Hampton Tuff and Frederick Butte data from Walker (1974; recalculated by Fiebelkorn (1982); and Iademarco (2009). Other age data from Jordan, et al. (2004), and Iademarco (2009).

2.2.2 Potato Lake tuff dating methods

Sample HJS-HTP-0064c_2 (herein referred to as 0064c_2) was chosen for age dating by the $^{40}\text{Ar}/^{39}\text{Ar}$ method at Oregon State University. A portion of this sample was prepared and analyzed for whole rock major and trace element analysis at WSU. The remainder of the sample measured 12 x 6.5 x 4.5 cm. Sample number 0064c_2 is a light colored pinkish-grey finely vesiculated pumice clast. Less than 1% of the sample is fractured plagioclase up to 2 mm. The pumice was crushed in a mini jaw-crusher and further crushed by hand with a clean mortar and pestle. The sample was cleaned in de-ionized water and allowed to overnight. The sample was sieved for fractions $>150\text{ }\mu\text{m}$ and $<250\text{ }\mu\text{m}$ which were then separated with a Frantz magnetic separator to eliminate magnetic glass shards and phenocrysts. The sample was then treated with a 5% HF bath for five minutes. After rinsing and drying, the sample was sieved again to remove any fines and then subject to LST heavy liquid separation. The density of the LST (lithium heteropolytungstates), measured with a hydrometer, was 2.582 g/cm^3 . This density allows for the less dense alkali-feldspar ($\sim 2.56\text{ g/cm}^3$) to float in the heavy liquid while the greater density plagioclase and quartz (2.62 g/cm^3 and 2.65 g/cm^3 , respectively) sink to the bottom. Floaters, presumably sanidine, and sinkers (plagioclase and quartz) were repeatedly rinsed and allowed to dry overnight. The 20 largest, clear, and inclusion-free floaters were handpicked under a binocular microscope and submitted for analysis. A second sample consisting of 20 mg of clear, inclusion-free sinkers (plagioclase) was also submitted for analysis.

After having been irradiated, 19 “floaters” were individually placed into a Cu-planchet, designed with 154 holes, with a blank placed between each crystal for single crystal laser total fusion method. Each sample was heated by a defocused 25 W CO₂ laser beam at 18% power for 90 seconds and then analyzed for six minutes, followed by purification of gas fractions, as previously outlined in section 2.2.1.

Plagioclase were irradiated and analyzed in the same manner as plagioclase samples for Hampton Tuff, as outlined previously.

⁴⁰Ar/³⁹Ar ages were calculated using the corrected decay constant of Steiger and Jäger (1977), of $5.530 \pm 0.097 \times 10^{-10}$ (per year) as published by Min et al. (2000); all other constants as in Koppers, et al. (2003). Single crystal total fusion ages were calculated and plots rendered using ArArCALC v2.6.2 software from Koppers, (2002), which is available from the <http://earthref.org/ArArCALC/> website.

2.3 XRF whole rock - Methods

2.3.1 XRF major and trace element analysis

Major and trace element analyses of seven samples from the Hampton Tuff and 11 samples of a previously unknown tuff were conducted at Washington State University (WSU) using a Thermo-ARL automated X-ray fluorescence spectrometer (XRF). Samples included 12 individual pumice and six bulk rock samples. Each sample was chosen based on collection location, size, and freshness of the sample. Bulk rock samples were reduced in size using a hammer and a metal plate, or a hydraulic press. Gravel sized chunks were then reduced to pea size chips using a chipmunk mini jaw-crusher with tungsten carbide (WC) plates. Samples were then ground into a fine powder using a WC milling chamber in a shatterbox mill for two minutes. Each sample was then fused at 1000°C with dilithium tetraborate ($B_4Li_2O_7$) flux at a 2:1 flux to powder ratio (Figure 2.4). The XRF bead was then re-ground to insure sample homogeneity before being fused a second time. Pumice samples were prepared using the same procedure except that they were placed directly into a mini jaw crusher for size reduction and not hit with a hammer. Loss on ignition (LOI) analysis was conducted on bulk rock and pumice samples. Powder from each sample was weighed before being heated in a muffle furnace at 900°C for 16 hours and then weighed again.

The estimation of accuracy of geologic samples analyzed by XRF at WSU is conducted by comparing measured values of standards analyzed as unknowns with theoretical intensity measurements. A detailed description of preparation techniques, precision, and accuracy has previously been published by Johnson et al. (1999).

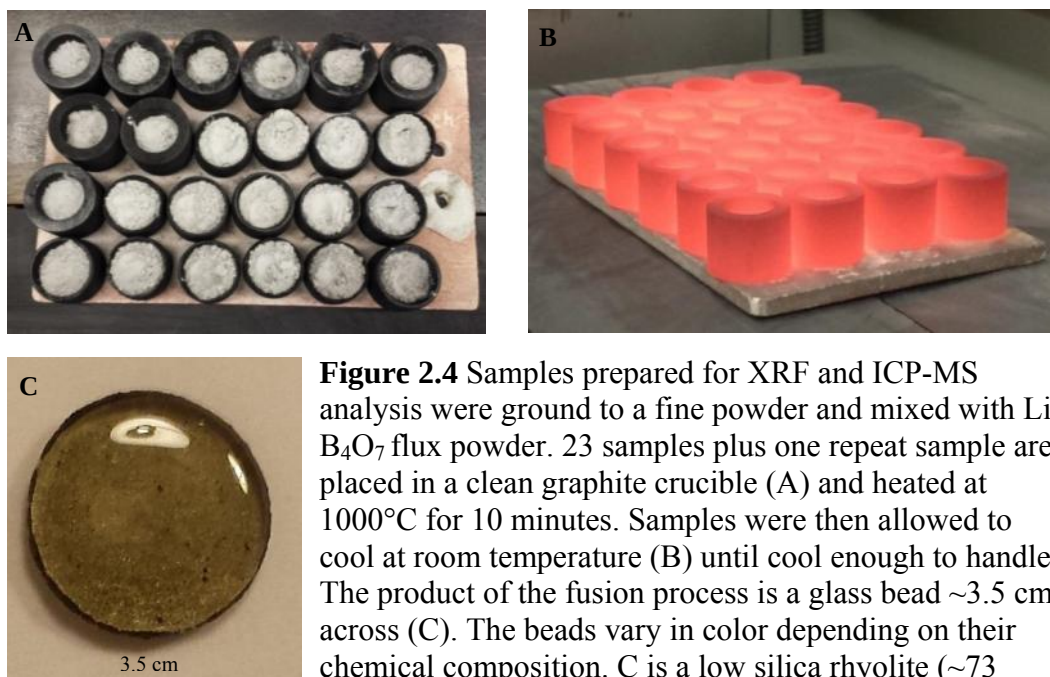


Figure 2.4 Samples prepared for XRF and ICP-MS analysis were ground to a fine powder and mixed with $\text{Li}_2\text{B}_4\text{O}_7$ flux powder. 23 samples plus one repeat sample are placed in a clean graphite crucible (A) and heated at 1000°C for 10 minutes. Samples were then allowed to cool at room temperature (B) until cool enough to handle. The product of the fusion process is a glass bead ~ 3.5 cm across (C). The beads vary in color depending on their chemical composition. C is a low silica rhyolite (~ 73 wt% SiO_2).

Results of XRF data were examined for accuracy and quality of returned values. A set of criteria was established to rule out anomalous data. Samples that returned anomalously high or low oxide values were not used for plotting, as well as samples returning totals less than 97%. Major elements were analyzed to 100% volatile-free.

2.3.2 ICP-MS trace element analysis

Trace elements analyzed on an Agilent model 4500 inductively coupled plasma-mass spectrometer (ICP-MS) at WSU were prepared using the same preparation techniques outlined for XRF. Samples were fused once before being ground and dissolved for analysis.

Precision for ICP-MS at WSU is monitored by the use of two internal standards analyzed as unknowns over the course of six months. Accuracy for ICP-MS is estimated by comparing the known values of 15 USGS reference standards with the

results of two sample beads prepared at WSU from each of the 15 reference standards. The maximum difference for measured values and known values is less than 40 ppm and in most cases is less than 10 ppm. Detection limit values and comparison tables for WSU and USGS references can be found in Appendix 1.

Trace element data provided by ICP-MS analysis were compared to trace data from XRF analysis and lie within error of one another (Figure 2.5).

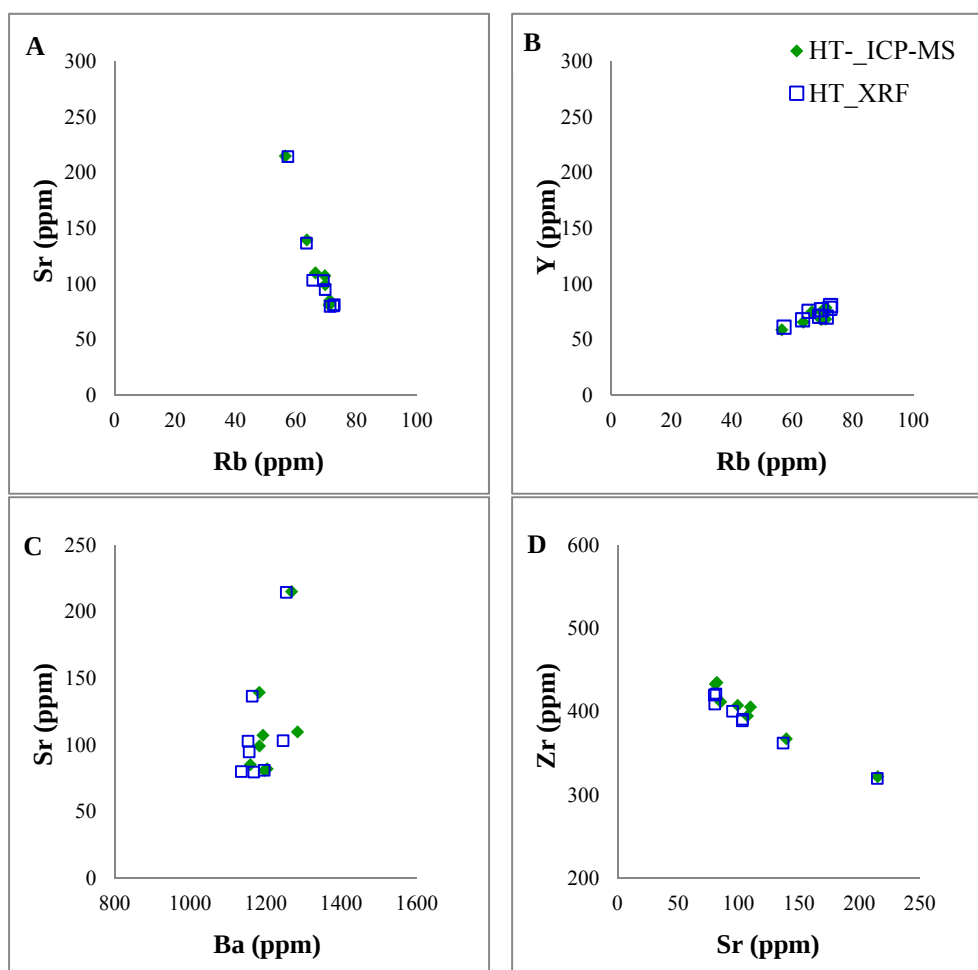


Figure 2.5 Variation diagrams of selected trace elements measured by XRF and ICP-MS at WSU. Figures A and B indicate 1:1 ratios when XRF and ICP-MS data are plotted for the Hampton Tuff. Figures C and D show slight variations between measured values for Sr and slightly greater variations for Ba. The variations for Sr and Ba are to be expected as these trace elements have the greatest maximum measured differences between known values and trace elements analyzed by ICP-MS at WSU (<30 and <40 ppm, respectively), but ratios of XRF/ICP-MS data result in 1:1.

2.4 Electron microprobe - Methods

Major element analysis of twelve samples of the Hampton Tuff that included glass shards from individual pumice, matrix glass from welded and non-welded vitrophyre, groundmass glass associated with nonwelded sections, and fiamme were analyzed at Oregon State University using a CAMECA SX-100 electron microprobe (EMP). Glass shards from a black and white banded pumice of a previously unknown tuff as well as pumice and groundmass glass of the Buckaroo Lake tuff (HP-91-9) were also analyzed. Glass was analyzed using a sample current of 10 nA and a 5 μm defocused sample beam. To reduce the effects of alkali migration (e.g. sodium-loss) (Kuehn et al., 2011) sodium is measured first and a zero-time intercept function is applied. Data reduction was performed using the X-PHI PeakSight software for glass analysis. While the use of a low sample current and zero-time intercept are employed to reduce alkali migration effects, the employment of a 5 μm beam may cause sodium values to deviate slightly from accepted values - but are concordant with regular measurements captured at OSU (Frank Tepley, personal communication). Back-scattered electron (BSE) images were obtained using the same instrument utilizing the CAMECA PeakSight software.

Two of the samples (0037, 0038) analyzed with the EMP were collected from a black vitric ash layer found below the welded section of the Lizard Creek quarry and include pumice clasts (Figure 3.8 and 3.9). Sample number 0022 is a pink pumice clast set in course-grained matrix ash (Figure 2.6 and 2.7); glass shards from the matrix and the pumice were analyzed. The four remaining samples are individual pumice clasts. Pumice samples vary in color from white, tan to light brown or pink,

grey or grey banded, black and black & white banded. Where possible, transects across obvious color boundaries were analyzed to determine compositional variations between bands. Glass shards from vitrophyre and matrix glass were chosen based on size, proximity to pumice or other visual distinctions, and color - where possible (Figures 2.6 and 2.7).



Figure 2.6 Sample number 0022 – a pink pumice with coarse grained ash matrix. Sample was mounted in clear epoxy and the surface polished to 1 μm .

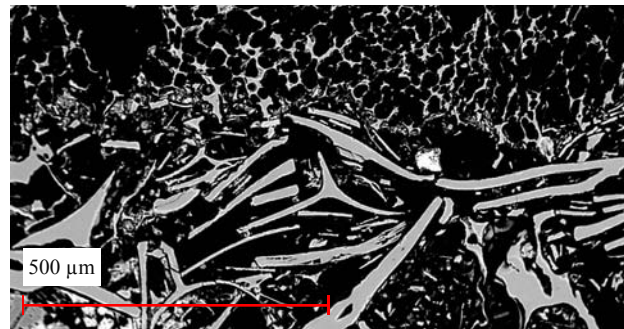


Figure 2.7 Back-scatter electron (BSE) image of sample number 0022. The upper part of the image is pink pumice. The coarse grained glass shards are the encapsulating ash matrix of a non-welded section of the tuff.

Chapter 3 Results

3.1 Field Results

3.1.1 Distribution: Where it is. Where it is not. Where it is something else.

The Hampton Tuff (Figure 3.1) crops out in a semi-circular pattern north of the Frederick Butte Volcanic Center, the inferred source of the ignimbrite (Walker, 1981; Johnson, 1998). Small outcrops have been mapped to the east of Frederick Butte (this study; Walker, 1967). There are no known outcrops to the west or southwest of Frederick Butte though being heavily traversed by the author in August of 2015. Outcrops to the south of Frederick Butte are likely covered by younger basalt.

Dating and geochemical composition confirm the correlation of outcrops mapped by Johnson (1998) as the Tuff of Espeland Draw, with all other outcrops of the Hampton Tuff. Outcrops previously mapped as the Rattlesnake Tuff in the Lizard Creek Rd. and Merrill Rd. areas were field checked and confirmed to be the Hampton Tuff. Tuffaceous sections containing a variety of units crops out along tributaries to Lizard Creek and along Lizard Creek Rd. and have previously been mapped as tuffaceous sandstone (Tst), by Walker (1967) and Iademarco (2009). This section includes a nonwelded ignimbrite that underlies the Hampton Tuff. Petrologic and geologic field relations remain unclear about the relationship to the Hampton Tuff.

A horst block 16.5 km east of Frederick Butte, with ~ 140 m (450 ft) of relief exposes a section of ignimbrite that is nonwelded to partially-welded with pumice. While similar in aspect to the nonwelded to partially-welded section of the Hampton Tuff, such as at the Camp Creek Rd. area, this ignimbrite is compositionally distinct

and is a previously unknown ignimbrite of the High Lava Plains (section 3.2).

Nonwelded to partially welded sections of the Hampton Tuff are distinguishable from the new tuff in that the groundmass of the Hampton Tuff is grey rather than the brown or orange and black. The Hampton Tuff has very few, if any, strikingly banded pumice (Figure 3.25). Banded pumice in the Hampton Tuff are less obvious as they are generally grey and darker grey or pink and grey (Figure 3.15).

An outcrop near the northern most extent of the tuff, east of Merrill Rd. (Figure 3.1), is a blocky grey outcrop that is partially-welded with pumice and has a salt and pepper groundmass. Pumice clasts range from stretched, finely vesicular white pumice to grey and black, and abundant banded pumice (black and grey or black and white). The tuff in this location is crystal poor, lacking the large euhedral plagioclase distinctive of the Hampton Tuff. This is likely a distal outcrop of the Rattlesnake Tuff and not the Hampton Tuff.

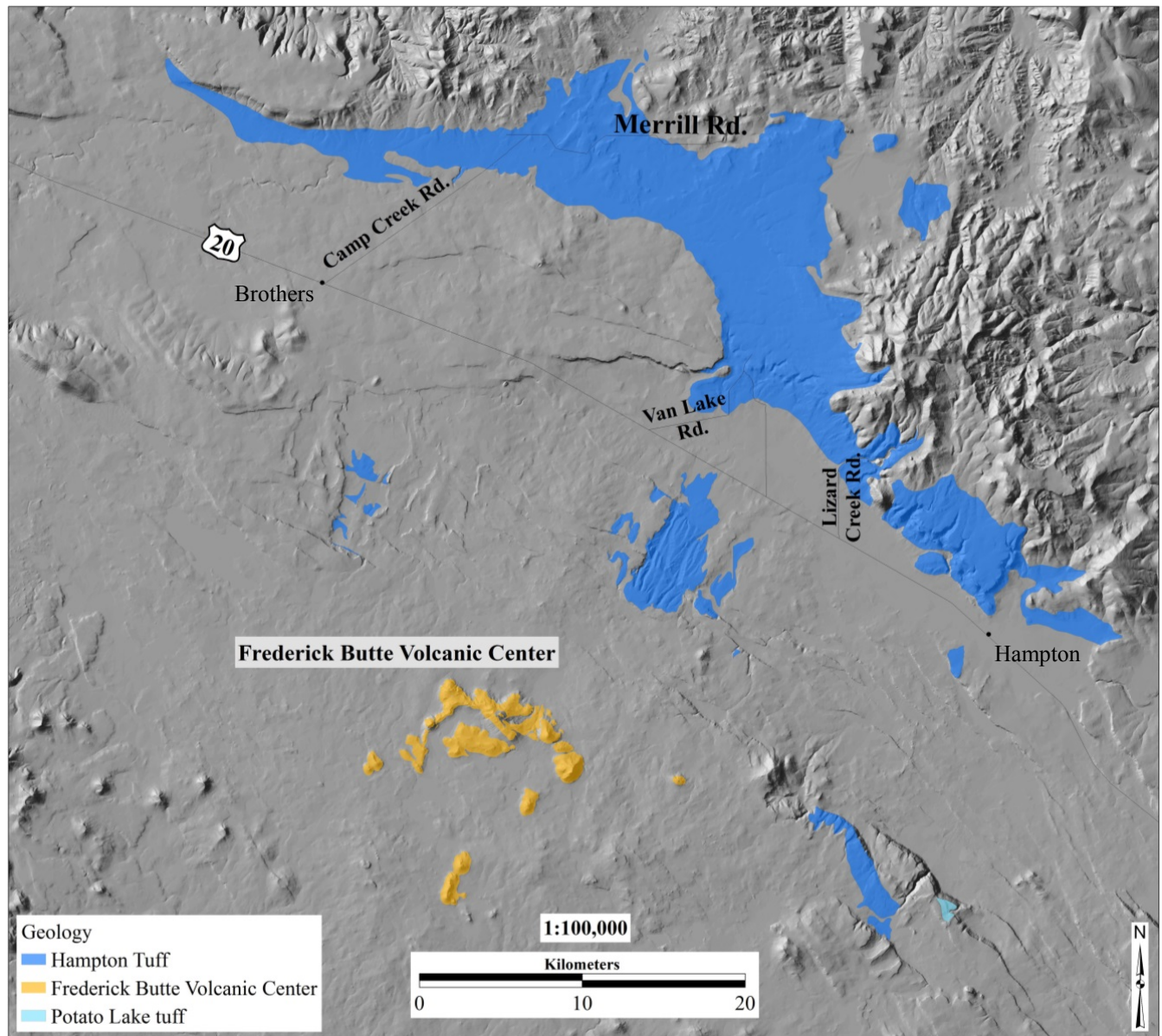


Figure 3.1 Outcrop map for the Hampton Tuff. The tuff outcrops in a semi-circular pattern north of the Frederick Butte Volcanic Center. Geologic layer compiled and edited from the ODGC-v5 (Oregon Digital Geologic Compilation, version 5) using ArcMap 10.1.

3.1.2 Lithology, thickness, and facies: petrology, petrography, and summary of sample descriptions.

Terminology and nomenclature used to describe lithologies and facies are based on Streck and Grunder, (1997 and 1999), Ross & Smith, (1961), and Smith, (1960a, b).

The Hampton Tuff is typically 7.5 - 8 m (~25 ft) thick and varies from nonwelded to densely-welded and may be locally devitrified with vapor phase alteration. Pervasively devitrified outcrops, like those found at the Lizard Creek Quarry, display perlitic textures, and incipient lythophysal crystallization in thin section. The majority of outcrops of the Hampton Tuff consist of a black, densely welded basal vitrophyre that abruptly transitions upward to brown or reddish-brown densely welded devitrified tuff with fiamme and further grades to densely welded devitrified tuff with deformed pumice (Figures 3.3 and 3.4). The brown densely welded section is typically 7.5 - 8 m (25 ft) thick, but can be greater than 15 m (50 ft) where the tuff has banked up against topographic highs, such as along the base of Cougar Butte. Outcrops display blocky jointing with a rounded and pockmarked weathering surface. Pockmarks vary in size and aspect ratio based on the deformation of the pumice which has weathered out of the surface. The brown densely welded section degrades into a brown grus (Figure 3.4). Grus is a term for the fragmental products of in-situ granular disintegration of silicic rocks, usually granite (Glossary of Geology, 4th edition). The weathering products of the brown densely welded section are distinctively lacking boulder and cobble sized fragments.

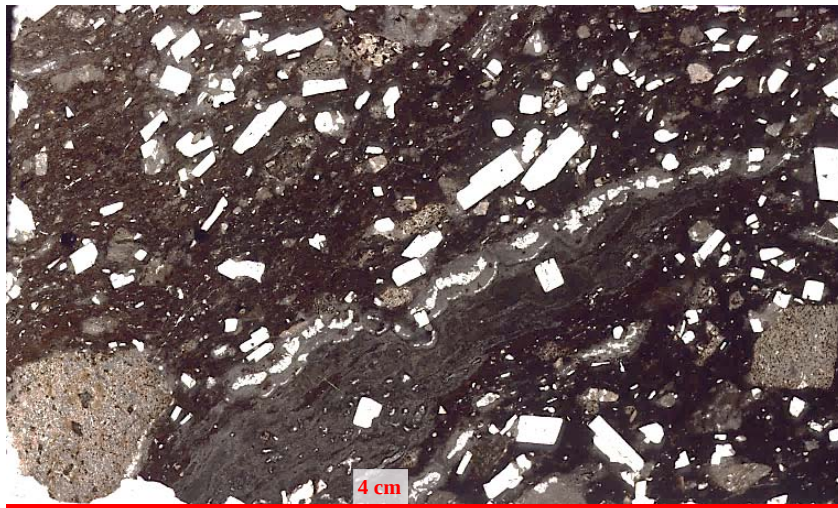


Figure 3.2 Scanned image of a thin section from Rimrock Draw (plain polar light). Abundant lithics and plagioclase dominate the sample.

In the area of Rim Rock Draw (Figure 3.5) the densely welded section is dark chocolate-brown with 5 – 7 % euhedral or fractured plagioclase that average 1 mm but may be as large as 5 mm (Figure 3.2). This section has abundant lithics that are typically 2 - 4 mm, but may be as large as 2 cm (Figure 3.2). Lithics consist mainly of angular mafic clasts of volcanic origin, aphanitic rhyolitic clasts, and angular clasts of sedimentary origin.

Upsection of the brown densely welded section of Rimrock Draw is a vapor-phase altered top that weathers to a sugary white or light grey grus. In hand sample, the vapor-phase altered facies is light grey when fresh with a fine grained sugary texture. Fractured plagioclase phenocrysts are less than 3% of the rock and are typically 1 mm. Outcrops of the vapor-phase altered facies at Rimrock Draw exists only as a thin veneer above the brown densely welded section, but ~3 km SE at Coyote Rock, the vapor-phase altered facies is a 6 – 7.5 m (20 – 25 ft) thick section of moderately welded with fiamme and flattened pumice. The groundmass displays no

distinct characteristics typical of deposition by pyroclastic flow. Features and textures associated with ignimbrite deposits such as pumice clasts, glass shards, or eutaxitic fabric have been completely destroyed by post emplacement vapor-phase alteration



Figure 3.3 The brown densely welded section of the Hampton Tuff displays blocky jointing that weathers to large rounded bouldery outcrops. The reddish-brown coloration is characteristic of this section of the Hampton Tuff. The basal vitrophyre is not exposed at this location although numerous pieces of vitrophyre float were found. This outcrop is along the southwestern side of Cougar Butte at an elevation of 4629 ft. The outcrop in the photograph is ~ 12 m (40 ft) thick but the top of the section is not visible and the base is not exposed.



Figure 3.4 The contact between the dense basal vitrophyre and densely welded section is sharp. The reddish-brown grus is characteristic of the brown densely welded section of the Hampton Tuff. The vitrophyre is glassy and densely welded with abundant euhedral plagioclase (1-4 mm), white pumice (~1-2 mm) and minor lithics.

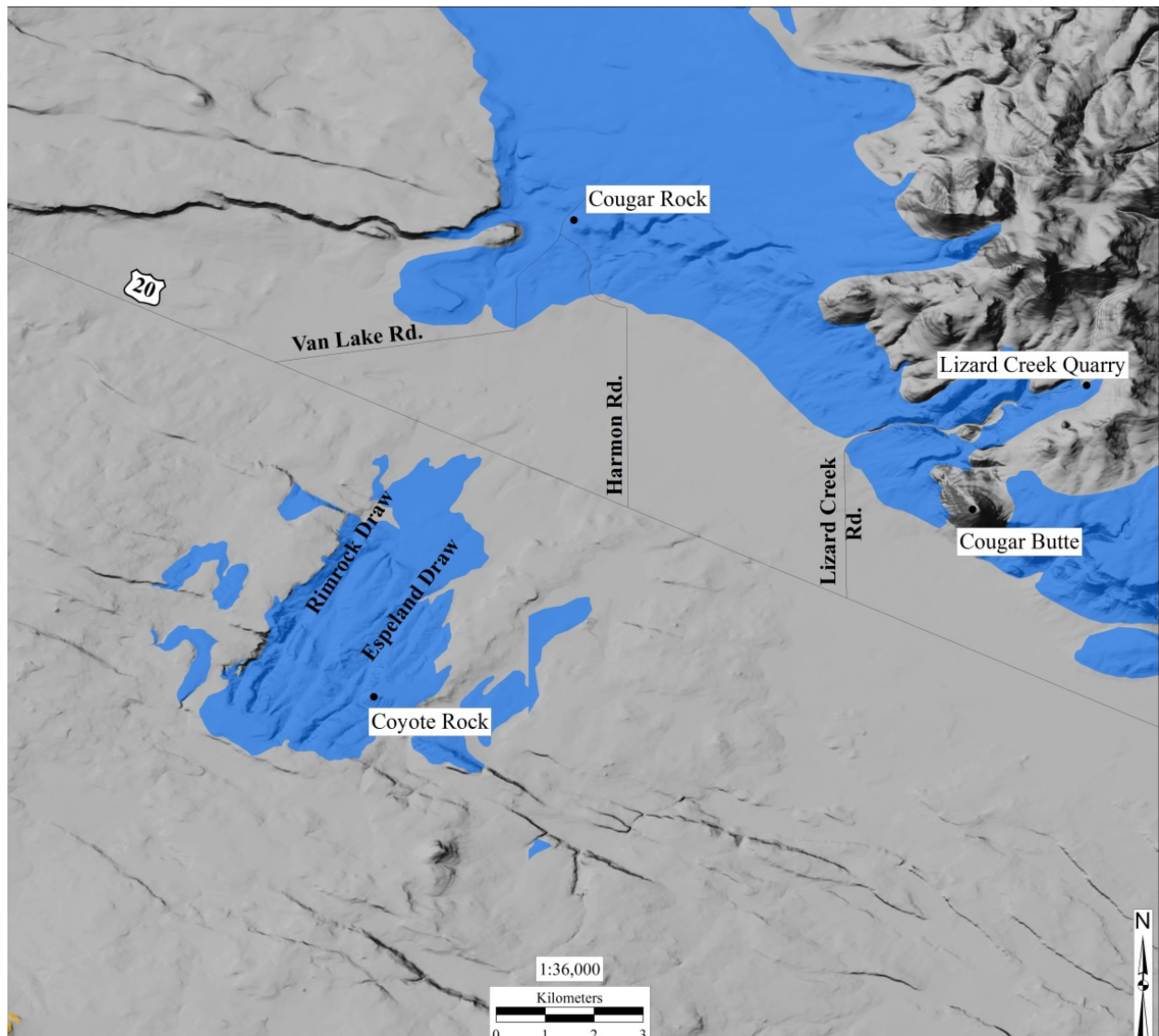


Figure 3.5 Map of Hampton Tuff outcrops and local feature names. Several outcrops and sample descriptions defined in the text are from these locations. Much of the landscape is now covered by younger basalts and alluvium limiting the discovery of large outcrops of the Hampton Tuff to fault scarps (e.g. Cougar Rock) and eroded channels (e.g. Rimrock Draw and Espeland Draw). Espeland Draw is the location referred to by Johnson (1998).

and crystallization of interstitial quartz (Figure 3.6B) Fiamme are vapor-phase altered and have a sugary texture. Flattened pumice clasts are mainly light colored, grey or white. The averages of the long dimension of five largest pumice counts for Coyote Rock is 16.3 cm. Pumice clasts are flattened 5:1. EMP analysis of glass for sample HJS-HTP-008, a banded black and white fiamme, returned no usable data due to post-emplacment alteration (Figure 3.6 A).

Most commonly, the black, densely welded vitrophyre crops out beneath the brown densely welded section (Figure 3.4). Abundant euhedral plagioclase, ~1-2 mm, pyroxene, and olivine are less than 3% of the rock. Where visible, the basal vitrophyre is less than 1 m in thickness, base not exposed.

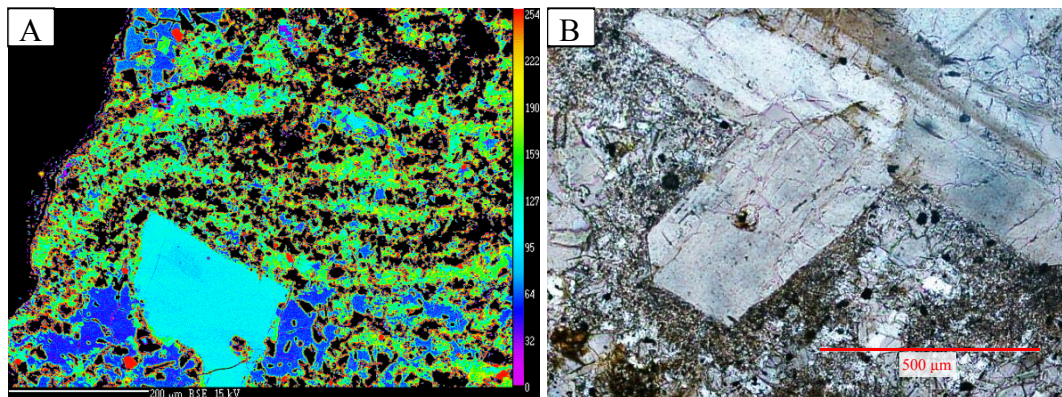


Figure 3.6 A. Back scatter electron image of sample 008. Post emplacement vapor phase alteration resulted in the interstitial growth of quartz polymorphs obviating EMP analysis of glass. **B.** Image of thin section of sample 007, a whole rock sample from the vapor-phase altered section of Coyote Rock. Twinned plagioclase dominates the upper right corner. The fabric of the tuff has been obliterated by post emplacement vapor-phase alteration and crystallization of interstitial quartz species, likely tridymite, or cristobalite.

The basal vitrophyre occurs as a black ash layer beneath the brown densely welded section of Lizard Creek Quarry and is coarse grained with small rounded pumice clasts that are mainly white or light tan (Figure 3.7). The nonwelded black ash transitions to an incipiently welded and then to partially welded ash that appears dark brown in outcrop but consists of compacted black ash, fractured plagioclase and compacted pumice clasts and fiamme (Figures 3.8 and 3.9).

Distal outcrops of the Hampton Tuff found north of Brothers, Oregon in the Camp Creek Rd area consist of two pumiceous sections which are typically 7.5 m (20-25 ft) thick where found. A lower non-welded slope-forming layer contains abundant pumice clasts that are mainly light colored (white, pink, tan or light brown) and typically 2-4 cm. Dark colored pumice that are mainly black are less than 1% of the deposit but are larger (up to 8 cm) than light colored pumice. Abundant euhedral



Figure 3.7 Non-welded basal vitrophyre at Lizard Creek quarry. Course grained black ash with small rounded white pumice and fractured plagioclase.

plagioclase phenocrysts (2 -3 mm) are 5% of the groundmass. Other phenocrysts include euhedral pyroxene and olivine. A platy parting separates the lower section from a partially to moderately welded ridge-forming cap rock (Figure 3.10). The upper section is more resistant to weathering and often weathers to large platy blocks where erosion of the platy parting undermines the cap rock. The ashy matrix is a lighter grey than the lower section

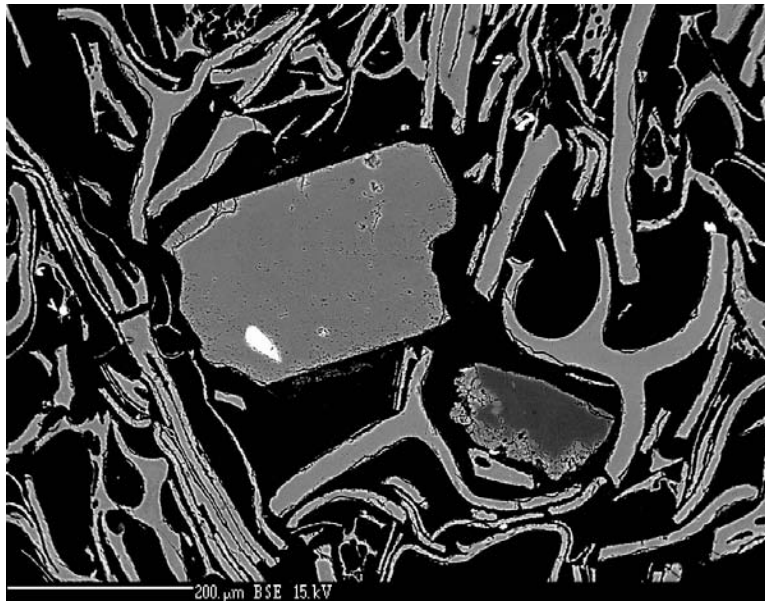


Figure 3.8 Back-scattered electron image of sample 0038 – coarse grained black ash from LCQ. Deformation of glass shards is most evident below and left of the plagioclase phenocrysts where glass shards are folded and being flattened

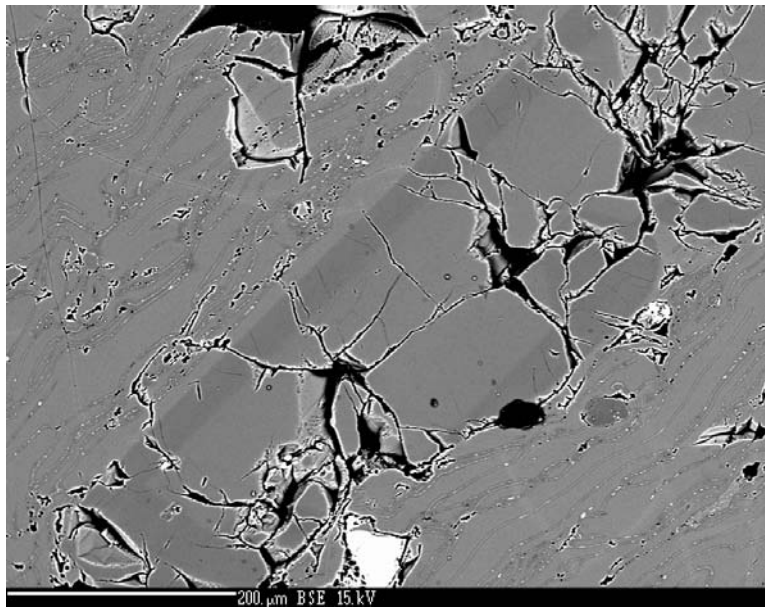


Figure 3.9 Back-scattered electron image of sample 0037 – partially welded vitrophyre that lies stratigraphically above sample 0038. Elongation and flattening of glass shards is evident throughout the sample. The previously euhedral fractured plagioclase displays minor zoning. The bright spot in the bottom center is likely Fe-Ti oxide.



Figure 3.10 Platy parting separates the nonwelded lower slope-forming section from the partially welded ridge-forming upper section. Photograph taken north of Brothers, Oregon, in the Camp Creek Rd. area.

and hosts large light to medium brown pumice clasts that vary in size up to 58.5 cm.

The abrupt change likely reflects a transition to vapor-phase altered tuff.

The average of the longest dimension of a five largest pumice count is 18 cm. Dark pumice are < 1% of the pumice population. The average of five largest dark pumice is 2.45 cm. Deformed pumice are flattened 6:1. Lithics are generally less than 0.5 cm and less than 5 % of the matrix. Clear euhedral plagioclase are 5 -7% of the matrix.

Volume

Modern outcrops of the Hampton Tuff cover an area of ~200 km². The estimated original extent of the tuff is 2418 km², based on a polygon drawn around existing outcrops and encompassing an area of low paleotopography (Figure 3.11). Nonwelded, pumiceous deposits of the Hampton Tuff are most apparent in the area of Camp Creek Rd. It is likely that the distal, nonwelded facies extends westward beyond this area but has eroded or is covered by younger basalts. Decreasing relief on northwest striking fault scarps of the Brothers Fault Zone reduce the chances that the Hampton Tuff will be found along scarp faces as the offset of the faults is continually reduced to the NW.

The tuff is not found north of topographic highs such as Logan Butte, or NE of Hampton Butte where it likely would have cropped out beneath basalts that have banked onto Hampton Butte dacite in areas of good exposure. This suggests that the pyroclastic flow lacked significant energy to overtop these barriers with significant deposits to withstand subsequent erosion. The Hampton Tuff is not found anywhere on Wagontire Mountain (Walker, 1967; Greene, 1972), or likely to be found at

Horsehead Mountain (MacLean, 1994). Wagontire Mountain is more than 50 km SE of the center of current distribution and is likely too far for the tuff to have traveled. Horsehead Mountain is further still. Outcrops in these areas that bear resemblance to the Hampton Tuff are likely the Buckaroo Lake tuff, or possibly the newly discovered Potato Lake tuff.

The Hampton Tuff is likely to have traveled at least as far to the south as it has to the north (~20 km). This is due to the fact that the deposits of pyroclastic eruptions will travel roughly the same distance from the source outward in all directions (Ross and Smith, 1961; Walker G.P.L., 1983). However, the tuff is not exposed south or southwest of the Frederick Butte Volcanic Center. Frederick Butte is set on a horst with a NW striking graben on the north side and a sub-parallel N-NW striking graben to the south. The southern graben is mainly covered by younger basalts and basaltic-andesite stemming from areas likely close to Frederick Butte as well as basalts from the Fort Rock Basin and Christmas Valley area. Fault blocks of the graben remain exposed SE of Frederick Butte near the Christmas Valley Sand Dunes.

The thickest outcrops of the Hampton Tuff are in the areas where the tuff has either ponded in paleo-river channels (Camp Creek Rd.) or banked up against paleo-highs (Cougar Butte and Hampton Buttes area). If the thickness of deposits found along exposed fault scarps, such as Cougar Rock and in the area of Rimrock Draw, which represent areas of low-paleo relief, are typical of the original deposition of the tuff then a minimal thickness of ~ 8 meters can be inferred. However, in an area south of the town of Hampton, Oregon, the thickness along a fault scarp was roughly

measured to be ~ 42 m, suggesting that a slightly higher average thickness might pertain to certain areas. Using a polygon that encloses known outcrops of the Hampton Tuff and an extent that the tuff is likely to have covered (Figure 3.11) a minimum areal extent of 2418 km^2 is determined. With a minimum deposit of 8 - 10 m the volume is estimated to be $19 - 24 \text{ km}^3$. This estimate does not include magma lost as distal pyroclastic deposits or tuff ponded in a buried caldera. The volume may be as much as double. Regardless, the Hampton Tuff is ten times less voluminous than the Rattlesnake Tuff.

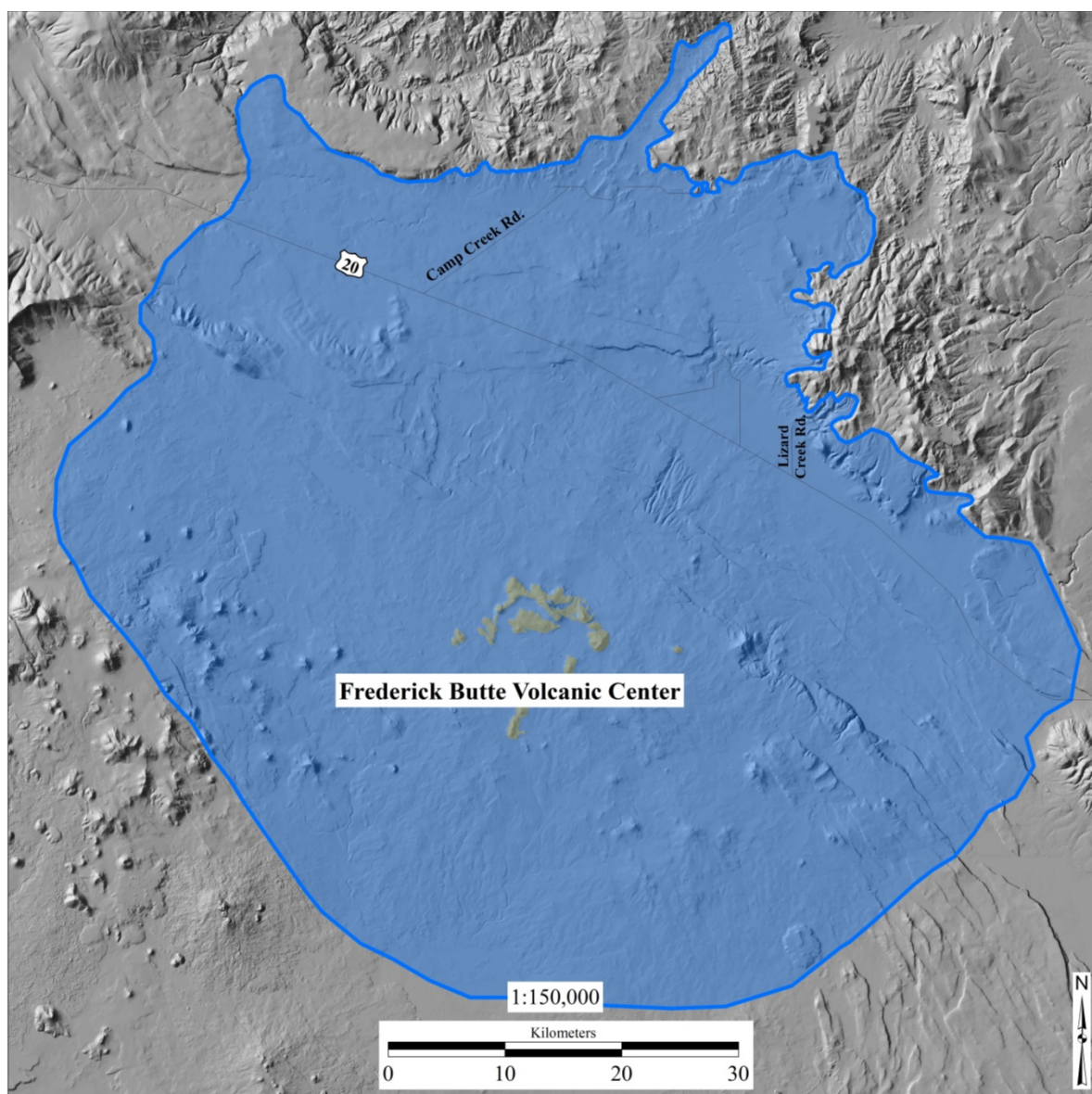


Figure 3.11 A blue polygon encloses the known outcrops of the Hampton Tuff and an area of probable original extent. Volume and original area are based on the idea that a high energy ash-flow will travel an equal distance in all directions from source of the eruption (Ross and Smith, 1961; Walker, G.P.L, 1983). The area of the polygon is 2418 km².

3.2 The Potato Lake tuff

3.2.1 Discovery and name

Exploration of an area south of Hampton, Oregon resulted in the discovery of a previously unknown tuff. An outcrop of a non-welded pumiceous tuff was discovered on the road through a small canyon (Figure 3.13). Geochemical analysis concludes that this outcrop is not the Hampton Tuff (Section 3.5). The age of the tuff has a weighted mean age of 5.13 ± 0.02 Ma (2σ).

The Ignimbrite is informally named the Potato Lake tuff.



Figure 3.12 Posing with Dr. Anita Grunder at the outcrop of a previously unknown ignimbrite. We name it the Potato Lake tuff.

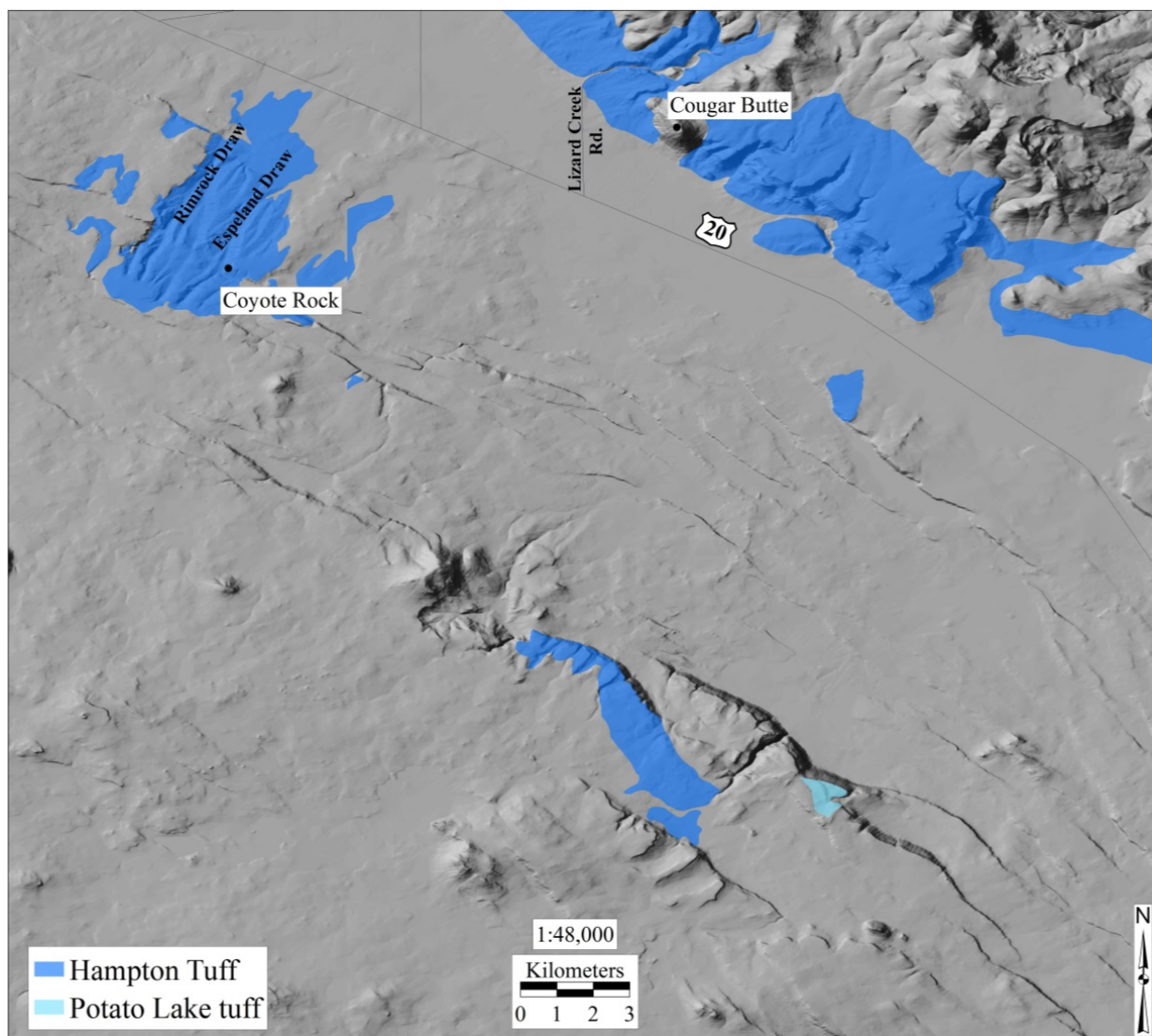


Figure 3.13 Map locations for the Potato Lake tuff. Outcrop of the Potato Lake tuff is near an outcrop of the brown densely welded section of the Hampton Tuff and was originally assumed to be a pumiceous section of the Hampton. Chemical analysis concludes that these samples are not the Hampton Tuff. Argon-argon dating gives a weighted mean age of $5.13 \pm .02$ Ma.

3.2.2 Location and description

The Potato Lake tuff crops out along an unpaved, backcountry roadway on the eastern edge of the Benjamin Lake Quadrangle, Oregon, 7.5-minute series. At an elevation of 1450 m (4760 ft), a 3 m high cliff is an outcrop of a pyroclastic deposit consisting of a pumiceous partially welded tuff. The weathered surface is dark brown or purple covered by various forms of lichen that are mainly white. The partially welded section consists of light brown to orange pumice clasts, typically 1- 2 cm, which are flattened 3:1, in a light brown vitriclastic matrix of orange and black glass shards. Sparse black pumice clasts are flattened 5:1. Clear euhedral plagioclase phenocrysts (~ 1 mm) are < 3% of the groundmass. Other, more sparse, phenocrysts include quartz, Fe-Ti oxides, and pyroxene. Angular lithics are typically 0.5 cm, but are occasionally as large as 1.5 cm, consists of pink rhyolite and oxidized basalt and basaltic scoria. The outcrop grades upward into nonwelded with large pumice, some greater than 15 cm. Figure 3.14 is a photograph of large pumice clasts, from the upper nonwelded section, in front of the partially welded cliff forming section that crops out near the road.

The partially welded cliff section grades from an incipiently welded section that consists of a darker vitriclastic groundmass where black glass shards dominate orange glass shards. Pumice clasts up to 4 cm, deformed 3:1, are mainly light brown. Lithics, 2 – 3% of the matrix, are typically 0.5 cm, but up to 2 cm, consist of angular, fine grained pink rhyolite and a few oxidized basaltic clasts.

In this location the Potato Lake tuff is >10 m thick, base not exposed, and consists of glassy pumice that are collapsed, or deformed, but maintain some

porosity. The tuff is not vapor-phase altered. The maximum welding grade at this location is partially welded with pumice.

This is presumably the nonwelded to incipiently welded marginal facies of a more extensive ignimbrite that would have a source further east, consistent with the westward propagation of silicic magmatism of the High Lava Plains.



Figure 3.14 Large pumice clasts were collected from above the partially welded cliff pictured here. Pumice clasts are mainly light colored, white, or tan, but include black and white banded pumice and a few black pumice. Hammer is ~ 42 cm (16.5 in).

3.3 $^{40}\text{Ar}/^{39}\text{Ar}$ results and discussion:

3.3.1 Hampton Tuff

Hampton Tuff samples analyzed in this study have a weighted mean age of 3.91 ± 0.02 Ma (2σ). Data for Hampton Tuff samples submitted for age determinations were evaluated based on the following criteria (after Duncan and Keller, 2002, Dalrymple et al., 1988a, Dalrymple and Lanphere, 1974):

1. A well-defined high-temperature plateau is formed by three or more contiguous gas fractions (steps) each representing $\geq 50\%$ ^{39}Ar released.
2. A well-defined inverse isochron exists for the same plateau steps.
3. The plateau and isochron ages are concordant.
4. The $^{40}\text{Ar}/^{36}\text{Ar}$ intercept is not significantly different than the atmospheric value of 295.5 at the 95% confidence level.

Plagioclase from samples HJS-HTP-006-2012 and HJS-HTP-0020-0913 meet the criteria outlined above and yielded $^{39}\text{Ar}/^{40}\text{Ar}$ ages of 3.89 ± 0.02 Ma and 3.91 ± 0.02 Ma, respectively, (figure 3.14). Although the glass from sample HJS-HTP-0020-0913 did produce a well-defined plateau it is not concordant with its associated inverse isochron age of 3.06 ± 0.22 Ma (figure 3.17 A); this glass age is also younger than the K/Ar age reported by Walker, 1979. The age obtained from the glass for sample HJS-HTP-0020-0913 is younger than the plagioclase ages obtained from plagioclase for either sample 0020 or sample 006 and does not meet the outlined criteria and is therefore rejected as an age for the Hampton Tuff.

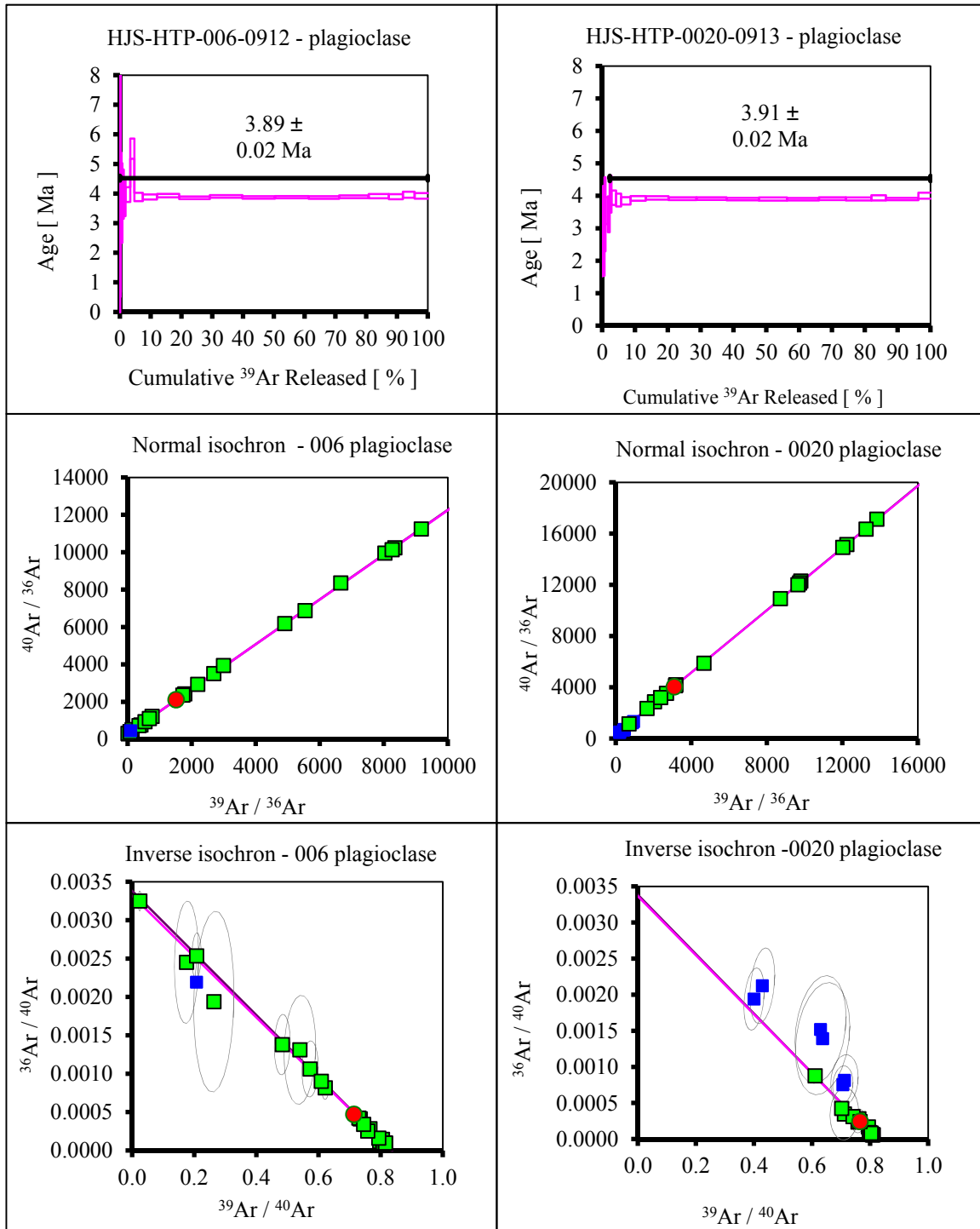


Figure 3.15 Age spectra plots of plagioclase for samples 006 and 0020. Ages for both 006 and 0020 meet outlined criteria – well-defined plateau formed by contiguous steps (16 and 13 respectively), well-defined isochrons for the same steps that are concordant. Blue squares are analyses not included in the age calculations. The red circle is the total fusion age.

Following a protocol provided by Brad Pitcher and Dan Miggins (personal communication, 2014), A second split of glass for 0020 was hand-picked and submitted for $^{39}\text{Ar}/^{40}\text{Ar}$ analysis. Glass shards were analyzed under a binocular microscope and chosen based on their size, thickness, and transparency. The color of the glass shards may also be of importance - but this will vary from sample to sample. Sample 0020 is a grey-banded pumice clast. Glass shards vary in color from light

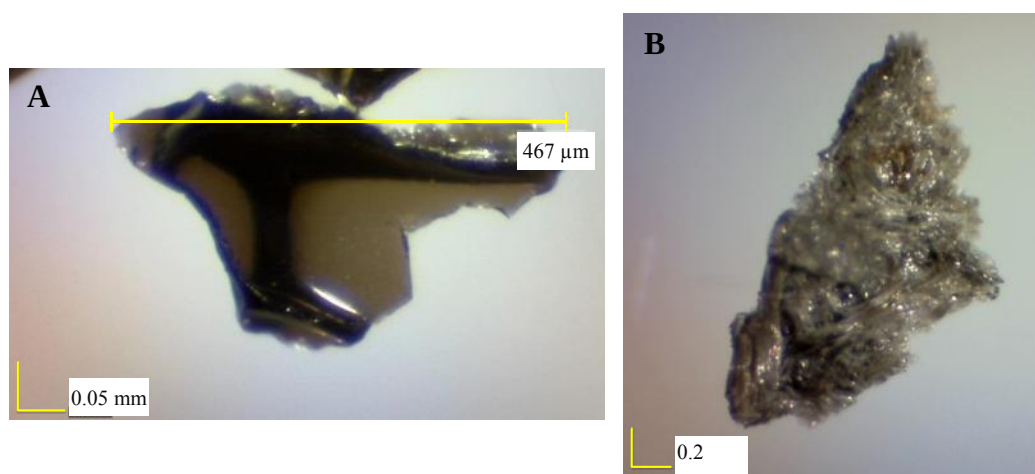


Figure 3.16 Images of glass shards from sample 0020 demonstrating size and shape of glass shards chosen for the second glass experiment. **A.** Vitric glass shard demonstrating thickened areas that are shard junctions between lighter bubble walls that remain intact. **B.** A “fluffy” glass shard. Although appearing vitric, the bubble walls and shard junctions are too thin to resist alteration and may allow the exchange of atmospheric argon and radiogenic argon.

grey to dark grey and in some cases appear black. Transparency and thickness may be the most important of the criteria. Shards that appeared “fluffy” (figure 3.16 B) were eliminated from the analysis based on the likelihood that minute vesicularity would promote hydration and alteration and has led to the “fluffy” appearance. Vitric glass shards $> 150\ \mu\text{m}$ and $< 500\ \mu\text{m}$ (Figure 3.16 A) were treated with 1N HNO_3 acid to

remove any organic material remaining after crushing and washing. Glass shards were then treated with a 5% HF solution for only 45 seconds to reduce loss of glass while eliminating birefringent edges and to loosen or remove phenocrysts or inflated/altered glass (Figure 3.16A and B). More importantly, the HF treatment dissolves any post-emplacement weathering products and outer glass rims that might contain abundant excess argon. Shards were then washed and dried overnight at 55° C drying. 10 mg of these vitric glass shards (Figure 3.16 A) were submitted for analysis.

Incremental heating of the second glass sample for 0020 produced a well-defined age plateau representing contiguous gas fractions for an age of 3.08 ± 0.28 Ma, which, again, is younger than the plagioclase age (Figure 3.17 B). However, while neither the inverse nor the normal isochrons are concordant with the age spectrum they are concordant with one another and suggest an age of 3.85 ± 0.19 Ma for the glass (Figure 3.18 A, B and C). The Isochron ages are also concordant with

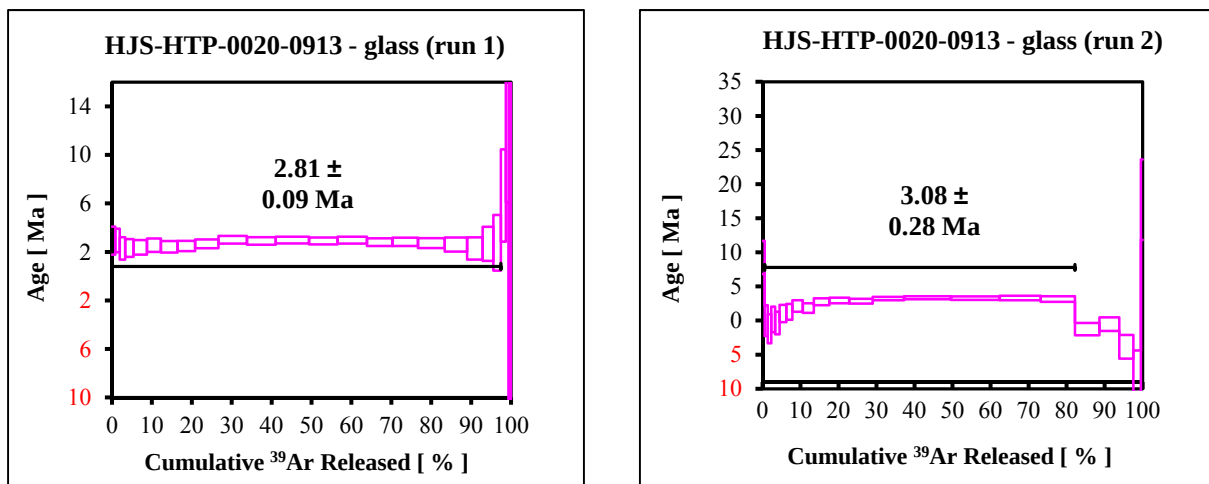


Figure 3.17 Age spectra plots for two separate analyses on glass shards handpicked from grey banded pumice, sample 0020. Neither analysis meets the criteria previously outlined. Age plateau are not concordant with isochron ages (normal or inverse).

the plagioclase ages (Figure 3.15). Regression of the slope and y-intercept of the inverse isochron results in an initial atmospheric argon ($^{40}\text{Ar}/^{36}\text{Ar}$) composition of 291.4 ± 0.8 for the second glass analysis. This value deviates from the accepted value of 295.5 recommended by Steiger and Jäger (1977).

By inserting the atmospheric argon value of 291.4 obtained for sample 0020 (rather than the standard value of 295.5) into the age calculations an age of 3.85 ± 0.10 Ma is obtained (Figure 3.18). The plateau age is well-defined and represents 16 contiguous step heating events and 81.6 % of the cumulative ^{39}Ar released. A well-defined isochrons exist for the same plateau steps and both isochrons are in accord with the plateau age.

Systematic use of the atmospheric argon value 295.5, since its recommendation by Steiger and Jäger (1977), is a standard normalization adopted so that measurements between varying laboratories can be directly compared (McDougall and Harrison, 1999). The $^{40}\text{Ar}/^{36}\text{Ar}$ value (atmospheric argon ratio) is used to determine and correct for non-radiogenic ^{40}Ar – which may exist within the sample or may be introduced from the vacuum system of the mass-spectrometer (Kuiper, 2002; McDougal and Harrison, 1999). The inverse isochron diagram from Kuiper (2002) (Figure 3.19) is used to graphically represent the ratio of atmospheric (non-radiogenic) argon to radiogenic argon (the y-intercept gives the composition of atmospheric argon and the x-intercept the radiogenic component). The inverse isochron diagram derives the age of the sample without the assumption of an atmospheric value of 295.5 (Kuiper, 2002, McDougal and Harrison, 1999; Heizler and Harrison, 1988). The use of isochron ages is preferred in some cases where the

presence of excess argon (trapped or atmospheric) corrupts the age spectra resulting in ages that are too old (Morgan et al., 2009; Heizler and Harrison, 1988).

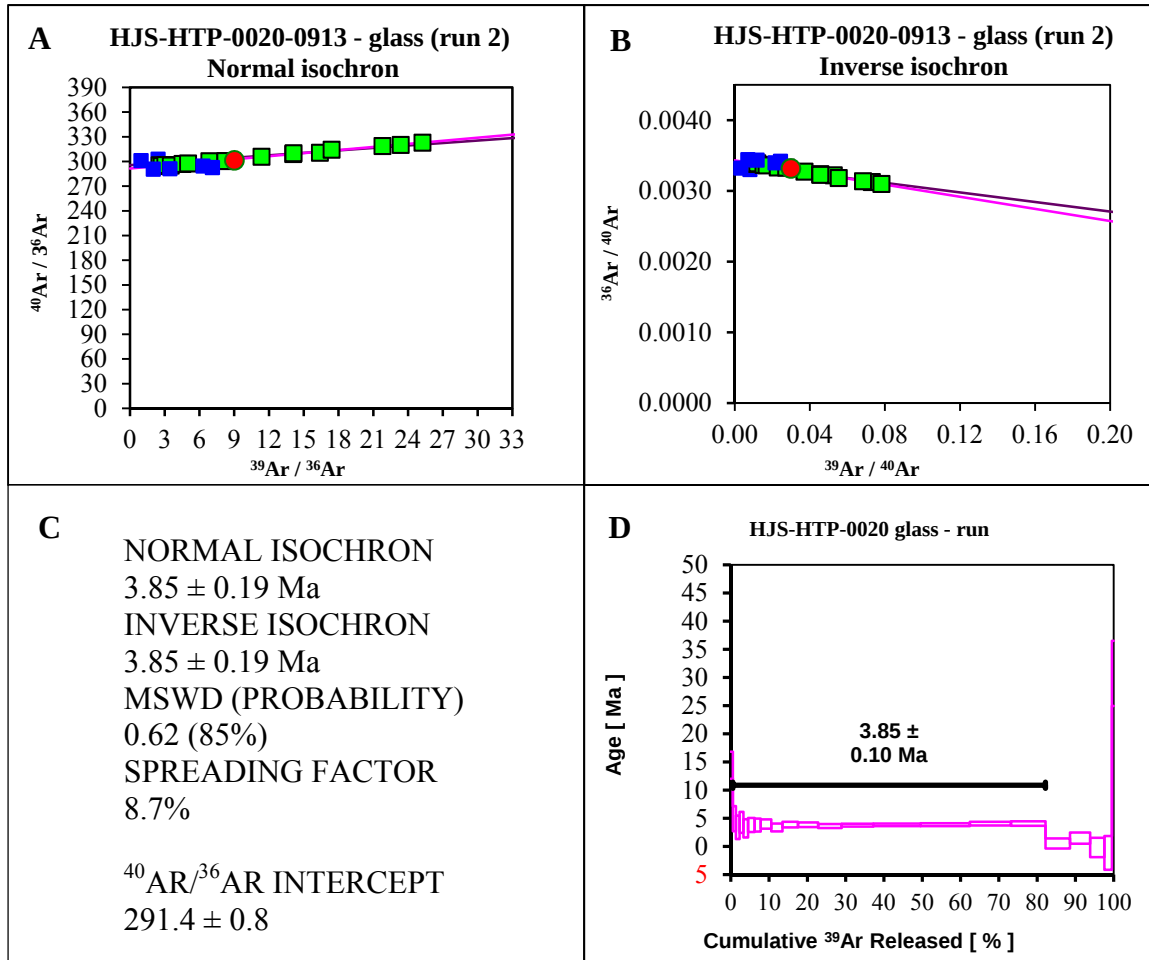


Figure 3.18 Isochron diagrams and corrected age spectrum for 0020 glass – run 2. **A** – Normal isochron diagram. **B** – Inverse isochron diagram. **C** – Values of age calculated for both isochrons with associated statistical data and atmospheric argon value. Calculated ages for normal and inverse isochron diagrams are concordant and provide an atmospheric value of 291.4. Isochron ages are derived independent of the assumption of $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 295.5 and therefore provide an accurate age for the glass regardless of the atmospheric argon value. **D** – Age spectrum plot for 0020 glass run 2 - incorporating a correction for sub-atmospheric argon value of 291.4 instead of the standard value of 295.5 results in an accurate age for the Hampton Tuff that is concordant with the plagioclase age obtained for this sample.

Complex release patterns occurring in samples that deviate from the assumed atmospheric argon value of 295.5 may reveal themselves in disturbed age plateau plots (Figure 3.20). Heizler and Harrison (1988) published data revealing that many of the minerals most commonly used for $^{40}\text{Ar}/^{39}\text{Ar}$ age dating contain excess argon rendering the generated age spectra meaningless. Figure 3.20 from Heizler and Harrison (1988) represents the gas fractions of an alkali-feldspar separate analyzed using the $^{40}\text{Ar}/^{39}\text{Ar}$ method. The initial age spectrum plotted which assumes an atmospheric value of 295.5, displays a “saddle-shaped” plateau, commonly indicating the presence of excess argon (McDougall and Harrison, 1999; Heizler and Harrison, 1988). However, linear regressions of the same gas fractions indicate two linear

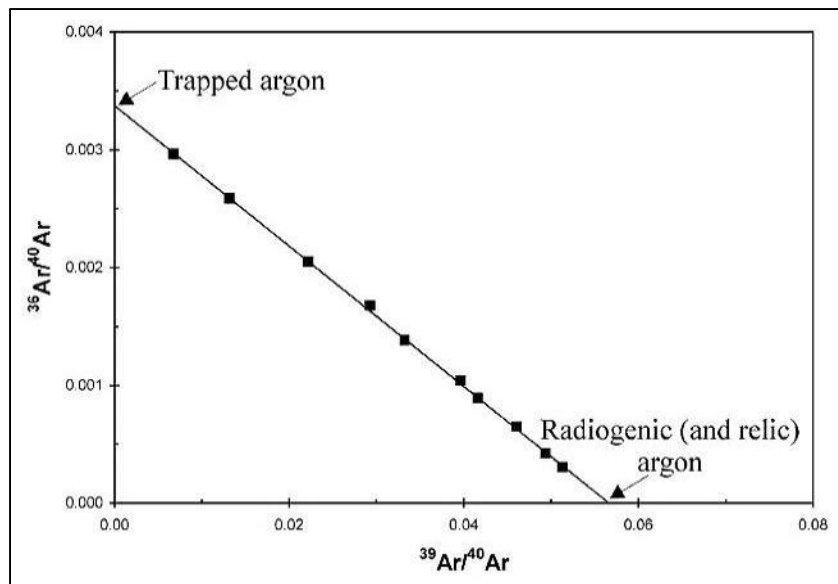


Figure 3.19 An idealized inverse isochron plot. The ratio of $^{36}\text{Ar}/^{40}\text{Ar}$ is plotted against the ratio of $^{39}\text{Ar}/^{40}\text{Ar}$. The x-intercept provides the radiogenic composition of argon in a sample while the y-intercept provides the composition of trapped argon in the sample. From these values an inverse isochron age can be calculated (Kuiper, 2002).

arrays each representing a separate excess argon composition (denoted by the inverse isochron diagram; Figure 3.19). Calculation of the age of the alkali-feldspar utilizing the composition of trapped argon provided by the inverse isochron flattens the age spectrum and reduces the age to that of the isochron. Heizler and Harrison (1988) presented the issue of excess argon in K-feldspar, biotite, muscovite, and hornblende – the four most commonly used minerals for determining geologic age.

While the forgotten implications of excess argon demonstrated by Heizler and Harrison could be far reaching in geochronology they don't necessarily resolve the issue of sub-atmospheric argon values of volcanic glasses. Cerling et al. (1985) indicate that mobility of argon and potassium components in glass - resulting from hydration and alteration which renders the glass unsuitable for dating – leads to an excess atmospheric argon component producing ages that are too old. Investigations

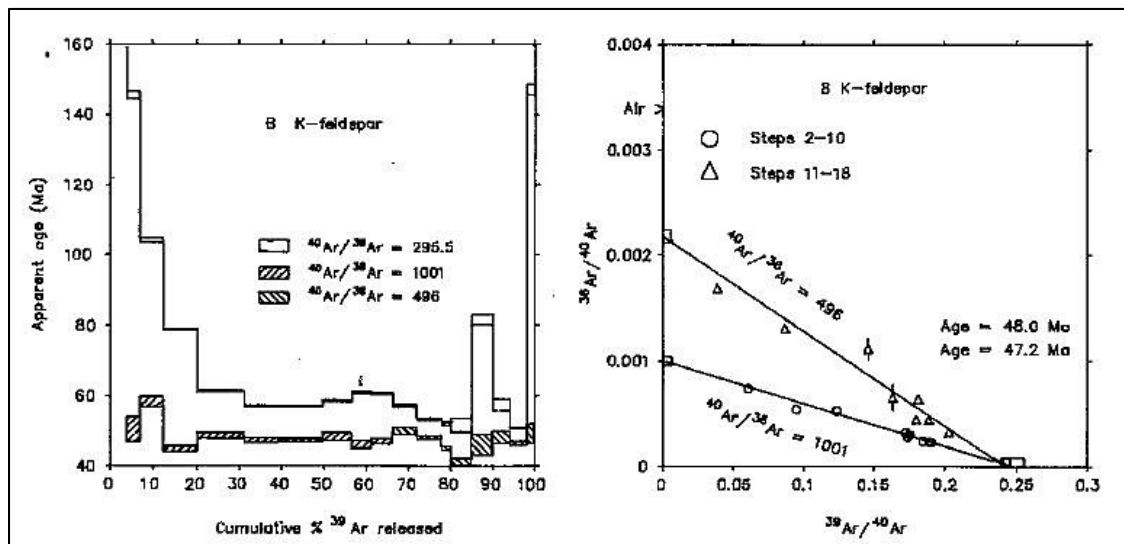


Figure 3.20 Age spectra and inverse isochron plots for K-feldspar published by Heizler and Harrison, 1988. The figure on the left is the age spectra generated for contiguous heating steps of a K-feldspar separate. The initial saddle-shaped plateau is rendered meaningful by the incorporation of the composition of excess argon obtained from the inverse isochron diagram on the right (Heizler and Harrison, 1988).

by Morgan et al., 2009 indicate that varying concentrations of $^{40}\text{Ar}_{\text{atm}}$ (excess or atmospheric) within lava flows suggests varying degrees of equilibration between the lava and the atmosphere at the time of eruption. Electron microprobe data (wt% K) was used to calculate the mass for individual samples and then calculate the concentration of atmospheric ^{40}Ar within individual lava flows. These calculations indicated variations greater than three orders of magnitude in $\text{mol } ^{40}\text{Ar}_{\text{atm}}/\text{grams}_{\text{sample}}$ in a single flow (Morgan et al., 2009).

Furthermore, mass-dependent fractionation laws (Young et al., 2002) dictate that ^{36}Ar should diffuse faster than ^{40}Ar into a lava when it comes into contact with the atmosphere and that incomplete equilibration resulting from the quenching of that lava will lead to sub-atmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratios within the lava flow (Morgan et al., 2009).

To mitigate the issue of variations in $^{40}\text{Ar}/^{36}\text{Ar}$ in volcanic glasses we use the isochron ages for sample 0020 (Figure 3.18 C) - as the isochron ages are determined independently of the composition of atmospheric argon - and accept the age of 3.85 ± 0.19 Ma as the apparent age of the volcanic glass. As indicated previously, the routine practice of calculating the age plateau with the standard value of 295.5 is not valid for this sample: therefore the calculated atmospheric composition of 291.4 ± 0.8 is used to determine the age spectrum (Figure 3.18 D) producing a concordant age of 3.85 Ma and increased precision of 0.10 Ma, which further substantiates the use of the calculated atmospheric value rather than the assumed value.

3.3.2 Age date results for the Potato Lake tuff

The weighted mean of the single crystal total fusion and the step heating method for the Potato Lake tuff is 5.13 ± 0.02 Ma.

Single crystal total fusion method ages of 19 crystals yields an average weighted mean age of 5.19 ± 0.09 Ma; releasing an average of 94.89 % of radiogenic argon (^{40}Ar). Figure 3.21 is the probability distribution, which is preferential to the age plateau when evaluating ages obtained by the single crystal total fusion method due to increased precision. The precision is greater because the calculation is not dependent upon the J-value whereas precision of the age plateau is reduced because of the propagation of the error associated with J.

Step heating $^{39}\text{Ar}/^{40}\text{Ar}$ analysis of plagioclase determined an age of $5.13 \pm$

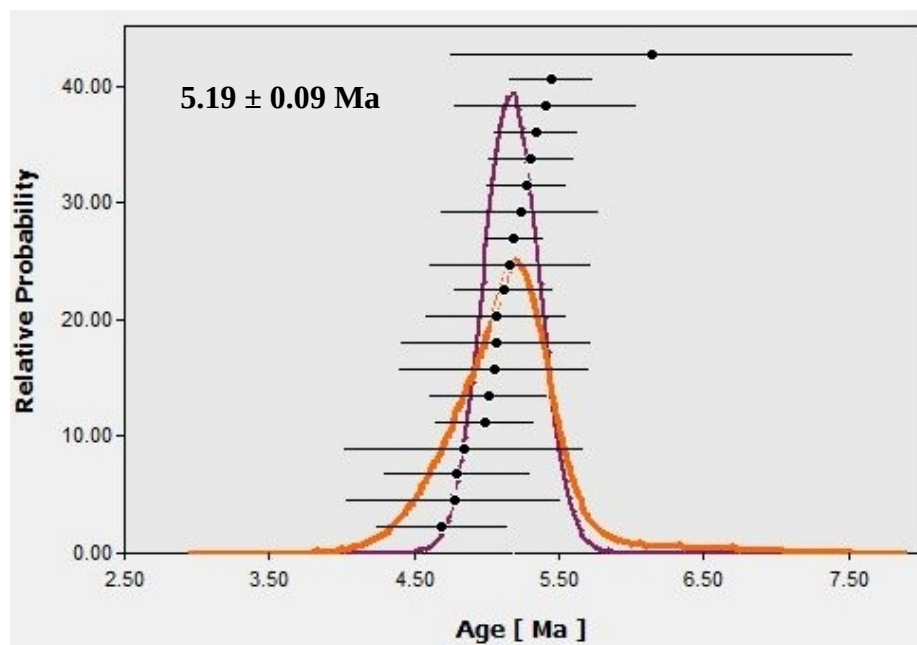


Figure 3.21 Results of 19 single crystal total fusion ages for sample 0064c_2 analyzed at Oregon State University are plotted on a relative probability diagram. The mode of peak distribution yields an age of 5.19 ± 0.09 Ma for the Potato Lake tuff.

0.01 Ma and meet the criteria outlined in section 3.3.1; producing a well-defined high-temperature plateau over 13 contiguous steps and representing ~90% of radiogenic argon released (Figure 3.22 A). Normal and inverse isochrons are well-defined; existing for the same plateau steps and are concordant with one another (Figure 3.22 B, C, and D).

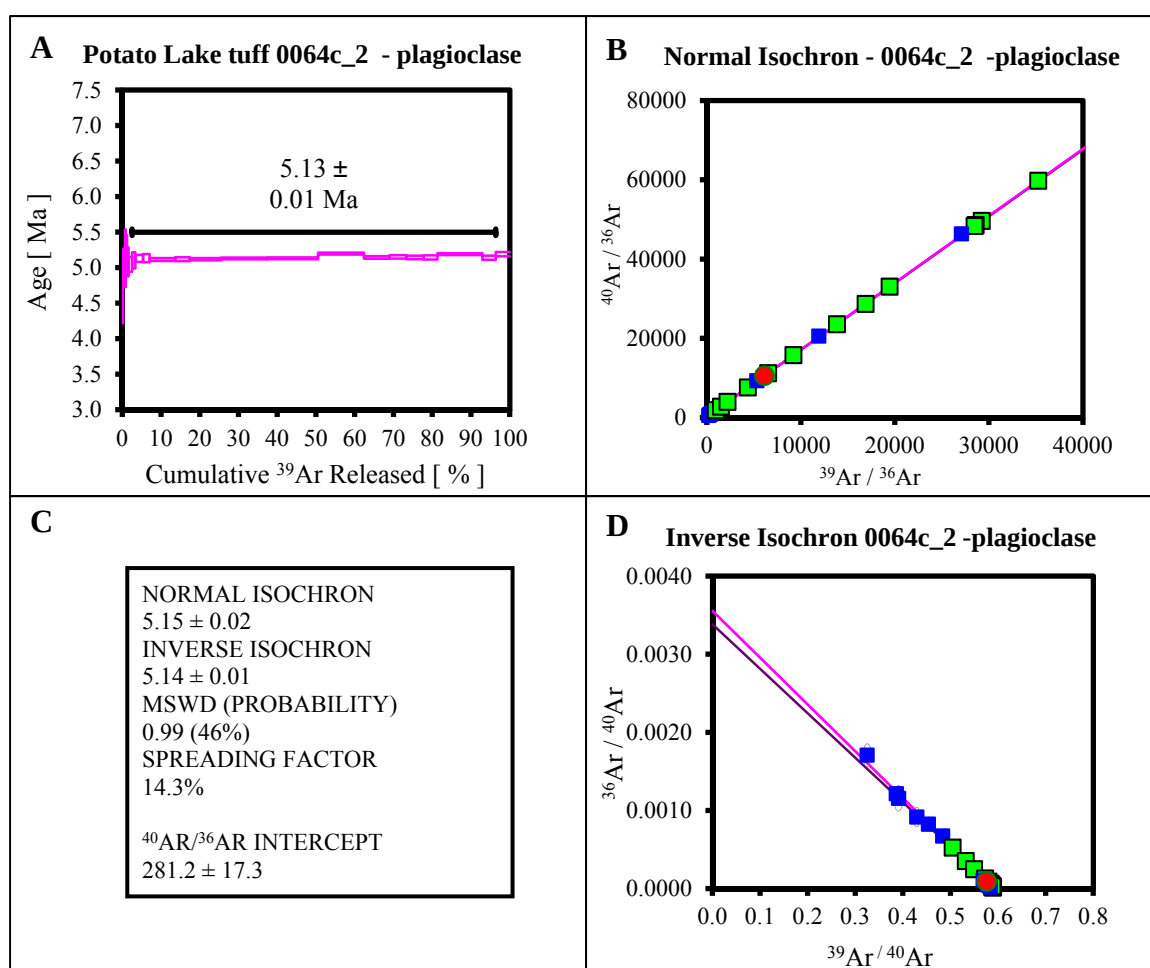


Figure 3.22 Isochron diagrams and age spectrum for the Potato Lake tuff, sample 0064c_2 plagioclase step heating method. **A** – Age spectra diagram. **B** - Inverse isochron diagram. **C** – Values of age calculated for normal and inverse isochrons with associated statistical data and atmospheric argon value. **D** – Age spectrum plot.

3.4 Geochemical Composition Results – The Hampton Tuff

3.4.1 Major Element Results - XRF

XRF analyses of seven whole rock samples conducted at Washington State University include one individual pumice sample, five bulk rock samples, and one fiamme. Silica content ranges from 72.3–74.1 wt% SiO₂. Total iron content, as FeO*, ranges from 2.8–3.6 wt% FeO* and decreases as silica increases. Variation diagrams of major elements versus SiO₂ (Figure 3.23) indicate decreasing trends with increasing silica content for all major elements, except K₂O which increases with increasing SiO₂ content. Whole rock analyses do not delineate compositional gaps and have limited compositional variation compared to glass shard analyses

3.4.2 Major Elements Results – Electron Microprobe

Electron microprobe (EMP) analysis conducted at Oregon State University included twelve samples. Silica concentration of glass shards ranges from 67. –77.5 wt% SiO₂ and total iron content ranges from 0.38–6.41 wt% FeO*. Major elements decrease with increasing SiO₂ content, except K₂O. Variation diagrams of EMP glass shard analysis indicate two distinct compositional clusters (Figure 3.24). A dacitic composition ranges from 67.1 – 68.4 wt% SiO₂ and is represented by two separate pumice samples. A rhyolitic composition is represented by nine samples and ranges from 73.4 – 77.5 wt% SiO₂. Analyses conducted on sample 0022, a single pumice and associated groundmass glass (Figures 2.6 and 2.7), indicate that there is no

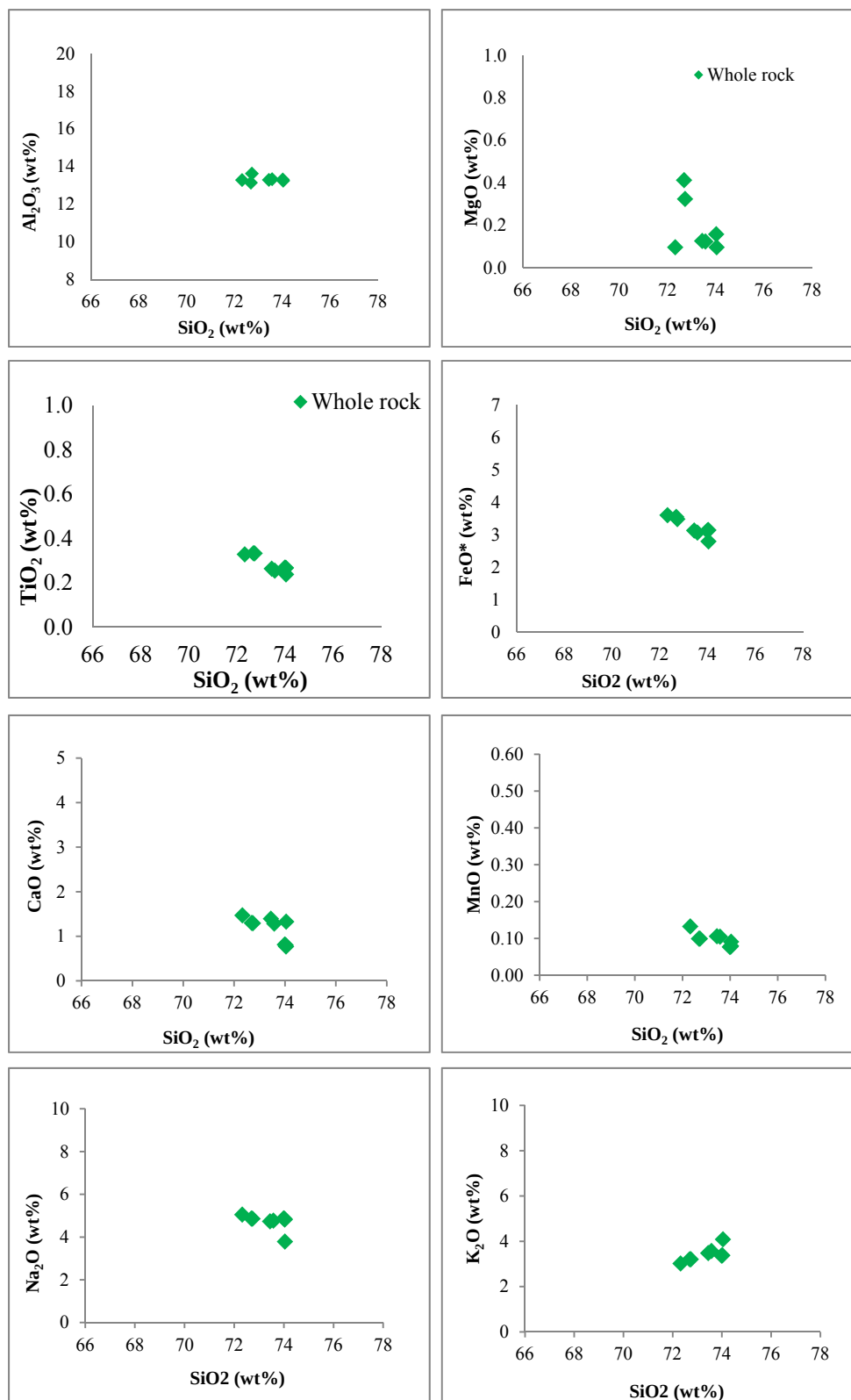


Figure 3.23 Silica variation diagrams for major elements – whole rock analysis from WSU for bulk rock and pumice samples. Whole rock analyses do not indicate compositional gaps and have limited compositional variation compared to glass shard analyses

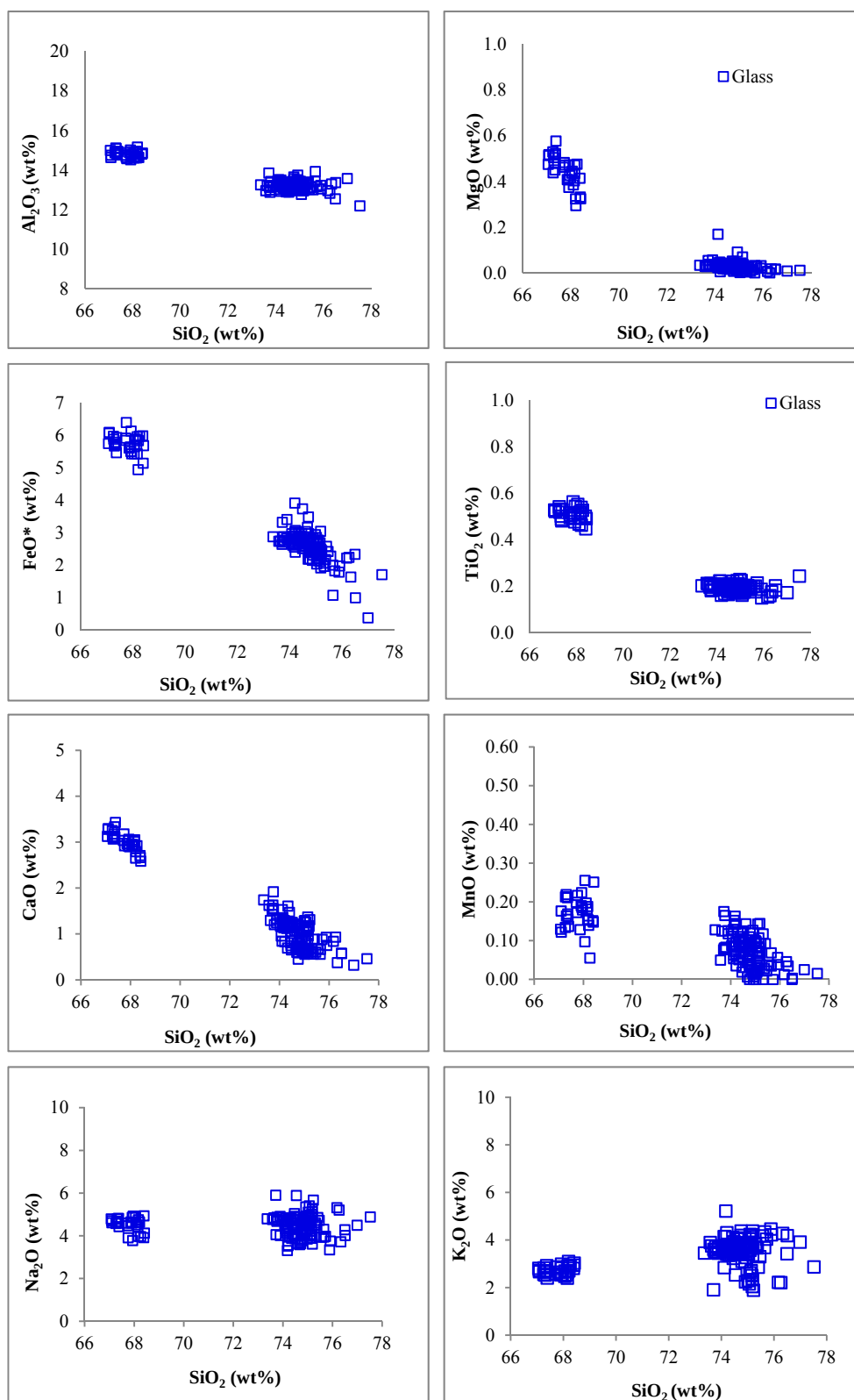


Figure 3.24 Variation diagrams of major elements versus silica for the Hampton Tuff - EMP glass shard analysis. Glass shards have a much wider variation in SiO_2 than whole rock XRF data. Data indicate a compositional gap and two compositional clusters.

statistically significant difference between the composition of the groundmass and the glass of the pumice.

3.4.3 Trace elements results – the Hampton Tuff

Selected trace elements and major elements SiO_2 and MgO (wt%) for the Hampton Tuff are plotted against Rb and compared to the Rattlesnake Tuff and the Devine Canyon Tuff (Figure 3.25 and 3.26). As Rb increases SiO_2 increases and MgO decreases. Compatible trace elements Sr, Ba, and Sc decrease with increasing Rb content (Figure 3.25). Incompatible elements Y, Yb, Th and Zr increase with increasing Rb (Figure 3.26). The increase in Zr with respect to Rb, in the Hampton Tuff, is a departure from the Rattlesnake Tuff in which Zr decreases with increasing Rb indicating zircon saturation and fractionation. The Hampton Tuff behaves more like the Devine Canyon Tuff. Although zircon saturation in the Devine Canyon Tuff is due to its peralkalinity while in the Hampton Tuff reflects that it is less silicic. The Hampton Tuff is enriched in Ba and U similar to the more evolved rhyolites of the Rattlesnake Tuff. The Hampton Tuff deviates from other the HLP ignimbrites in that it is depleted in Ta and Nb.

Rare Earth element diagram (Figure 3.27) for the Hampton Tuff indicates a negative Eu anomaly owing to the fractionation of plagioclase as Eu^{2+} readily substitutes for Ca^{2+} in the plagioclase crystal lattice. Variations in samples LCQ003d and LCQ005c are the likely result of post emplacement alteration localized to the Lizard Creek Quarry area.

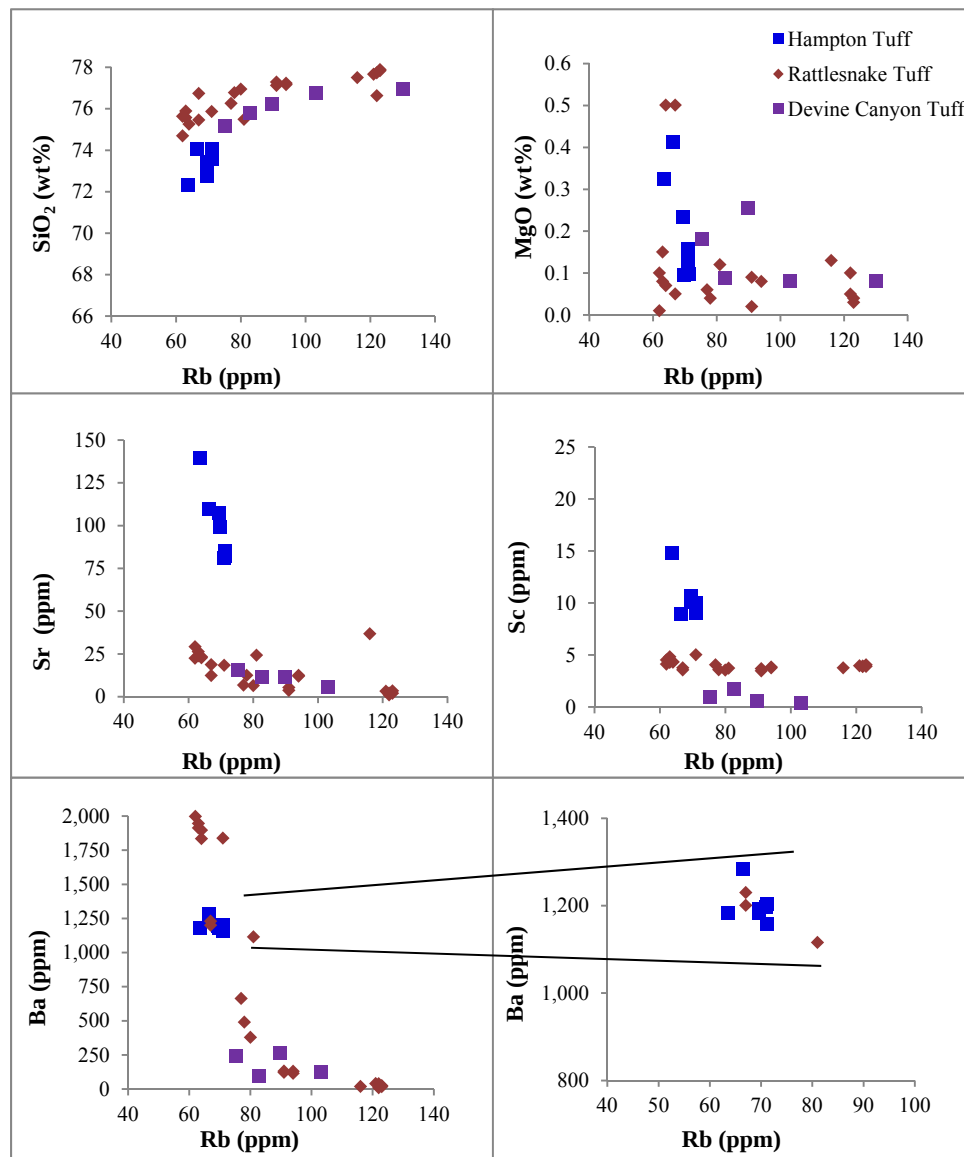


Figure 3.25 Variation diagrams of SiO₂ and MgO (wt%) vs. Rb and selected compatible trace elements versus Rb for the Hampton Tuff, Rattlesnake Tuff and the Devine Canyon Tuff. Silica content increases with increasing Rb, but MgO decreases as Rb increases. Compatible trace elements decrease with increasing Rb.

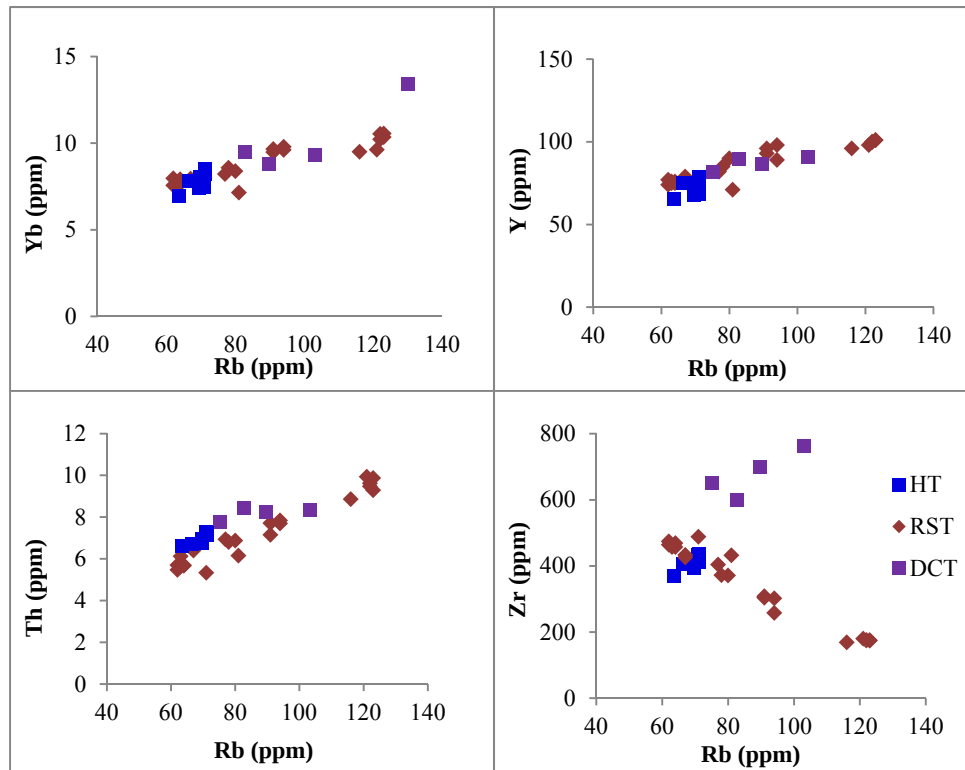


Figure 3.26 Variation diagrams for selected incompatible elements vs. Rb for the Hampton Tuff, Rattlesnake Tuff (RST), and the Devine Canyon Tuff (DCT). Th, Yb, and Y increase with increasing Rb for all three ignimbrites. However, Zr increases as Rb increases in the DCT due to zircon saturation and fractionation owing to the peralkalinity of the tuff. Whereas the increasing trend in the Hampton Tuff signifies that it is a less evolved and has lower silica content.

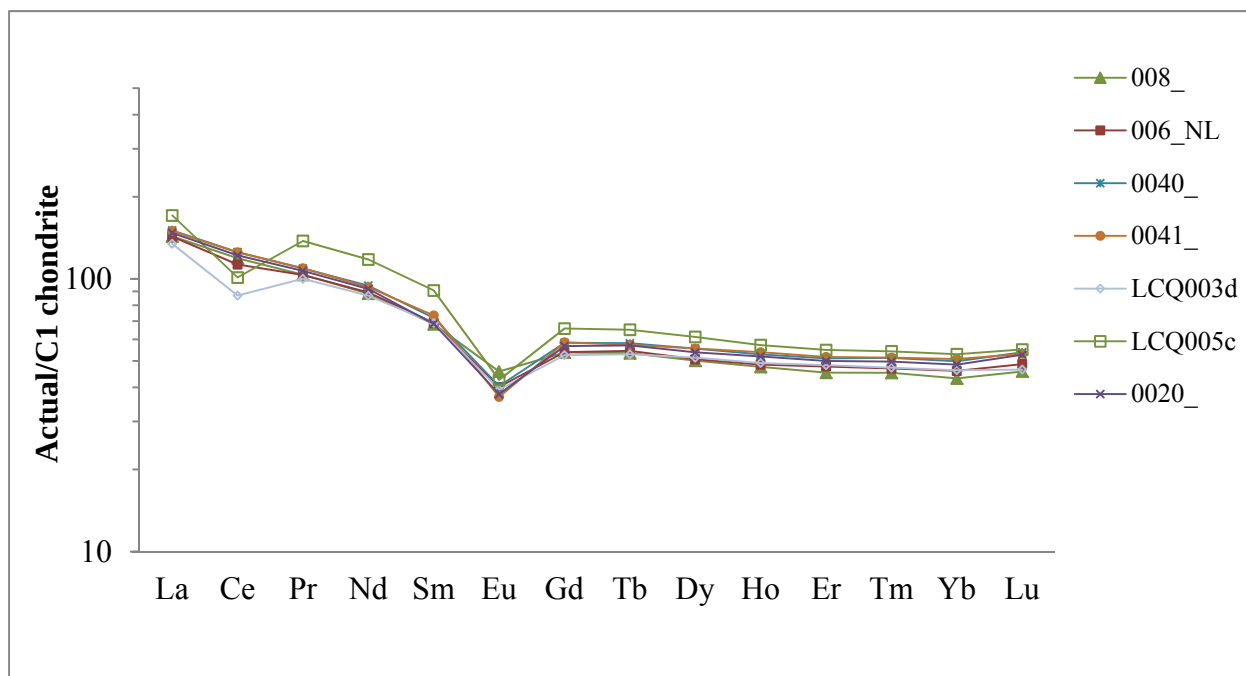


Figure 3.27 Spider diagram of rare Earth elements (REE) normalized to C1 chondrite for the Hampton Tuff. REE diagram has a slightly concave up appearance with a slight increase in Lu. Negative Eu anomaly is evident though not as great as the more evolved Rattlesnake Tuff. Deviations from the majority of Hampton Tuff by LCQ samples may be due to interaction with a localized waterbody resulting in post emplacement alteration. Symbols are organized by ascending silica content. Normalization standards of McDonough & Sun, 1995.

3.5 Geochemical composition results – Potato Lake tuff

3.5.1 Major Elements Results – XRF

XRF analysis of 11 whole rock samples were conducted at Washington State University included 11 individual pumice samples. Silica content ranges from 69.4 – 74.0 wt% SiO_2 . Total iron content ranges from 2.5 – 4.8 wt% FeO^* and decreases as silica increases. A compositional gap exists between 70.1 – 72.1 wt% SiO_2 . Variation diagrams of major elements versus SiO_2 (Figure 3.29) indicate decreasing trends, with increasing silica content, for all major elements except K_2O which increases with SiO_2 content. Bulk rock samples cluster into two, possibly three, distinct compositional clusters, except in the case of MgO , where pumice samples fall into three, and possibly four, compositional clusters (Figure 3.29). The additional clusters are the result of banding in pumice samples that have different compositions.

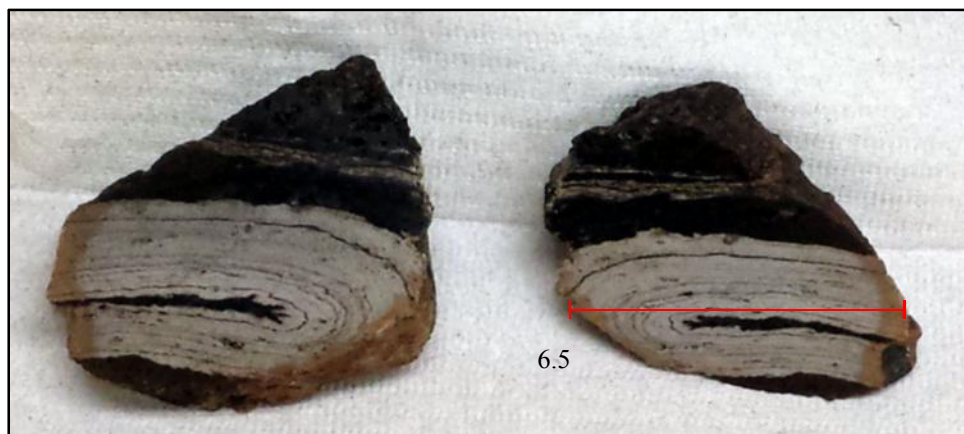


Figure 3.28 Image of sample number 0064a_4, a black and white banded pumice. XRF whole rock results indicate a silica content of 72.5 wt% SiO_2 , which may be somewhat misleading.

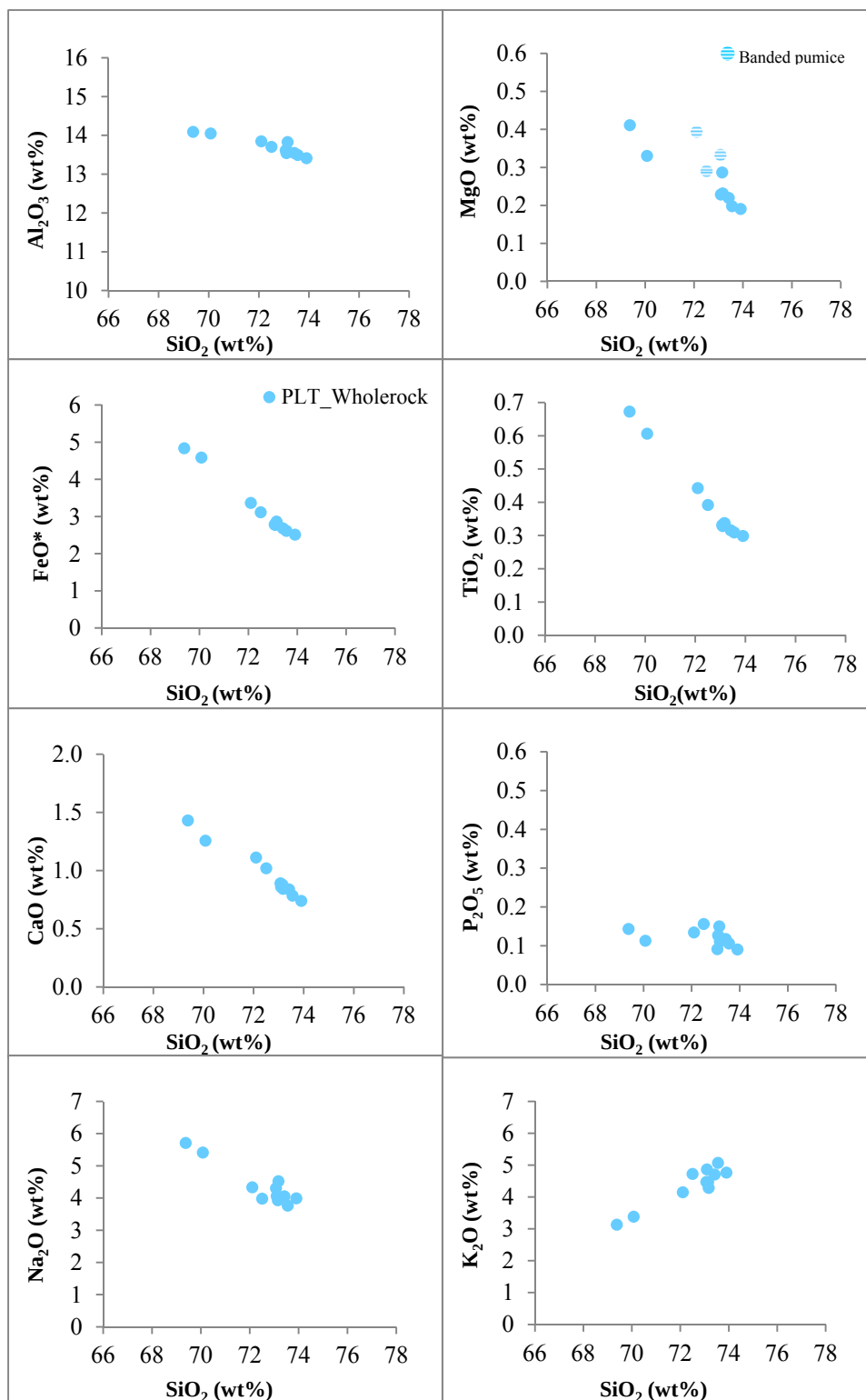


Figure 3.29 Potato Lake tuff - silica variation diagrams for major elements – whole rock analysis of 11 pumice samples analyzed at WSU. SiO_2 content ranges from 69.4 – 74.0 wt%. A compositional gap exists between 70.1 and 72.1 wt% SiO_2 . The banded pumice creates a cluster that minimizes the compositional gap and causes a disorganized scatter which is very obvious in MgO .

3.5.2 Major Elements Results – EMP

Electron microprobe (EMP) analysis conducted at Oregon State University included sample number 0064a_4, black and white banded pumice (Figure 3.28). Silica concentration of glass shards ranges from 69.4 – 75.3 wt% SiO_2 and total iron content ranges from 2.0 – 4.6 wt% FeO^* . As with whole rock analysis, all major elements decrease with increasing SiO_2 content, except K_2O .

Adjacent black and white bands have distinct compositions, as indicated by variation diagrams (Figure 3.31). The black bands are rhyodacitic (69.3 – 71.1 wt% SiO_2) and the white bands are rhyolitic (74.1 – 75.3 wt% SiO_2). The transition across these boundaries is abrupt suggesting that the two compositions did not exist together long enough for much diffusion to occur across the compositional boundaries (Figure 3.32 A and B).



Figure 3.30 Image of a polished thick section for sample number 0064a_4, a black and white banded pumice. The dashed orange line is the approximate location of a 5 mm transect sampled for EMP analysis.

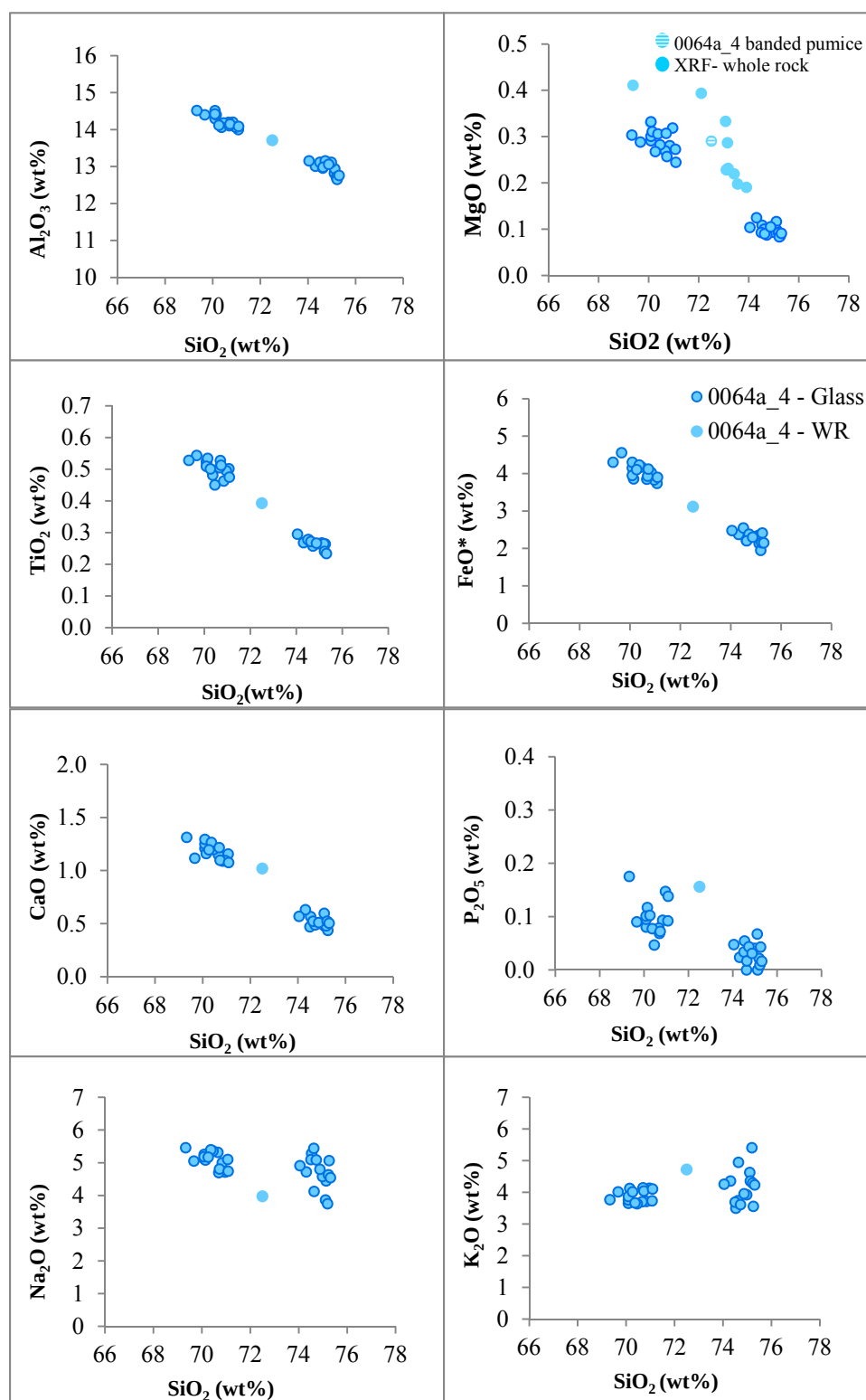


Figure 3.31 Variation diagrams of major elements vs. SiO_2 (wt%) for the Potato Lake tuff. EMP analysis or sample 0064a_4 indicates a bimodal composition. All pumice clasts analyzed by XRF have been included in the MgO plot to show that sample 0064a_4 may not be representative of the end member compositions in the Potato Lake tuff.

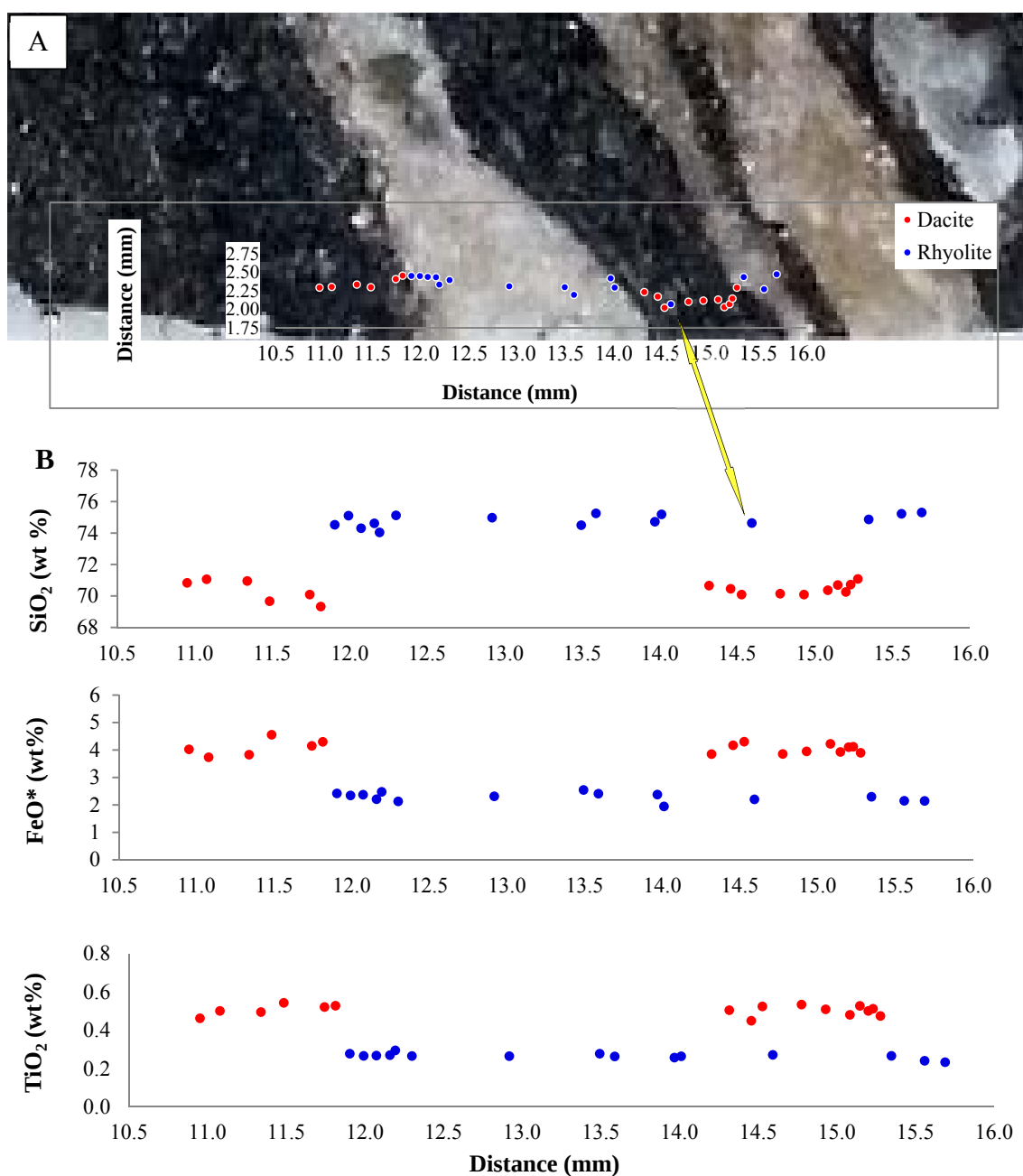


Figure 3.32 A, B Enlarged portion of Figure 2.27 to highlight a 5 mm transect across black and white bands of sample number 0064a_4. **A.** Plot of EMP glass shard analysis (distance in mm) overlays an image of the transect area. The locations of points with respect to the image are approximate as a 5 μ m beam sized was used for analysis. **B.** Plot of wt% silica, FeO* and TiO₂ vs. distance shows variation of chemical composition between black and white bands of sample 0064a_4. Symbols for A and B are the same. While many bands are clearly visible some micro-bands are only visible with the aid of a microscope, or by microprobe analysis (yellow arrow).

3.5.3 Trace element results – Potato Lake tuff

Major elements SiO_2 and MgO (wt%) and selected trace elements for the Potato Lake tuff are plotted against Rb and compared to the Rattlesnake Tuff and the Devine Canyon Tuff (Figures 3.33 and 3.34). Silica content increases with increasing Rb content indicating that the Potato Lake tuff was on a trajectory to becoming a more evolved magma like the Rattlesnake Tuff. MgO and compatible elements decrease as Rb increases. Both the Potato Lake tuff and the Hampton Tuff are depleted in Ba, Ta, and Y, as compared to the Rattlesnake and Devine Canyon Tuffs (Figure 3.36 A, B). The younger tuffs are more like the least evolved Rattlesnake E magmas (Streck and Grunder, 1997). Ta and Nb are increasing with increasing Y suggesting that given time the magmas would have become more evolved like the Rattlesnake A magmas.

Spider diagrams of Rare Earth Elements (REE) for the Hampton Tuff (Figure 3.27) and the Potato Lake tuff (Figure 3.35) show prominent negative Eu anomalies for rhyolitic compositions in both tuffs. The dacitic compositions of the Potato Lake tuff have a flat Eu aspect. The ratio of Eu/Eu^* for the Hampton Tuff is ~ 0.6 for rhyolitic compositions and ~ 0.8 for a mixed fiamme (Figure 3.36 C). The Potato Lake tuff ranges from 0.4 - 0.6 for higher silica samples and ~ 1.0 for samples of dacitic composition. Neither the Hampton Tuff nor the Potato Lake tuff have the low Eu/Eu^* of the more evolved Rattlesnake Tuff (Figure 3.36 C).

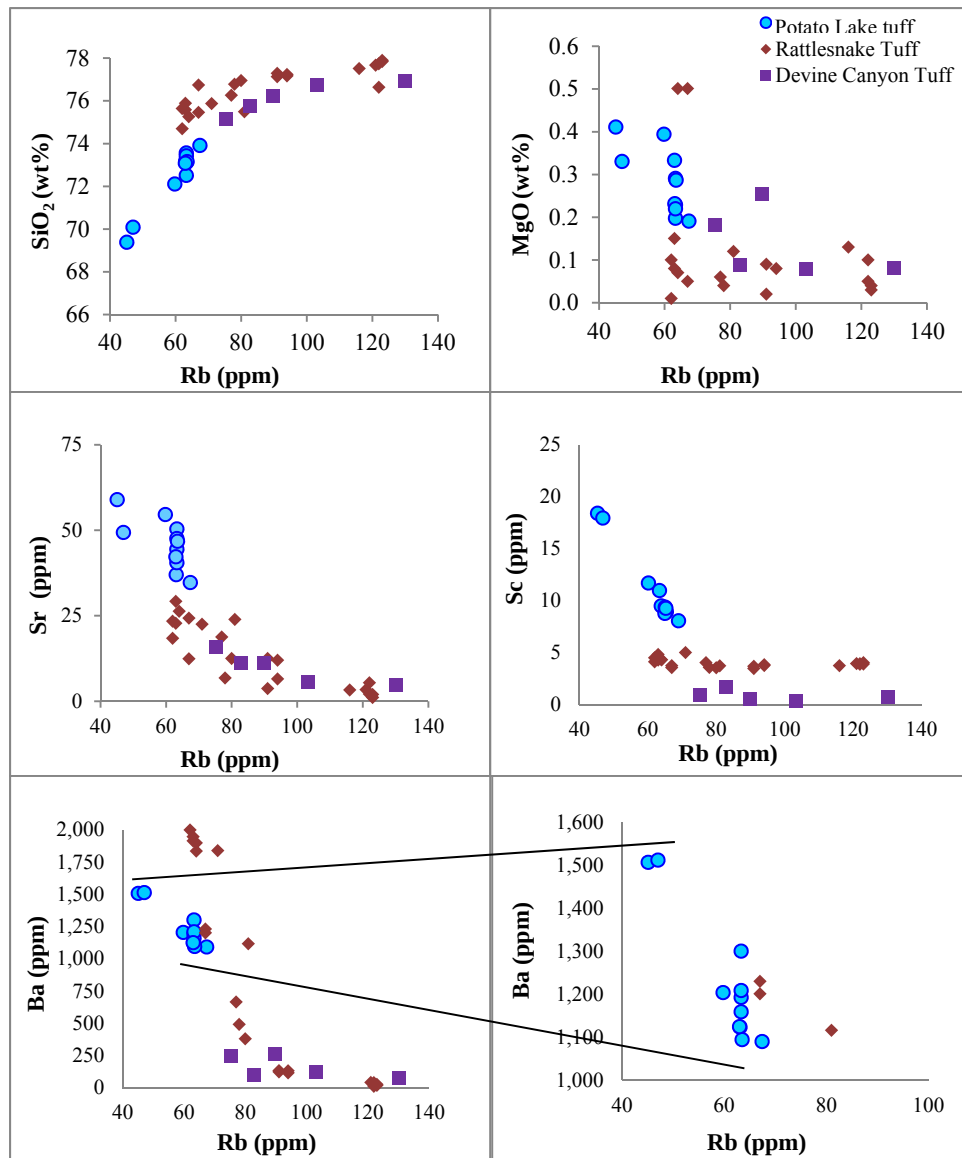


Figure 3.33 Variation diagram of SiO₂ and MgO (wt%) and selected compatible trace elements vs. Rb for the Potato Lake tuff, Rattlesnake Tuff, and the Devine Canyon Tuff. Silica content increases with increasing Rb while MgO decreases with increasing Rb. Compatible trace elements decrease with increasing Rb.

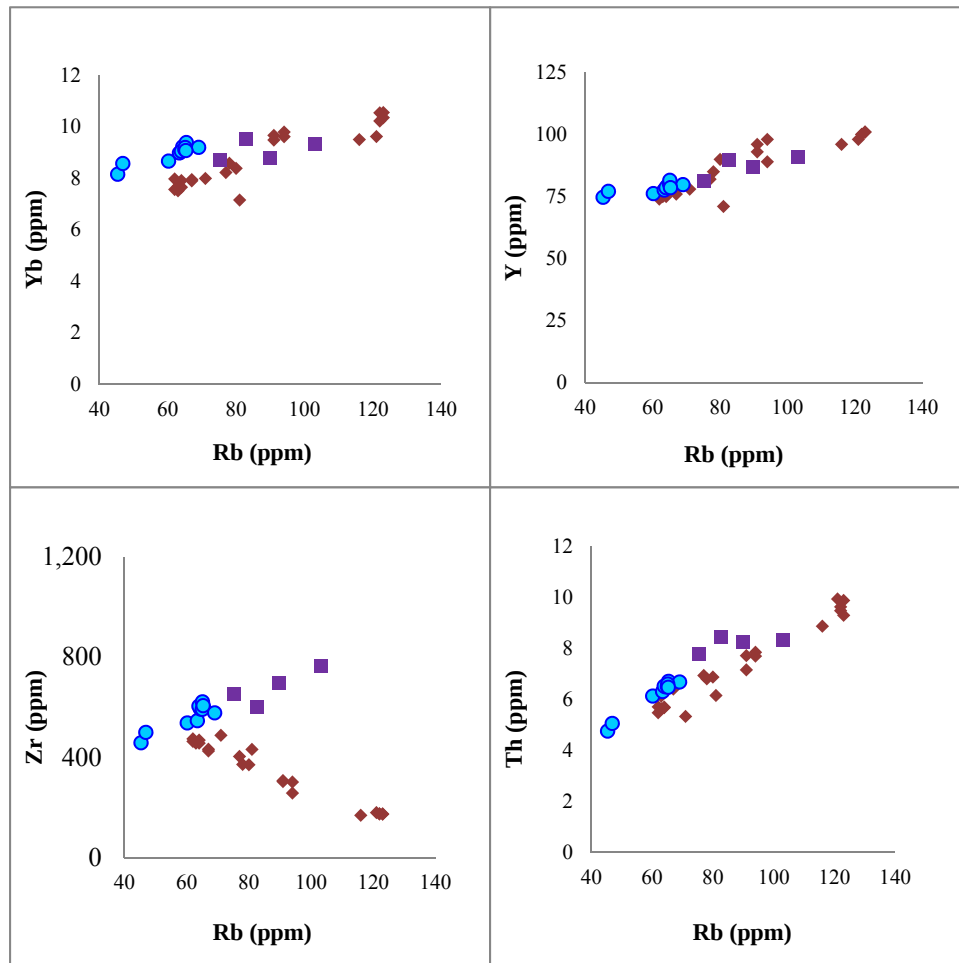


Figure 3.34 Selected trace elements versus Rb for the Potato Lake tuff compared to the Rattlesnake Tuff and the Devine Canyon Tuff. Like the Hampton Tuff, Zr increases with Rb, the result of it having low silica content as compared to the Rattlesnake Tuff. Other incompatible elements increase with increasing Rb content. Symbols as in figure 3.33

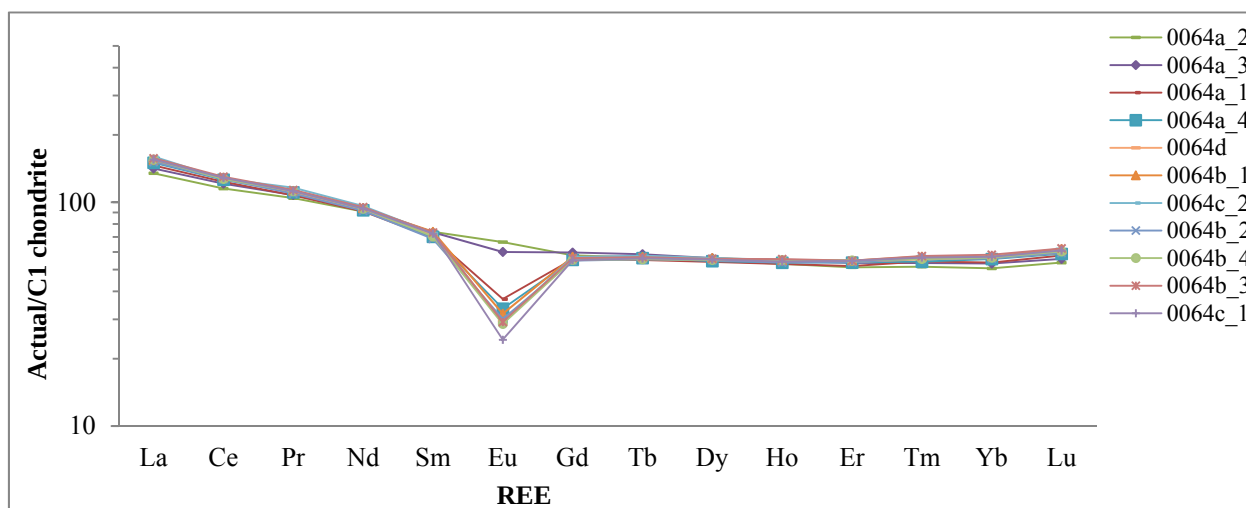


Figure 3.35 Spider diagram of rare Earth elements for the Potato Lake tuff normalized to C1 chondrite. The negative Eu anomaly is more pronounced for sample number 0064c_1 which also has the highest SiO₂ and Rb content. The Eu anomaly for sample 0064a_2 is slightly positive. This sample has the lowest SiO₂ and Rb content.

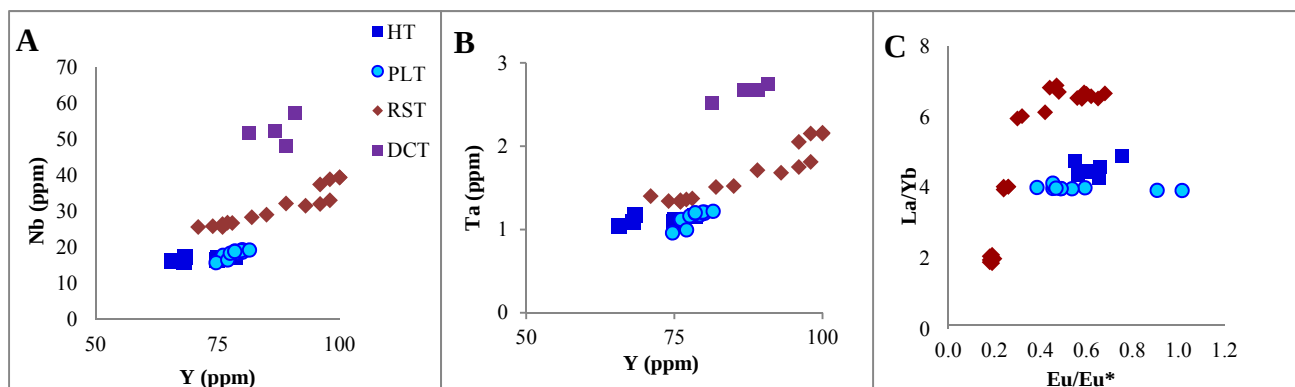


Figure 3.36 A, B, and C Variation diagrams for Nb and Ta vs. Y and La/Yb vs. Eu/Eu* for the Hampton Tuff, Potato Lake tuff, Rattlesnake Tuff (RST), and the Devine Canyon Tuff (DCT). **A, B.** The Hampton and Potato Lake tuff are both depleted in Nb and Ta as compared to the more highly evolved RST and DCT. **C.** La/Yb remain relatively constant for the HT, PLT, and the least evolved RST (Streck and Grunder, 1997). Trace element data for the Devine Canyon Tuff is limited and especially lacking in REE trace analysis.

3.6 Geochemical composition – Buckaroo Lake tuff HP-91-9

3.6.1 Major element – EMP glass

Silica content of the Buckaroo Lake tuff (sample HP-91-9) ranges from 51 - 3.5 wt% SiO_2 and total iron ranges from 2 - 13 wt% FeO^* (Figure 3.40). There are at least four, if not five, distinct compositional clusters that vary from basaltic to basaltic andesite, andesite, and dacite to low silica rhyolite (Figure 3.38). It is possible that mafic lithics were inadvertently sampled, several ~1 mm sized oxidized lithics are visible mainly in the lower right corner of Figure 3.38, but they are relatively obvious in the BSE (Figure 3.39) and easy to avoid. I believe the basaltic constituents to be juvenile. A total alkali-silica diagram indicates a strong trachytic component (Figure 3.37).

Variation diagrams of major elements versus silica content (Figure 3.40) indicate decreasing trends with increasing SiO_2 for all major elements except K_2O , which is expected, and Na_2O which is a departure from other High Lava Plains ignimbrites. There are two compositional clusters within the basaltic to basaltic

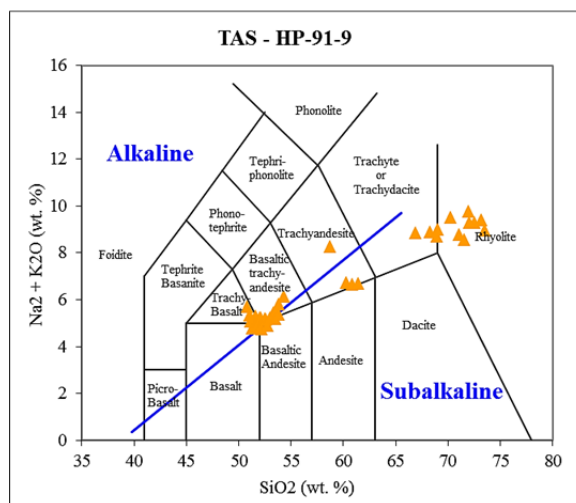


Figure 3.37 TAS diagram of Buckaroo Lake tuff glass shard analysis for sample HP-91-9.

andesite silica range; one that ranges from 4.5 – 5.3 wt% Na_2O and a second which ranges from 3.3 – 3.7 wt% Na_2O (Figure 3.40). These clusters are also apparent in K_2O wt%.



Figure 3.38 Image of epoxy impregnated plug made of sample HP-91-9 for EMP glass shard analysis. At least two pumice populations are evident by the glassy black vesiculated area of the upper section and the brownish vesiculated area on the lower left. Below the brownish pumice is an area of ashy matrix. Abundant oxidized lithics are visible mainly in the lower right. Yellow circle is an area where several glass shards were sampled, see next figure.

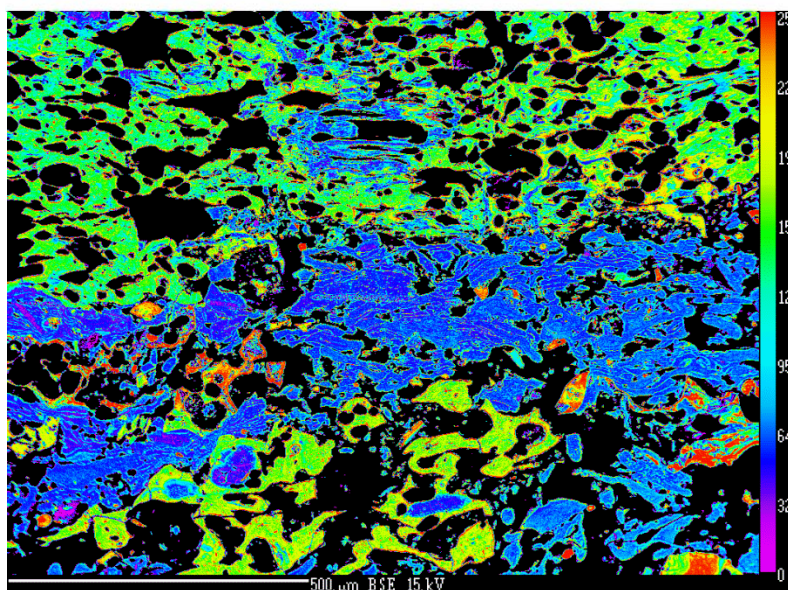


Figure 3.39 Color BSE image of sample HP-91-9 of enlarged area approximately located by the yellow circle in Figure 3.36. The scale on the right illustrates the color map of the BSE. The warmer the color the greater the abundance of high atomic number elements. In this image, glass shards in green have iron content >7 wt% FeO^* , shards in blue are < 3 wt% FeO^* . Red features in lower right are likely more iron-rich.

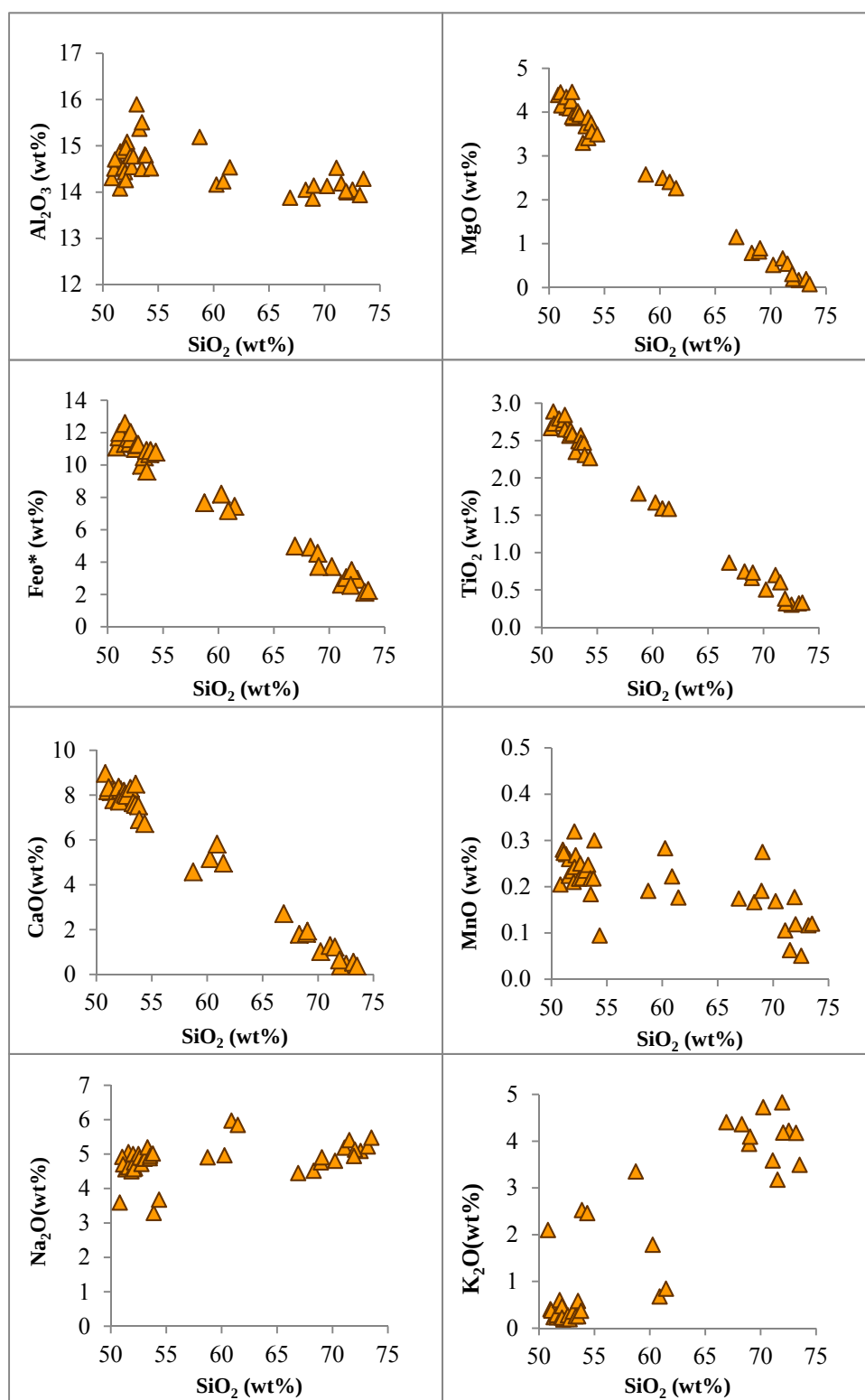


Figure 3.40 Variation diagrams of major elements versus silica for HP-91-9, the Buckaroo Lake tuff. Major elements decrease with increasing SiO₂ content, except K₂O and Na₂O. Data are un-normalized.

Chapter 4 Summary and Discussion

4.1 The Hampton Tuff

4.1.1 Correlations – age, lithology, composition, and mineral characteristics

The Hampton Tuff has a weighted mean age of 3.9 ± 0.02 Ma (2σ). Within error, age data consistently conform to this time period (Walker, 1974, recalculated by Fiebelkorn, 1984; Iademarco, 2009). The age of the Hampton Tuff fits the temporal frame for the westward migration of silicic volcanism across the High Lava Plains (Figure 1.1).

Outcrops of the Hampton Tuff are typically 8 - 10 m thick (25 – 30 ft), but may be up to 45m (150 ft) where the tuff has banked against paleo-topography of high relief. In many places, the tuff crops out as rounded, blocky-jointed stacks of brown densely welded tuff (Figure 3.3). The densely welded section is comprised of elongated black fiamme at the bottom that grade upward to deformed pumice (Figure 2.1). The uppermost part of the brown densely welded section may weather into large platy blocks >5 m in length. The base of the brown densely welded section is comprised of a densely welded vitrophyre that appears black or very dark chocolate brown (Figures 3.3 and 3.4). In places where the basal vitrophyre is not completely welded it may appear as a coarse grained black ash layer (e.g. Lizard Creek Quarry, Figure 3.7). Close to the vent, the brown densely welded section has abundant angular lithic clasts that consist of basalt, or basaltic andesite, fine grained rhyolite, and some clasts that appear sedimentary (Figure 3.2). Distal outcrops of this section are less lithic rich and contain lithics that are scoriaceous, black or oxidized.

Table 4.1 Data table for all Hampton Tuff ages. HJS samples (this study) and HTB sample (Iademarco, 2009) done at OSU Argon Geochronology Lab. GWW sample from Walker (1974; recalculated by Fiebelkorn, 1982). Age determinations in bold typeface are the preferred age. The weighted mean of all ages is 3.9 ± 0.02 Ma (2σ).

	Ar/Ar method			Plateau			Normal Isochron		
Sample number	Sample location	Rock type	Material dated	Age, Ma	± 2σ	Steps	Age, Ma	± 2σ	⁴⁰ Ar/ ³⁶ Ar Intercept
HJS-HTP-006-0912	43° 52' 55.34" N, 120° 27' 37.29" W	Welded tuff	Plagioclase	3.89	0.02	13	3.88	0.02	300.86
HJS-HTP-0020-2013	43° 43' 4.37" N, 120° 24' 38.51" W	Pumice	Plagioclase	3.91	0.02	16	3.90	0.02	297.88
HJS-HTP-0020-2013*	43° 43' 4.37" N, 120° 24' 38.51" W	Pumice	Glass	2.71	0.09	26	3.85	0.20	290.01
HTB-0701	43° 45' 3.31" N, 120° 16' 26.58" W	Welded Tuff	Plagioclase	3.80	0.16	8	3.70	0.16	310.00
	K-Ar method								
GWW-121-64	43° 47' 48.00" N, 120° 22' 48.00" W	Ash-flow Tuff	Plagioclase	3.7	0.6				

*Second analysis of 0020 glass

Outcrops of the Hampton Tuff that are nonwelded to partially welded are characterized by a ridge-forming cap-rock over a hilly slope-forming section (Figure 3.10). The cap-rock consists of large light colored pumice clasts that are mainly white or light brown. Some pumice clasts reach nearly 60 cm in length. This section also weathers into large platy slabs. The matrix consists of coarse grained dark grey or black glass shards (Figures 2.6 and 2.7), scoriaceous lithic fragments, and euhedral plagioclase up to 3 mm in length. A platy parting separates the upper partially welded section from the lower slope-forming section that may have resulted from a transition to vapor phase alteration in the upper section (Figure 4.1). The groundmass of the lower section is darker than the upper section and has abundant small pumice clasts (>10 cm) and vary in color from white and pink to brown, black and banded. Lithics are mainly angular chert, 1 – 2.5 cm.

Although considered crystal poor, the Hampton Tuff plays host to 5-7% clear, euhedral plagioclase that are typically 2-3 mm but may be as large as 6 mm. Plagioclase phenocrysts are as likely to be found in juvenile pumice clasts as they are to be found in the groundmass of the nonwelded to densely welded sections; although plagioclase are less abundant in black pumice of dacitic composition.

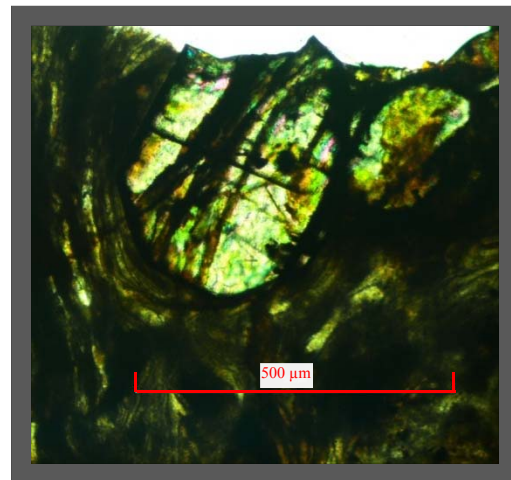


Figure 4.1 Photomicrograph of an olivine phenocryst (under crossed-polars) from the densely welded top of the Lizard Creek Quarry section. Glass shards are completely compacted and conform to the shape of the phenocryst.

Other phenocrysts of the Hampton Tuff include clinopyroxene, olivine, and Fe-Ti oxides. Pyroxenes are euhedral, dark green, almost black, and typically 3 - 4 mm, but are often as large as 6 to 8 mm. Pyroxene phenocrysts are often clustered with Fe-Ti oxides (Figure 4.2). Sparse olivine phenocrysts are subhedral to anhedral (Figure 4.1). Some olivine phenocrysts bear iddingsitized rims, or are nearly obliterated by alteration.

The Hampton Tuff does not have sanidine. Heavy liquid separation during the preparation of samples for $^{40}\text{Ar}/^{39}\text{Ar}$ analysis (outlined in section 3.1) failed to expose sanidine for sample number 006, from Rimrock Draw, or sample number 0020, a pumice clast from the partially welded section of the Camp Creek Rd. area.

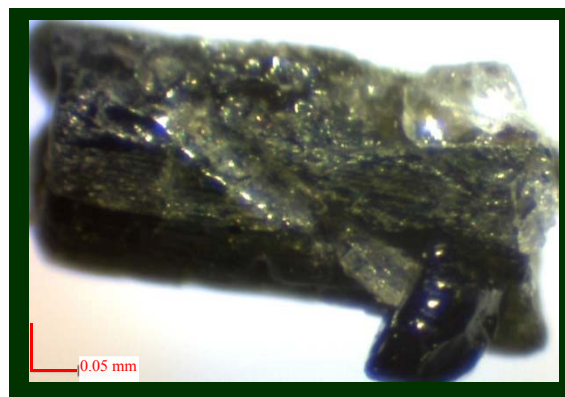


Figure 4.2 Photograph of twinned clinopyroxene from pumice sample number 0020, likely hedenbergite. In the upper right is a small, clear plagioclase and Fe-Ti oxide in the lower right.

4.1.2 Welding facies

Welding degrees of the Hampton Tuff are divided into six categories: Densely welded (DW), densely welded with fiamme (DWF), densely welded with pumice (DWP), partially welded with pumice (PWP), incipiently welded with pumice (IWP), and nonwelded with pumice (NWP). The six welding facies of the Hampton Tuff varies from the five welding facies of the Rattlesnake Tuff. A partially welded with fiamme facies (PWF) of the Rattlesnake Tuff has not been reliably located in the Hampton Tuff. Only one outcrop has fiamme with anything other than dense welding and that is the outcrop at Coyote Rock. However, the Coyote Rock outcrop is so badly altered by post-emplacement vapor-phase alteration that all traces of pyroclastic textures have been obliterated (Figure 3.6 B). The DWF facies of the Hampton Tuff grades upward into a DWP facies. The upper sections of partial to nonwelded have not been preserved in most locations.

A facies model developed by Iademarco (2009) for a section of the Hampton Tuff exposed at the Lizard Creek quarry divides the section into seven welding facies and suggests that there are two cooling units separated by a break in volcanic activity (Figure 4.3 B). The model suggested here differs from Iademarco's model in that it consists of a single cooling unit for the Hampton Tuff (Figure 4.3 C and D).

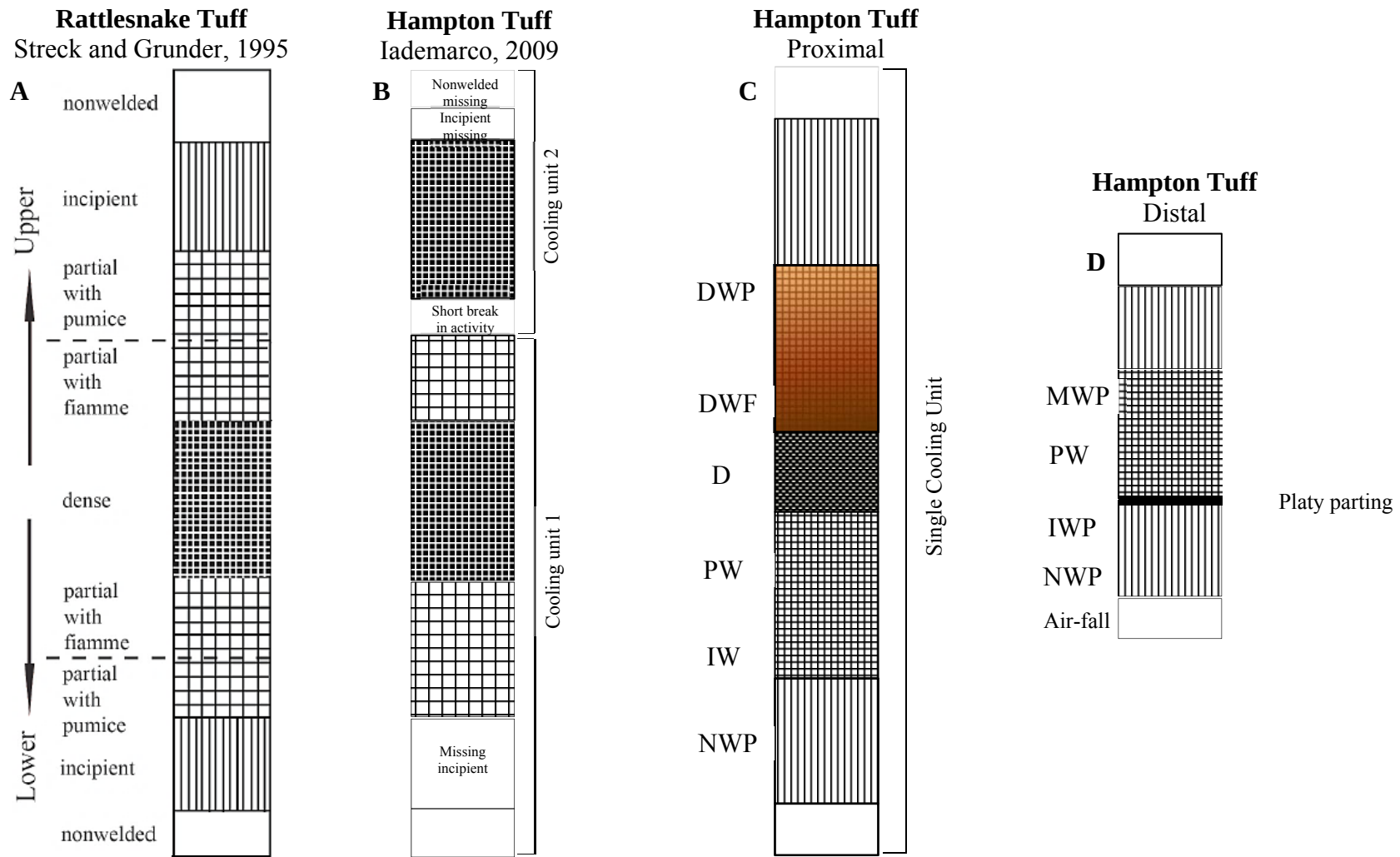


Figure 4.3 **A.** Idealized welding facies of the Rattlesnake Tuff (Streck and Grunder, 1995) **B.** Welding facies of Iademarco (2009) for the Hampton Tuff. **C and D:** Welding facies of the Hampton Tuff: **C.** Proximal facies include the six facies described in the text. The basal air-fall may be preserved in some locations. **D.** Distal welding facies model is based on outcrops of pumiceous sections near the Camp Creek Road area. The platy parting may vary depending on the localized degree of vapor-phase alteration.

The outcrop at the Lizard Creek quarry (LCQ) is similar to the brown densely welded section found at numerous other locations, but the differences are marked and suggest localized post-emplacement alteration and local faulting. The initial difference lies in the weathered surface of the outcrop such that it lacks the rounded, bouldery weathering of other outcrops. This is wholly due to the fact that the surface has only been exposed since the initiation of modern quarry activities. Another difference between the outcrop at the LCQ and other densely welded sections is the smaller size of the blocks. Outcrops of the brown densely welded section routinely consist of blocks that are thicker than 1.5 m (> 5 ft) (Figure 3.3). The largest block measured by Iademarco (2009) at the LCQ measures 1.2 m thick. Iademarco also describes two thin platy partings in the quarry. These partings are more likely the result of localized faulting and block movement rather than being separate welding facies. Other factors that suggest localized alteration are textural. The vitrophyre at the quarry is nonwelded to incipiently welded at the base and grades upward into partially welded (Figures 3.6, 3.7, and 3.10). Everything above the vitrophyre is densely welded and pervasively devitrified. Photomicrographs show perlitic cracking and incipient lithophysae, which are indicative of vapor-phase alteration. Trace element analyses also indicate alteration (Figure 3.27). I suggest that the pervasive devitrification and the anomalous behavior of the REEs occurred when the tuff was deposited upon a local spring or small water body.

4.1.3 Source – based on facies, thickness, and welding

The source of the Hampton Tuff has previously been attributed to the Frederick Butte Volcanic Center (Figure 3.1) (Walker, 1974; Walker, 1981; Johnson, 1998; Iademarco, 2009). The association to Frederick Butte has been primarily based on proximity and that the center appears to be a post-emplacement dome complex surrounding a ring-fault structure (Walker, 1974; Walker 1981; and Johnson, 1998). An age obtained from the potassium-argon method for the rhyolite dome of Frederick Butte Hampton is 4.0 ± 0.4 Ma (Walker, 1974, recalculated by Fiebelkorn, 1982). No other age data exist for domes of the Frederick Butte Volcanic Center. Mapping done by Jenda Johnson (1998) of the Frederick Butte Volcanic Center indicates that there are no outcrops of the Hampton Tuff on the peaks of any of the domes. There is one outcrop of a tuff weathering out beneath dacite lava on the north side of Soldiers Cap (Johnson, 1998). Stratigraphic relationships would suggest that the domes and lavas of the FBVC are younger than the Hampton Tuff and is consistent with the tuff emanating from that area.

Comparison of major elements for the Hampton Tuff and lavas from the Frederick Butte Volcanic Center (FBVC) indicate a relatively good match for rhyolitic compositions, but are not as good for dacitic compositions (Figure 4.5). Except in the case of the rhyolite of Corral Butte, trace element compositions do not provide especially good correlation between lavas of the FBVC and the Hampton Tuff, (Figure 4.6). Variation diagrams, Figures 4.5 and 4.6, include the analysis of one rhyolitic pumice clast from this outcrop. This sample is very close in composition to the rhyolite of Corral Butte. Trace element analyses of the FBVC samples include

only trace elements which can be measured by XRF. No ICP-MS analysis has been done - limiting the comparisons that can be made. Analysis of yttrium (Y) for the pumice sample is anomalously low and not necessarily representative of the pumice or the outcrop from which it was collected.

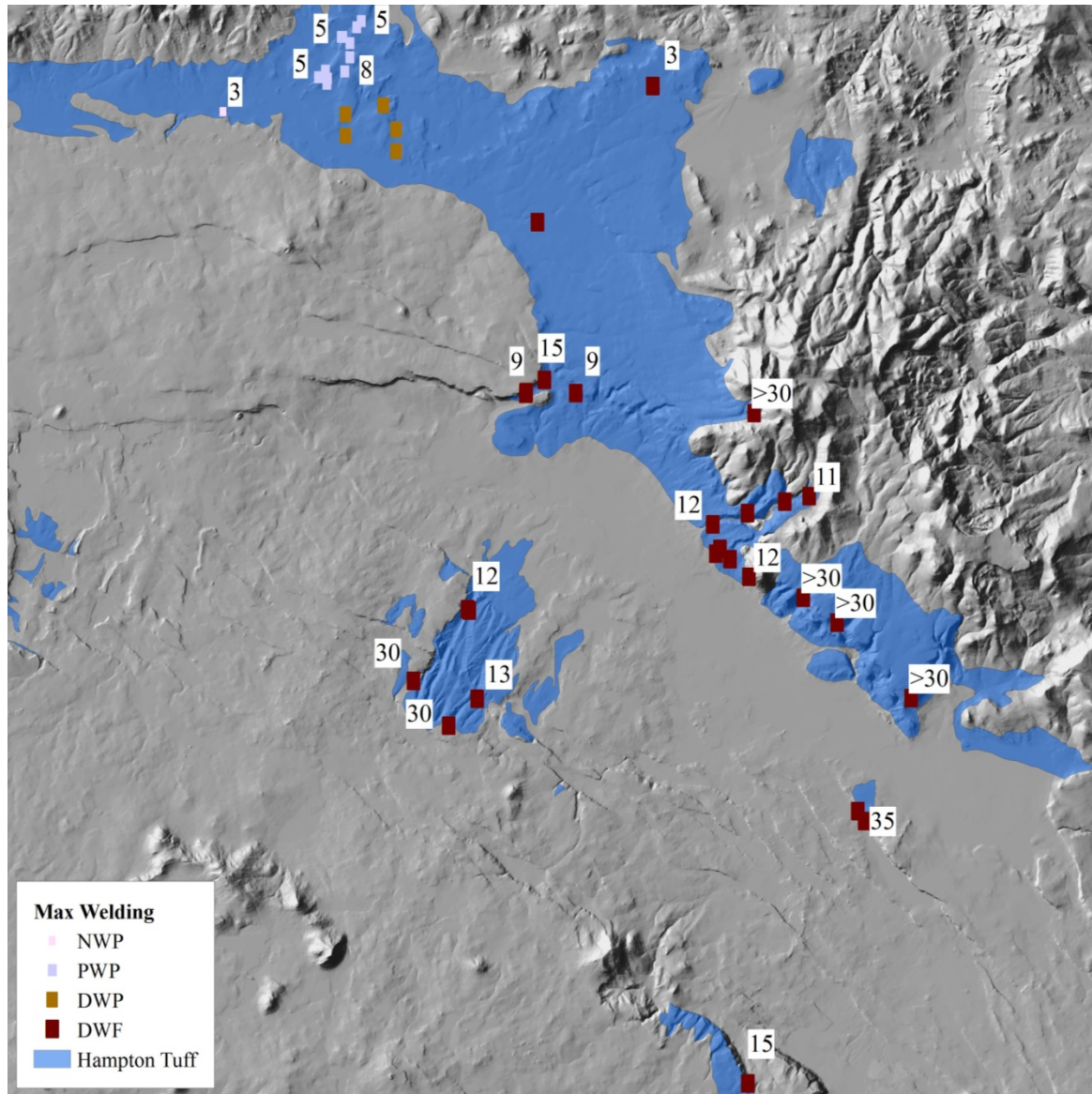


Figure 4.3 Map of Hampton Tuff outcrops, thickness, and maximum welding facies. The darkest rectangles indicate maximum welding, while the light pink rectangles indicate nonwelded outcrops. Numbered boxes indicate the thickness of the Hampton Tuff for those locations where thickness could be measured. Max welding facies are DWF – densely welded with fiamme, DWP – densely welded with pumice, PWP – partially welded with pumice, and NWP – non-welded with pumice.

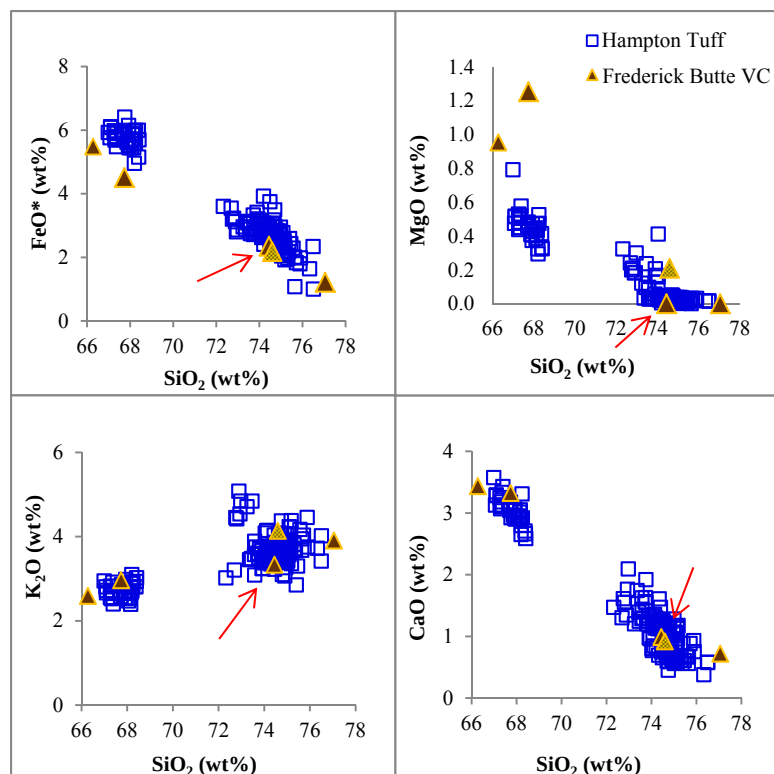


Figure 4.5 Variation diagrams of select major elements versus SiO₂ content for the Hampton Tuff and FBVC lavas. Major elements for rhyolitic lavas of FBVC are similar to the Hampton Tuff, but dacitic compositions are not as closely matched. CaO and K₂O content of FBVC lavas are closer in composition to the Hampton. Stippled triangle is a rhyolitic pumice sample collected from beneath the dacite of Soldiers Cap. Red arrows point to the rhyolite of Corral Butte. FBVC data from Johnson, 1998

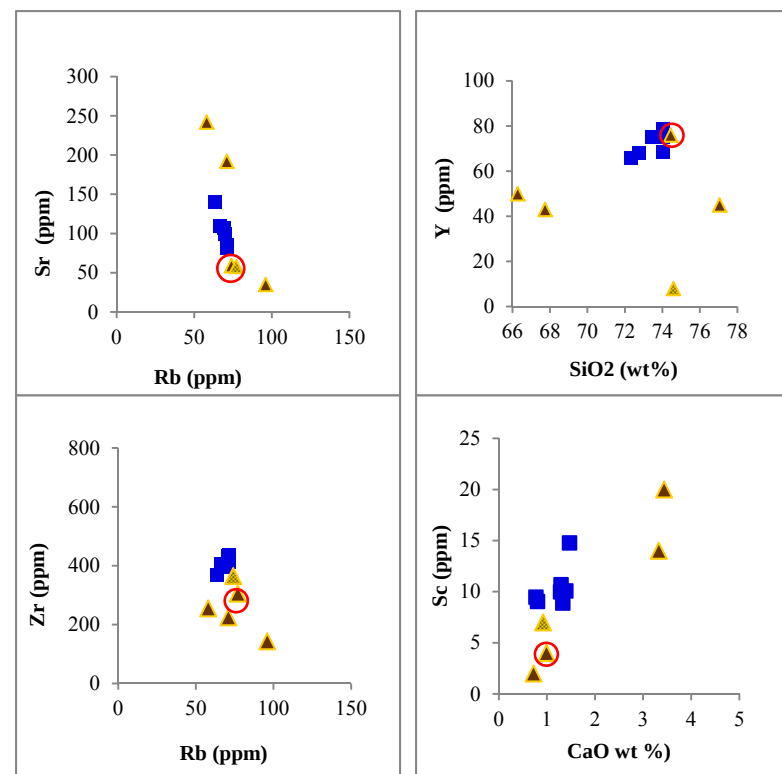


Figure 4.6 Variation diagrams of Sr and Zr versus Rb (ppm); Sc ppm versus CaO (wt%) and Y versus SiO₂ (wt%) for the Hampton Tuff and lavas of the FBVC. Trace element compositions for the rhyolite of Corral Butte (red circles) and a rhyolitic pumice collected from beneath the dacite of Soldiers Cap are a relatively good match for the Hampton Tuff in all but Sc/CaO. Y value for the pumice may be anomalously low and not necessarily representative of the unit. Symbols as in Figure 4.4. FBVC data from Johnson, 1998

4.1.4 Geochemistry discussion - Glass shard vs. pumice vs. whole rock chemistry

Comparison of geochemical analyses of major elements conducted for the Hampton Tuff illustrate that the method of analysis and the type of sample analyzed produce varying results which may obfuscate actual chemical compositions (Figure 4.7). The compositional gap between dacitic and rhyolitic components is obscured by whole rock analysis of bulk rock samples as well as pumice clasts. This disparity is much more obvious in the black and white banded pumice (0064a_4) of the Potato Lake tuff discussed in Section 3.5.2.

Whole rock analysis, in general, creates an average of the compositional whole which is problematic when glass of mixed composition is erupted and forms banded pumice, such as sample 0020. The mixed bands of sample 0020 are not obvious in hand sample (Figure 3.15 B) and are not captured by EMP analysis.

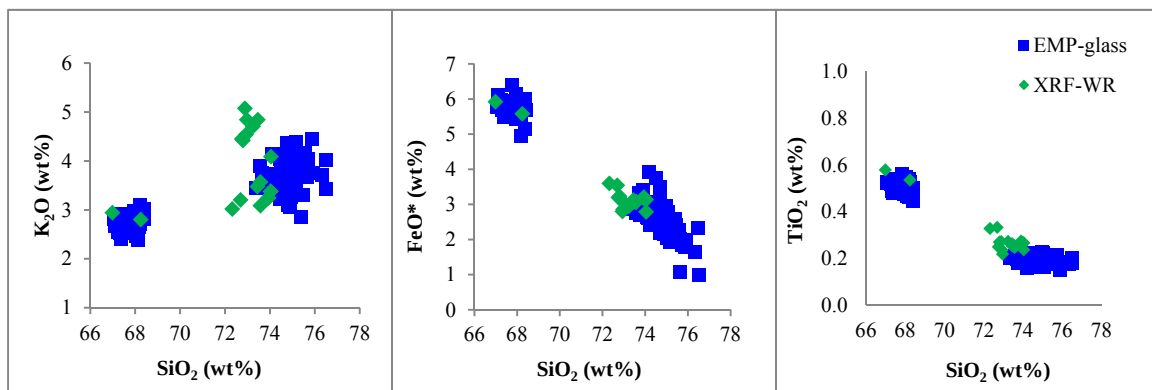


Figure 4.7 variation diagrams for select major elements vs. SiO₂ (wt%) for EMP – glass shard analysis and XRF whole rock analysis of bulk rock and pumice clasts for the Hampton Tuff. The compositional gap for silica is reduced when XRF and EMP data are combined. Extraneous compositional clusters are introduced by whole rock analysis for K₂O and TiO₂. EMP data from this study. XRF analysis include data from this study and Johnson, 1998; Tucker, 2007; Iademarco, 2009, and Ford, 2012.

4.1.5 Major and trace element comparison with High Lava Plains Ignimbrites

Ignimbrites of the High Lava Plains are characterized by their high iron concentration at given silica content (Figure 4.8). FeO* ranges from 4.1-5.76 wt% in HLP dacites to 2.0-2.5 wt% in the most silicic rhyolites. The larger ignimbrites are highly evolved having only minor low-silica constituents; the Rattlesnake Tuff is > 99% high-silica rhyolite (Streck and Grunder, 1997).

The outlier in this case is the Buckaroo Lake tuff which has generally lower FeO* in dacite and rhyolite. The tuff has two silica gaps separating basaltic to basaltic-andesite, and from andesitic to rhyodacitic (Figures 3.40 and 4.8). However, the Buckaroo Lake analyses are from glass shards of a single sample and not necessarily representative of the entire ignimbrite.

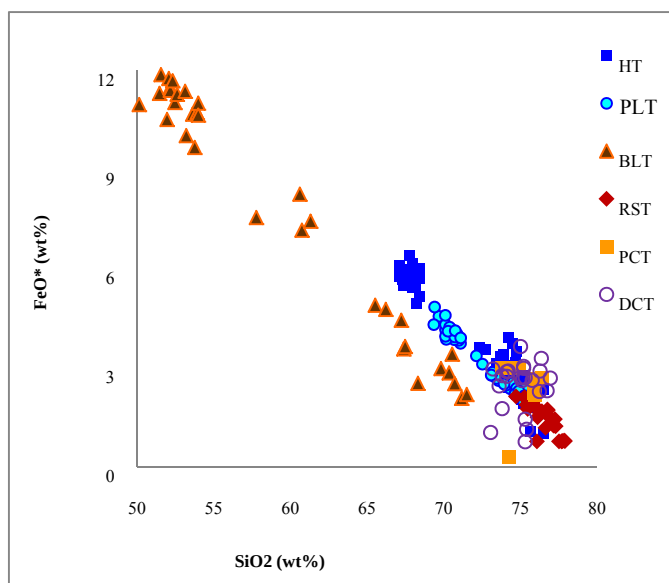


Figure 4.8 Variation diagram of FeO* vs. SiO₂ (wt%) for HLP ignimbrites including new data for the Buckaroo Lake tuff (BLT), Potato Lake tuff (PLT), and the Hampton Tuff (HT). Data from Beeson, 1969; Greene, 1972; Parker, 1974; Streck and Grunder, 1997; Streck, 2015.

The Potato Lake tuff and the Hampton Tuff mimic the High Lava Plains ignimbrites with respect to iron content. The Fe-line of Ford (2012) seeks to delineate the High Lava Plains compositions from those of the volcanic arc influenced rocks of the High Cascades (Figure 4.9). The Fe-line works well for dacitic to rhyolitic samples, but is less relevant at lower silica content. While higher FeO* do exist for the High Cascades the majority sit on or below the Fe-line; this is also true for volcanic samples of Newberry Volcano. Ignimbrites and pyroclastic deposits of the Deschutes Formation vary more widely than either the High Cascades or Newberry samples, but may include a much larger population of ones with intermediate to low silica. Deschutes Formation volcanic samples >74 wt% SiO₂ are distinctly divided above and below the Fe-line, while High Lava Plains magmas are above the line for the range of silica content depicted in figure 4.8 (66-78 wt% SiO₂).

Discrimination diagrams for granitic rocks have been used to determine tectonic setting of felsic magmatic systems where the settings have been obscured by other processes (Whalen, 1987; Eby, 1990). Ignimbrites of the High Lava Plains plot in the A-type granite field of Whalen et al. (1987) (Figure 4.10). Using the methods of Watson and Harrison (1983) and Boehnke et al. (2013) zircon thermometry calculations indicate a minimum temperature of 825-895 °C for the Hampton Tuff and 860-900 °C for the Potato Lake tuff (Table 4.1).

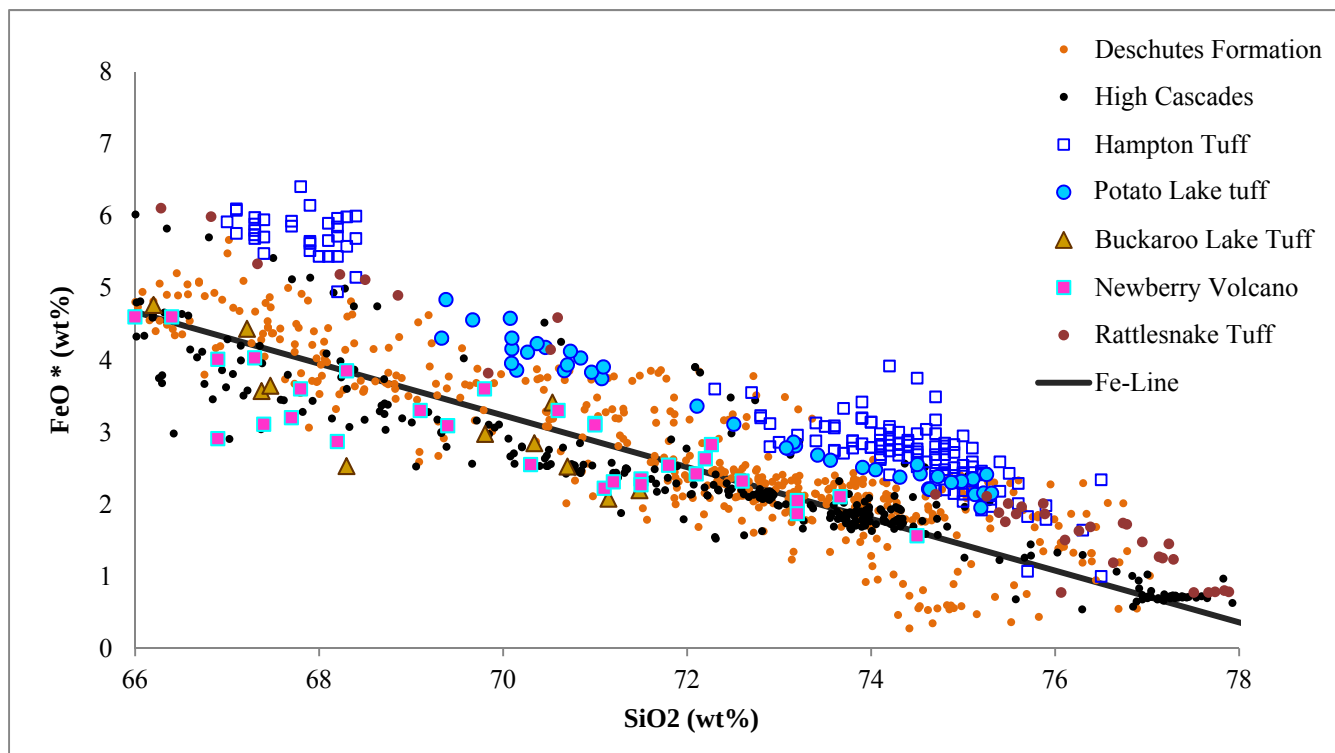


Figure 4.9 Plot of total iron as FeO* vs. silica. The Fe-line of Ford (2012) delineates a boundary between the volcanic magmas of the High Lava Plains and the volcanic arc rocks of the High Cascades. Newberry Volcano samples are lower in FeO* for given silica content. Ignimbrites and pyroclastic deposits of the Deschutes Formation are scattered above and below the Fe-line, but are generally less iron-rich than ignimbrites of the High Lava Plains. Deschutes data courtesy of Brad Pitcher (unpublished data). High Cascades and Newberry Volcano data from PetDB (<http://www.earthchem.org/petdb>, last accessed 11/30/2015).

The Yb/Ta versus Y/Nb diagram of Eby (1990) used to discriminate A-type granite suites is especially revealing for the High Lava Plains ignimbrites (Figure 4.14). Temporal and spatial transition from magmas influenced by an Island Arc Basalt (IAB) trace element signature on the eastern margin (DCT, PCT) to magmas influenced by Island Arc Basalt (IAB) trace element signatures. This indicates that the youngest ignimbrites, the Potato Lake tuff and Hampton Tuff, which are closer to the Cascades arc, are geochemically influenced by subduction.

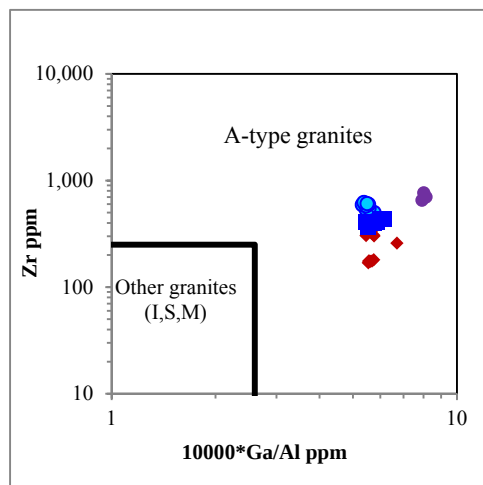


Figure 4.10 Discrimination diagram for tectonic settings of granitic rocks (Whalen et al., 1987). Ignimbrites of the HLP plot in the hot and dry field of A-type granites.

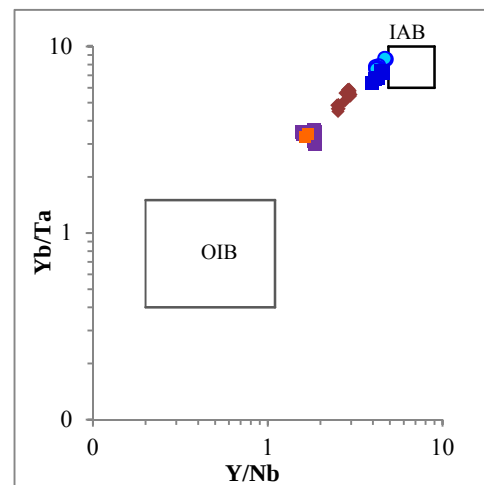


Figure 4.11 Discrimination diagram of A-type granitic suites (Eby, 1990). Westward migration of HLP ignimbrites is apparent as magma compositions migrate from the field of Ocean Island Basalts (OIB) to the Island Arc Basalt (IAB) field. Symbols as in 4.8.

Table 4.1 Table of temperatures calculated for the Hampton Tuff and the Potato Lake tuff using the equation by Watson and Harrison, 1983, and modified by Boehnke et al., 2013: $\ln(D_{Zr}) = 10108/T(K) - (1.16)*(M-1) - 1.48$. M is a proxy for the mechanism of zircon solution (Watson and Harrison, 1983): $M = (Na+K+2*Ca)/(Al*Si)$. D_{Zr} is the distribution coefficient determined by the dividing the zirconium abundance for zircon ($Zr = 497644$ ppm) by zirconium in the melt (Zr_{melt} (ppm)).

	Zr_{melt}	M	$\ln(D_{Zr})$	T_{Zr} (°C)
Hampton Tuff			$D_{Zr} = D/Zr_{melt}$	Boehnke et al., 2013
HJS-006_NL	395	1.23	7.14	864
HJS-008	368	1.25	7.21	852
HJS-0020	406	1.53	7.11	825
HJS-0040	408	1.36	7.11	849
HJS-0041	412	1.35	7.10	852
LCQ003d	433	1.13	7.05	892
LCQ005c	435	1.11	7.04	895
HB-0701	397	1.16	7.13	876
HTB 07-01-MTF	402	1.16	7.12	878
Potato Lake tuff				
HJS-0064a_1	537	1.42	6.83	876
HJS-0064a_2	459	1.26	6.99	879
HJS-0064a_3	500	1.26	6.90	890
HJS-0064a_4	546	1.55	6.81	859
HJS-0064b_1	593	1.54	6.73	871
HJS-0064b_2	604	1.37	6.71	900
HJS-0064b_3	601	1.57	6.72	868
HJS-0064b_4	591	1.48	6.74	879
HJS-0064c_1	578	1.47	6.76	878
HJS-0064c_2	622	1.41	6.69	897
HJS-0064d	606	1.43	6.71	890

4.1.6 Volume vs. time

A combination of tectonic processes over the past ~ 17 Ma years is responsible for the volcanism of the High Lava Plains. Long et al. (2012) suggest that trench rollback along the Juan de Fuca trench initiated at ~ 20 Ma and has proceeded at a rate of 33 mm/yr. Trench rollback and subsequent steepening of the down going plate is followed by the outpouring of the Steens Basalts beginning ~16.6 Ma and continues with the Columbia River Flood Basalt Group until 14 Ma. The oblique subduction of the Juan de Fuca Plate (with respect to the North American Plate) and steepening angle of the subducting plate focused mantle upwelling around the southern edge of the subducting slab of the Juan de Fuca Plate (Long et al., 2012). Syntectonic extension of the Basin and Range extensional province, reaching Oregon ~ 22 Ma, terminates at the Brothers Fault Zone beginning ~ 10 Ma (Long et al., 2012). Volcanism of the High Lava Plains is concentrated along the Brothers Fault Zone beginning in earnest at ~ 12 Ma.

The westward migration of silicic volcanism across the High Lava Plains casts a mirror image of the Yellowstone-Snake River Plain (YSRP) hot spot track from ~12 Ma to the present (Figure 1.3). Along this temporal and spatial migration the magmatic input seems to have diminished toward the western margin as the volume of ignimbrite deposits has declined over time, with the 400 km³ Devine Canyon Tuff down to the 20 km³ Hampton Tuff (Figure 4.12). Sparse research has been devoted to the Prater Creek Tuff, so its actual volume and extent are unknown (Walker, 1979). The Prater Creek Tuff is likely greater in volume than the 200 km³ that has been estimated (Parker, 1974).

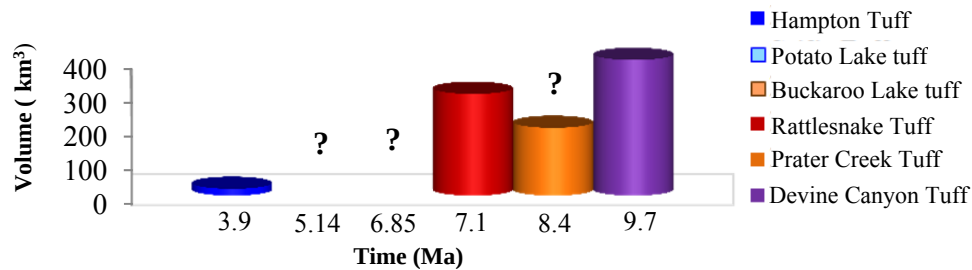


Figure 4.12 A graphical representation of the volume of High Lava Plains ignimbrites over time. The volume of the Buckaroo Lake tuff and the newly discovered Potato Lake tuff is unknown, but they are presumably lower in volume than the Rattlesnake Tuff. The true extent of the Prater Creek Tuff is also unknown. Little specific research has been devoted to the middle child of the HLP ignimbrites.

The volume of the Buckaroo Lake tuff and the newly discovered Potato Lake tuff is unknown. If they were large conspicuous sheets greater than 100 km^3 they likely would have drawn attention earlier (Figure 4.12). I presume them to be on the order of a few 10s of km^3 based on the restricted areal extent.

There is a $\sim 1.4 \text{ m.y.}$ periodicity to the occurrence of major ignimbrites with westward migration (Figure 4.13). The largest break in magmatism is a 1.8 m.y. span separating the Prater Creek Tuff and the Rattlesnake Tuff. The shortest break is a 1.2 m.y. divide between the Potato Lake tuff and the Hampton Tuff. The frequency of explosive eruptions across the High Lava Plains is about half that of the Central Snake River Plain which records a periodicity of $2.3 - 2.4 \text{ m.y.}$ (Ellis et al., 2013).

The thickness of the continental crust across the High Lava Plains varies from $\sim 25 \text{ km}$ to $\sim 35 \text{ km}$, with the thinnest portion being in the central area (Eager, et al., 2011; Till et al., 2013). The continental crust thickens to $\sim 42 \text{ km}$ along the edge of the Cascade Range to the west of the High Lava Plains. The eastern boundary of the

High Lava Plains is characterized by a crustal thickness that increases from ~31 km to ~38 km over a distance of about 20 km (Eager, 2011). The thickening of the crust on the eastern margin coincides with the $^{87}\text{Sr}/^{86}\text{Sr}$ isopleths of 0.704 and 0.706 (Eager et al., 2011). The 0.704 and 0.706 lines (Figure 1.1) denote a Sr isotope discontinuity that delineates the transition to the craton margin, the ~0.706 line (Jordan, et al. 2004).

Trench rollback and the steepening angle of the subducting plate resulted in focused upwelling around the southern edge of the Juan de Fuca Plate, coinciding with the southeastern margin of the High Lava Plains (see above). I suggest that mantle-derived magmatic input to the High Lava Plains system has not waned in time, but rather, that the thinning of the continental crust inhibits the ability of the crust to store and generate large silicic magma bodies.

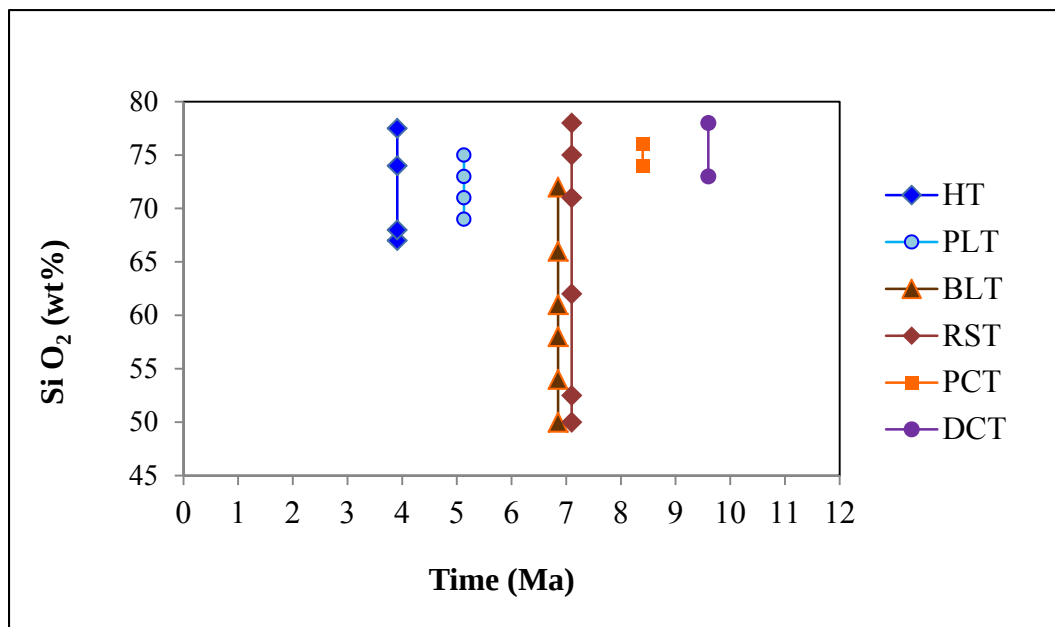


Figure 4.13 Plot of silica vs. time for High lava Plains ignimbrites. The largest break in activity is 1.8 m.y and the shortest is 1.2 m.y with an average recurrence interval of 1.4 m.y. The Rattlesnake Tuff and the Buckaroo Lake tuff are treated as one episode.

Chapter 5 Conclusions

5.1 The Hampton Tuff

The Hampton Tuff is a 3.9 ± 0.02 Ma (2σ) ignimbrite of the High Lava Plains, Oregon. Modern outcrops of the tuff cover an area of ~ 200 km², but the original areal extent was likely ~ 2400 km² with an estimated minimum volume of $19 - 24$ km³, and probably on the order of 40 km³.

Outcrops of the Hampton Tuff form a semi-circular pattern north of the Frederick Butte Volcanic Center, the possible source. The majority of outcroppings are densely welded with 5-7% clear, euhedral plagioclase (2-3 mm). Other phenocrysts include large, euhedral pyroxenes up to 8 mm in length, olivine, and Fe-Ti oxides. Fiamme or flattened pumice clasts are abundant as are angular dense, aphanitic or scoriaceous mafic lithics. Densely welded outcrops are characterized by large jointed blocks that are usually dark red or chocolate brown and weather into large platy slabs with a pockmarked surface. The brown densely welded section further weathers into a red or brown grus that is distinctly lacking in boulder or cobble sized fragments. A densely welded black basal vitrophyre is found at the base of many exposures of the brown densely welded section. These sections are generally 8 – 10 m thick. A vapor-phase altered zone crops out above the densely welded section in areas that are proximal to the source. It is generally grey or light grey in hand sample and has a coarse sugary texture. Interstitial quartz has replaced much of the glassy groundmass, but plagioclase phenocrysts are still evident.

Distal pumiceous outcrops of the Hampton Tuff generally appear as a slope-forming nonwelded section that is capped by a partially welded ridge-forming cap

rock. The two sections are locally separated by a platy parting that is easily weathered to undermine the large platy blocks of the upper section. Pumice clasts of the upper section are considerably larger than the lower section; up to ~ 60 cm. Light colored (white or light brown) pumice clasts are larger and more abundant than brown pumice. Black pumice clasts are sparse (< 1%). The Hampton Tuff generally lacks the strikingly black and white banded pumice found in the Rattlesnake Tuff and the Potato Lake tuff.

The groundmass glasses of the distal sections are coarse grained light to medium grey ash with 5 -7% clear, euhedral plagioclase (2-3 mm). This differs from the Rattlesnake Tuff's salt and pepper glass coloration and nearly aphyric nature, and the Potato Lake tuff's rusty orange and black ash matrix with 1- 3 % smaller plagioclase (1 mm).

The Hampton Tuff ranges from 67 – 77.5 wt% SiO₂ and has a compositional gap between 68 and 73 wt% SiO₂ which is best represented by electron microprobe analysis of glass shards. Whole rock analysis of bulk rock and pumice clasts masks the true silica content and range of the sample, regardless of preferential removal of obvious lithics. Trace element analyses indicate a moderate negative Eu anomaly and lower concentrations of SiO₂ and Rb than the Rattlesnake Tuff. This suggests that the Hampton Tuff magma was not as evolved as the Rattlesnake magma at the time of its eruption.

5.2 The Potato Lake tuff

The Potato Lake tuff is a newly discovered ignimbrite of the High Lava Plains. It is 5.13 ± 0.02 Ma (2σ). The tuff is described from a single outcropping exposed along a fault scarp on the eastern margin of the Benjamin Lake Quadrangle, Oregon, 7.5-minute series.

The outcrop consists of greater than 5 m of nonwelded to partially welded tuff above and below a 3 m high cliff of partially welded tuff. The partially welded section consists of an orange and black vitriclastic matrix with < 3% plagioclase phenocrysts (~1 mm). Pumice clasts are mainly light brown to orange and typically 1 – 2 cm, flattened 3:1. Black pumice clasts are less abundant and flattened 5:1. The partially welded section grades upward into a nonwelded section that has large pumice clasts, some larger than 15 cm. Lithics are typically 0.5 cm, but may be as large as 1.5 cm. The incipiently welded bottom consists of a groundmass that is darker than the partially welded section that lies above it. Black glass shards dominate orange glass shards and give the groundmass a darker color. Pumice clasts, up to 4 cm, are deformed 3:1 and mainly light brown. Lithics are 2 -3% of the groundmass and consist of angular fine grained pink rhyolite and minor oxidized basaltic clasts. Lithics in this section are typically 0.5 cm.

This single outcrop of the Potato Lake tuff exposes more than 10 m of tuff; neither the base nor the top of the tuff are exposed. This outcrop is the probable marginal facies of a larger ignimbrite that has a source further to the east. The discovery of the Potato Lake tuff fills a time gap in the High Lava Plains ignimbrite

sequence that existed between the 7.1 Ma Rattlesnake Tuff and the younger 3.9 Ma Hampton Tuff.

The Potato Lake tuff ranges from 69 – 75 wt% SiO₂ and has a compositional gap between 71 – 74 wt% SiO₂. Like the Hampton Tuff, the compositional gap is best represented by EMP analysis of glass shards. Although whole rock samples analyzed for the tuff were individual pumice clasts the whole rock data indicates a compositional gap between 70 – 72 wt% and reduces the overall high-silica nature of at least part of the ignimbrite. Of the 11 pumice samples submitted for XRF whole rock analyses, at least four were very obviously banded (e.g black and white, grey and white). None of the whole rock analyses resulted in high-silica rhyolites compositions. Sample number 0064a_4 is a black and white banded pumice that has a whole rock SiO₂ content of 72.5 wt% and 3.1 wt% FeO*. EMP analysis of this sample resulted in two distinct compositional clusters (69 – 71 and 74 – 75 wt% SiO₂). The average of 39 glass shard analyses for this sample is 72.5 wt% SiO₂. This makes the choice of major element analysis of ignimbrites an important one as whole rock - bulk rock analysis does not provide the data needed to complete a full compositional characterization.

5.3 The Buckaroo Lake tuff

The Buckaroo Lake tuff has an age of 6.85 Ma (Jordan et al., 2004). Major element analysis was conducted on sample HP-91-9, which was the sample used to obtain the age of the tuff, to determine whether or not the outcrop now called the Potato Lake tuff was possibly a previously unknown tuff.

The Buckaroo Lake tuff has a chemical composition that easily distinguishes it from the Hampton Tuff and the Potato Lake tuff. EMP analysis of glass shards for a 15 mm portion of sample HP-91-9 indicate at least four compositional clusters that range from basaltic all the way to low-silica rhyolite.

The Buckaroo Lake tuff major element analysis indicates that the tuff is somewhat different from the other High Lava Plains ignimbrite and deserves further research. Careful mapping of outcrops and a complete major and trace element analysis should be undertaken to better understand this unit.

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Appendix I - XRF - whole rock - major and trace elements

Hampton Tuff							
	OSU	OSU	OSU	OSU	OSU	OSU	OSU
	HJS_006_NL	HJS_008	HJS-0020	HJS-0040	HJS-0041	LCQ003d	LCQ005c
	DWF	banded fiamme	grey banded pumice	DW - vitrophyre	DW - vitrophyre	DWF	DWF
Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO*.							
SiO ₂	71.91	71.27	70.32	71.44	71.26	72.59	73.31
TiO ₂	0.33	0.32	0.23	0.26	0.25	0.26	0.26
Al ₂ O ₃	13.54	13.43	12.49	12.92	12.83	13.04	13.19
FeO*	3.44	3.55	2.65	3.04	2.97	3.08	3.11
MnO	0.10	0.13	0.09	0.10	0.10	0.08	0.08
MgO	0.23	0.32	0.39	0.09	0.09	0.12	0.16
CaO	1.28	1.45	1.26	1.36	1.24	0.79	0.76
Na ₂ O	4.81	4.98	3.60	4.61	4.62	4.76	4.77
K ₂ O	3.17	2.98	3.88	3.38	3.46	3.31	3.35
P ₂ O ₅	0.05	0.11	0.06	0.06	0.02	0.03	0.03
Total*	98.86	98.54	94.97	97.27	96.85	98.06	99.02
LOI %	0.79	0.71	4.14	2.41	2.65	1.07	1.15
Unnormalized Trace Elements (ppm):							
Ni	4.92	1.01	0.00	0.20	1.61	2.21	0.90
Cr	9.85	3.32	3.62	3.92	3.02	5.43	6.43
Sc	10.95	13.87	9.55	9.55	10.65	8.54	9.05
V	17.49	10.45	5.43	4.12	5.43	16.48	17.09
Ba	1152.74	1163.69	1245.50	1155.75	1135.25	1168.01	1195.85
Rb	69.04	63.42	65.53	69.65	72.46	71.25	72.66
Sr	103.01	136.78	103.31	94.97	80.20	79.80	81.20
Zr	389.24	362.40	391.05	400.69	409.34	420.09	421.40
Y	70.75	67.54	75.17	76.68	77.99	70.05	80.40
Nb	17.59	17.19	17.29	18.19	18.19	18.79	18.19
Ga	20.80	20.00	18.99	20.60	20.50	21.00	21.61
Cu	9.45	6.53	5.43	5.43	6.13	9.95	9.65
Zn	96.08	102.61	84.32	104.02	105.42	89.55	124.72
Pb	12.56	25.63	10.85	14.07	14.57	13.77	11.96
La	34.47	33.06	34.87	32.86	35.68	29.45	40.20
Ce	66.83	77.08	72.06	71.66	73.06	52.16	58.99
Th	6.23	7.44	6.23	6.73	7.24	7.94	7.24
Nd	38.39	40.50	41.41	41.41	42.91	37.59	53.16
U	2.31	1.81	2.11	2.01	3.52	2.61	0.70

Total* - original analysis total

Potato Lake Tuff											
	0064a_1	0064a_2	0064a_3	0064a_4	0064b_1	0064b_2	0064b_3	0064b_4	0064c_1	0064c_2	0064d
	grey/white banded pumice	black pumice	black pumice	black/white banded pumice	grey pumice	grey pumice	light grey pumice	light grey/white banded pumice	light grey pumice	tan pumice	grey/white banded pumice
Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO*.											
SiO ₂	72.11	69.38	70.08	72.51	73.11	73.18	73.56	73.42	73.91	73.16	73.08
TiO ₂	0.44	0.67	0.61	0.39	0.33	0.34	0.31	0.32	0.30	0.34	0.33
Al ₂ O ₃	13.84	14.09	14.05	13.71	13.54	13.58	13.49	13.55	13.41	13.83	13.61
FeO*	3.36	4.84	4.58	3.11	2.77	2.81	2.61	2.68	2.51	2.86	2.78
MnO	0.13	0.20	0.19	0.12	0.12	0.11	0.11	0.11	0.10	0.11	0.11
MgO	0.39	0.41	0.33	0.29	0.23	0.23	0.20	0.22	0.19	0.29	0.33
CaO	1.11	1.43	1.26	1.02	0.86	0.84	0.78	0.84	0.74	0.88	0.89
Na ₂ O	4.33	5.71	5.41	3.97	4.06	4.52	3.76	4.05	3.98	3.93	4.30
K ₂ O	4.15	3.13	3.38	4.72	4.86	4.28	5.07	4.70	4.76	4.47	4.47
P ₂ O ₅	0.13	0.14	0.11	0.16	0.13	0.11	0.11	0.12	0.09	0.15	0.09
Total*	95.28	96.40	96.37	95.05	96.37	95.40	95.87	95.05	95.06	94.74	95.83
Unnormalized Trace Elements (ppm):											
Ni	4.22	2.11	2.91	3.32	2.91	2.21	3.82	3.42	0.90	1.81	0.50
Cr	5.33	2.41	3.02	5.03	4.02	2.81	2.81	3.82	4.32	3.62	3.82
Sc	10.45	18.39	18.09	10.85	8.64	9.45	8.14	8.24	7.94	9.45	8.34
V	11.46	2.71	4.42	6.23	2.21	3.22	1.41	2.61	2.71	4.32	2.21
Ba	1203.69	1506.70	1512.02	1192.43	1299.97	1123.19	1158.87	1208.31	1089.72	1094.14	1124.39
Rb	59.80	45.12	47.03	63.32	63.32	63.11	63.32	63.32	67.44	63.52	63.01
Sr	54.57	58.89	49.35	50.35	47.54	36.98	40.50	44.42	34.67	46.73	42.21
Zr	525.62	452.35	489.94	530.94	576.67	579.68	567.83	566.22	553.25	592.55	575.76
Y	77.89	76.48	78.29	78.89	82.21	79.60	78.89	80.50	80.50	81.71	78.79
Nb	18.89	16.68	17.89	19.10	19.50	19.70	19.50	19.60	20.40	20.00	19.50
Ga	20.00	21.61	21.41	20.20	19.90	19.60	19.30	19.10	19.40	19.70	19.80
Cu	7.64	5.33	6.63	10.55	5.03	5.13	6.33	5.13	2.71	6.43	7.04
Zn	89.65	124.52	125.93	86.33	80.40	83.52	75.27	78.89	76.58	84.72	82.11
Pb	13.67	10.25	8.34	11.66	12.26	13.07	12.36	11.76	14.67	13.57	13.77
La	33.37	32.36	33.97	32.16	35.68	35.98	35.48	33.97	34.67	34.87	32.26
Ce	71.86	69.85	74.77	73.97	77.89	69.85	72.96	73.06	74.77	71.56	71.76
Th	5.83	4.82	5.33	5.63	6.63	6.03	6.63	6.33	7.64	6.43	6.03
Nd	40.80	41.10	41.41	39.09	41.81	40.00	38.79	40.70	40.10	40.70	39.40
U	1.81	1.41	1.41	2.81	2.01	0.00	2.31	2.01	3.22	2.41	1.51

Total* - original analysis total

Appendix II ICP-MS Trace element analysis

	Hampton Tuff						
	OSU	OSU	OSU	OSU	OSU	OSU	OSU
	HJS_006	HJS_008	HJS-0020	HJS-0040	HJS-0041	LCQ003d	LCQ005c
	DWF	banded fiamme	grey banded pumice	DW - vitrophyre	DW - vitrophyre	DWF	DWF
Ce ppm	69.21	72.94	74.75	76.85	76.74	53.25	62.03
Pr ppm	9.59	9.61	9.93	10.13	10.16	9.29	12.78
Nd ppm	40.73	40.38	41.97	43.12	42.59	39.65	53.83
Sm ppm	10.22	10.10	10.13	10.64	10.86	10.19	13.42
Eu ppm	2.26	2.57	2.13	2.28	2.08	2.21	2.40
Gd ppm	10.72	10.68	11.29	11.61	11.64	10.45	13.09
Tb ppm	1.96	1.93	2.06	2.10	2.07	1.91	2.35
Dy ppm	12.48	12.33	13.23	13.65	13.66	12.65	15.07
Ho ppm	2.65	2.60	2.84	2.89	2.94	2.68	3.12
Er ppm	7.63	7.25	8.00	8.18	8.28	7.72	8.78
Tm ppm	1.16	1.12	1.23	1.27	1.27	1.17	1.34
Yb ppm	7.40	6.95	7.81	8.03	8.19	7.45	8.52
Lu ppm	1.20	1.13	1.30	1.32	1.31	1.14	1.36
Ba ppm	1193	1183	1284	1183	1159	1196	1204
Th ppm	6.74	6.60	6.73	6.93	7.13	7.30	7.25
Nb ppm	15.99	16.04	16.45	16.59	16.88	17.29	17.26
Y ppm	68.07	65.60	74.92	75.25	75.07	68.35	78.47
Hf ppm	10.59	9.65	10.67	10.86	10.95	11.49	11.44
Ta ppm	1.09	1.04	1.09	1.11	1.11	1.18	1.16
U ppm	2.50	2.48	2.57	2.62	2.65	2.77	2.69
Pb ppm	11.55	24.44	9.92	13.50	13.91	13.19	12.83
Rb ppm	69.6	63.6	66.5	69.7	71.2	71.0	71.2
Cs ppm	1.95	1.21	2.45	2.58	2.70	2.06	1.93
Sr ppm	107	140	110	99	85	81	82
Sc ppm	10.7	14.8	8.9	10.1	10.0	9.0	9.5
Zr ppm	395	368	406	408	412	433	435
La/Yb	4.57	4.89	4.47	4.44	4.34	4.28	4.75
Eu/Eu*	0.04	0.04	0.03	0.04	0.03	0.04	0.03

	Potato Lake Tuff										
	0064a_1	0064a_2	0064a_3	0064a_4	0064b_1	0064b_2	0064b_3	0064b_4	0064c_1	0064c_2	0064d
	grey/white banded pumice	black pumice	black pumice	black/white banded pumice	grey pumice	grey pumice	light grey pumice	light grey/white banded pumice	light grey pumice	tan pumice	grey/white banded pumice
La ppm	34.62	31.96	33.59	35.64	36.60	35.89	37.29	36.78	36.81	37.91	36.17
Ce ppm	75.77	70.63	74.31	77.39	79.04	77.70	79.76	77.89	78.87	78.13	78.80
Pr ppm	9.96	9.69	10.00	10.29	10.44	10.15	10.54	10.40	10.40	10.78	10.25
Nd ppm	41.63	41.59	42.92	42.16	43.06	41.91	43.47	42.79	42.86	43.96	42.12
Sm ppm	10.29	10.93	10.87	10.38	10.93	10.16	10.84	10.41	10.72	10.76	10.59
Eu ppm	2.08	3.74	3.38	1.89	1.79	1.69	1.64	1.61	1.37	1.65	1.65
Gd ppm	11.08	11.53	11.87	11.02	11.36	10.93	11.21	11.00	10.96	11.35	10.95
Tb ppm	1.99	2.05	2.12	2.04	2.06	2.01	2.05	2.01	2.03	2.08	2.02
Dy ppm	13.32	13.48	13.85	13.44	13.86	13.54	13.75	13.59	13.65	13.88	13.55
Ho ppm	2.89	2.90	2.98	2.94	3.01	2.94	3.04	3.01	2.97	3.02	2.97
Er ppm	8.30	8.20	8.58	8.61	8.77	8.64	8.78	8.80	8.76	8.79	8.65
Tm ppm	1.34	1.27	1.32	1.34	1.41	1.38	1.42	1.38	1.40	1.39	1.37
Yb ppm	8.66	8.15	8.57	8.98	9.22	9.04	9.38	9.11	9.19	9.19	9.07
Lu ppm	1.42	1.32	1.37	1.45	1.52	1.46	1.53	1.48	1.50	1.48	1.46
Ba ppm	1239	1535	1559	1242	1336	1158	1220	1259	1130	1143	1180
Th ppm	6.12	4.75	5.05	6.30	6.48	6.51	6.70	6.51	6.67	6.60	6.47
Nb ppm	17.74	15.68	16.45	18.33	18.40	18.92	19.31	18.59	19.03	19.21	18.80
Y ppm	76.14	74.68	77.07	77.61	79.33	78.53	80.06	80.07	79.79	81.54	78.53
Hf ppm	13.97	11.63	12.52	14.10	15.24	15.46	15.48	15.08	14.94	15.89	15.37
Ta ppm	1.12	0.96	0.99	1.16	1.17	1.19	1.21	1.19	1.21	1.22	1.20
U ppm	2.20	1.73	1.86	2.25	2.31	2.31	2.45	2.38	2.39	2.28	2.29
Pb ppm	12.52	9.65	8.43	11.54	11.83	13.02	11.71	11.93	13.29	13.44	13.12
Rb ppm	60.2	45.3	46.9	63.4	64.4	64.0	65.4	65.0	69.0	65.1	65.3
Cs ppm	1.86	1.39	1.45	1.95	1.93	1.94	2.03	1.94	2.09	1.93	1.96
Sr ppm	55	60	51	53	49	39	44	48	37	51	49
Sc ppm	11.7	18.4	17.9	11.0	9.4	9.5	8.9	8.8	8.1	9.4	9.3
Zr ppm	537	459	500	546	593	604	601	591	578	622	606
La/Yb	4.00	3.92	3.92	3.97	3.97	3.97	3.97	4.04	4.00	4.12	3.99
Eu/Eu*	0.03	0.06	0.05	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.03

Appendix III EMP - Glass shard analysis - major elements

Hampton Tuff - glass shard analysis											
Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO*.											
Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total*
0038_g3	73.4	0.20	13.26	2.88	0.128	0.033	1.74	4.80	3.45	0.02	97.55
0038_g4	73.7	0.21	13.14	2.71	0.081	0.037	1.63	4.77	3.57	0.03	97.77
0038_g5	74.0	0.20	13.23	2.79	0.087	0.028	1.17	4.74	3.58	0.03	97.64
0038_g6	73.8	0.18	13.01	2.88	0.165	0.032	1.55	4.87	3.50	0.02	97.01
0038_g7	73.8	0.18	12.89	2.88	0.078	0.029	1.92	4.68	3.45	0.03	97.36
0038_g8	74.2	0.20	13.36	2.41	0.066	0.005	1.22	4.67	3.74	0.03	96.80
0038_g9	73.6	0.21	12.96	2.74	0.050	0.028	1.62	4.77	3.89	0.02	98.00
0038_g10	74.8	0.19	13.38	2.20	0.041	0.007	0.75	4.48	4.08	0.02	96.45
0038_g11	73.6	0.21	13.23	2.75	0.125	0.028	1.30	4.84	3.75	0.03	97.75
0038_g12	74.5	0.17	13.27	2.52	0.031	0.031	1.06	4.76	3.52	0.06	98.04
0050_g1	74.5	0.20	12.99	2.73	0.125	0.023	1.15	4.79	3.38	0.05	97.60
0050_g2	74.8	0.19	13.28	2.42	0.032	0.029	1.18	4.63	3.40	0.00	96.40
0050_g3	74.4	0.19	13.21	2.87	0.104	0.024	1.18	4.60	3.39	0.01	96.87
0050_g4	74.3	0.21	13.17	2.84	0.123	0.037	1.12	4.80	3.35	0.00	97.08
0050_g5	74.3	0.19	13.11	2.68	0.098	0.017	1.23	4.71	3.51	0.03	96.83
0050_g6	75.2	0.18	12.96	2.13	0.073	0.017	1.13	4.07	4.22	0.06	95.00
0050_g7	73.9	0.20	13.21	2.84	0.126	0.035	1.25	4.91	3.44	0.00	96.85
0050_g8	74.5	0.18	13.17	2.69	0.121	0.033	1.18	4.91	3.22	0.00	96.07
0050_g9	75.1	0.16	12.78	2.52	0.072	0.018	1.06	4.21	4.04	0.01	95.93
0050_g10	74.2	0.19	13.27	2.91	0.144	0.026	1.13	4.54	3.58	0.00	97.18
0020_g1	74.9	0.19	13.26	2.72	0.018	0.018	0.60	4.32	3.86	0.00	99.11
0020_g7	75.6	0.20	13.44	2.01	0.069	0.000	0.56	4.31	3.68	0.00	96.38
0020_g8	74.9	0.20	13.52	2.40	0.016	0.015	0.64	4.11	4.06	0.04	97.11
0020_g9	74.7	0.18	13.39	3.49	0.096	0.019	0.67	3.64	3.60	0.04	97.95
0020_g9	74.7	0.20	13.17	2.80	0.063	0.051	1.07	3.70	4.07	0.05	96.77
0020_g9	75.1	0.18	13.13	2.59	0.085	0.033	0.79	4.06	3.82	0.04	96.70
0020_g010	74.7	0.20	13.44	2.39	0.077	0.050	0.79	4.55	3.66	0.00	96.16
0020_g012	75.1	0.19	13.12	2.21	0.022	0.024	0.69	4.63	3.90	0.00	95.82
0020_g013	75.2	0.19	13.08	2.43	0.060	0.008	0.57	4.34	4.05	0.01	97.12
0020_g014	74.8	0.21	13.57	2.44	0.035	0.025	0.59	3.86	4.37	0.05	96.10
0020_g015	74.8	0.20	13.34	2.40	0.087	0.036	1.12	4.08	3.80	0.00	97.96
0020_g016	74.7	0.22	13.33	3.17	0.006	0.038	0.72	3.59	4.08	0.02	97.81
0021_g4	74.3	0.20	13.06	3.00	0.084	0.029	1.61	3.88	3.68	0.02	98.08
0021_g5	73.7	0.20	13.20	3.33	0.175	0.033	1.56	4.06	3.60	0.01	97.35

Total* - original analysis total

EMP analysis- Hampton Tuff cont.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total*
0021_g6	75.6	0.20	13.02	2.29	0.037	0.014	0.68	3.94	4.17	0.00	98.03
0021_g7	73.9	0.20	13.16	3.42	0.118	0.057	1.33	4.02	3.67	0.01	98.23
0021_g8	74.1	0.22	13.37	2.81	0.152	0.030	1.36	4.12	3.63	0.05	96.87
0021_g9	74.6	0.19	13.40	2.59	0.144	0.024	1.08	3.98	3.83	0.03	97.80
0021_g010	74.2	0.20	13.47	3.03	0.072	0.026	1.30	3.94	3.60	0.04	97.86
0022_g1	75.2	0.20	13.23	2.41	0.029	0.026	1.16	4.02	3.66	0.00	95.27
0022_g2	74.4	0.20	13.24	2.89	0.070	0.043	1.47	4.09	3.48	0.00	95.94
0022_g6	75.1	0.20	13.28	2.35	0.061	0.022	0.66	3.99	4.24	0.03	95.55
0022_g7	75.0	0.20	13.09	2.95	0.092	0.037	1.04	3.85	3.59	0.05	95.72
0022_g8	74.7	0.19	13.30	2.62	0.077	0.031	1.13	4.02	3.81	0.00	95.56
0022_g9	74.7	0.21	13.24	2.98	0.086	0.036	1.21	3.86	3.53	0.04	96.34
0022_g010	75.1	0.17	13.11	2.78	0.143	0.037	1.05	3.91	3.57	0.02	96.11
0022_g012	75.7	0.21	13.18	1.83	0.000	0.027	0.88	3.98	4.03	0.05	96.32
0022_g015	75.9	0.19	13.23	1.79	0.038	0.020	0.93	3.34	4.46	0.02	95.71
0037_T1	74.6	0.19	13.04	3.04	0.08	0.03	1.20	4.03	3.63	0.01	97.44
0037_T2	74.5	0.16	12.95	3.75	0.07	0.02	0.65	3.92	3.86	0.03	96.70
0037_T3	76.3	0.18	13.31	1.64	0.03	0.02	0.38	4.27	3.72	0.00	96.94
0037_T6	76.5	0.18	13.38	1.00	0.00	0.02	0.57	4.18	4.02	0.03	97.81
0037_T7	74.2	0.20	13.51	2.82	0.10	0.04	1.15	4.30	3.56	0.00	96.98
0037_T8	74.2	0.16	12.94	3.92	0.14	0.05	1.18	3.78	3.52	0.00	98.46
0037_T9	75.9	0.15	13.06	1.98	0.06	0.03	0.75	4.22	3.75	0.00	96.65
0037_T10	74.8	0.17	13.66	2.69	0.09	0.02	0.45	4.19	3.77	0.07	97.53
0037_T11	75.2	0.18	13.02	2.46	0.04	0.04	0.96	4.14	3.88	0.00	98.37
0037_T13	74.4	0.18	12.91	2.82	0.10	0.03	1.26	4.11	4.04	0.01	98.79
0037_T14	75.7	0.18	13.94	1.07	0.03	0.03	0.66	4.34	3.95	0.02	97.07
0023_g1	68.4	0.49	14.87	5.69	0.25	0.32	2.59	4.13	3.02	0.09	97.56
0023_g2	67.8	0.50	14.59	6.41	0.22	0.47	2.92	3.91	2.86	0.20	97.86
0023_g3	68.3	0.53	14.64	5.99	0.06	0.48	2.92	3.96	2.92	0.09	98.81
0023_g4	68.2	0.50	14.71	5.97	0.19	0.44	2.91	3.98	2.89	0.12	97.83
0023_g5	67.9	0.49	14.70	6.15	0.19	0.47	3.06	3.78	2.98	0.12	97.80
0023_g6	68.4	0.50	14.81	6.00	0.15	0.41	2.71	3.92	2.81	0.17	97.93
001_g1	67.9	0.56	14.91	5.62	0.13	0.41	2.97	4.65	2.65	0.15	97.22
001_g2	67.1	0.53	15.00	5.76	0.13	0.48	3.13	4.79	2.81	0.17	96.34
001_g3	67.3	0.53	14.89	5.89	0.21	0.44	3.13	4.60	2.83	0.11	97.01
001_g4	67.3	0.50	14.78	5.80	0.21	0.45	3.18	4.81	2.70	0.12	97.98

Total* - original analysis total

EMP analysis- Hampton Tuff cont.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total*
001_g5	67.3	0.53	15.10	5.74	0.16	0.48	3.10	4.80	2.52	0.13	96.42
001_g6	68.1	0.55	14.89	5.44	0.10	0.44	2.95	4.87	2.47	0.09	97.00
001_g7	67.9	0.51	15.02	5.65	0.19	0.41	2.92	4.60	2.54	0.12	97.39
001_g8	67.7	0.49	14.66	5.93	0.17	0.48	3.18	4.48	2.56	0.16	98.78
001_g9	67.4	0.53	14.94	5.95	0.14	0.58	3.43	4.43	2.40	0.11	97.77
001_g10	68.2	0.54	15.17	4.95	0.15	0.32	2.65	4.65	3.10	0.15	95.60
001_g11	67.4	0.48	14.95	5.48	0.16	0.52	3.11	4.81	2.92	0.07	96.13
001_g16	67.1	0.52	14.76	6.10	0.12	0.52	3.29	4.61	2.67	0.14	97.12
001_g17	67.7	0.51	14.76	5.86	0.20	0.46	3.04	4.60	2.57	0.15	97.73
001_g19	67.1	0.52	14.65	6.08	0.18	0.51	3.28	4.71	2.72	0.13	98.19
001_g21	67.4	0.49	14.84	5.71	0.17	0.52	3.33	4.60	2.70	0.15	97.27
001_g22	68.1	0.47	14.67	5.90	0.20	0.39	2.95	4.52	2.53	0.15	97.17
001_g23	68.2	0.46	14.66	5.85	0.14	0.29	2.80	4.64	2.71	0.11	98.00
001_g24	67.9	0.48	14.53	5.52	0.22	0.37	3.04	4.87	2.81	0.11	97.88
001_g26	68.4	0.45	14.83	5.15	0.15	0.33	2.66	4.94	2.93	0.06	96.62
001_g27	68.2	0.52	14.96	5.72	0.18	0.40	3.02	4.40	2.39	0.11	97.03
001_g28	67.3	0.54	14.90	5.98	0.13	0.53	3.25	4.58	2.56	0.15	97.36
001_g29	68.0	0.54	14.81	5.44	0.18	0.43	2.90	4.92	2.55	0.13	98.31
001_g30	68.1	0.51	14.63	5.66	0.26	0.45	2.91	4.63	2.70	0.09	98.80
001_g31	68.2	0.51	14.63	5.44	0.16	0.47	3.05	4.75	2.66	0.06	98.17
001_g32	67.3	0.52	15.12	5.69	0.22	0.50	3.07	4.68	2.65	0.12	95.91
003_g1	75.0	0.22	13.26	2.43	0.08	0.02	0.60	4.83	3.43	0.00	97.24
003_g2	74.1	0.21	13.32	2.89	0.13	0.03	0.85	4.84	3.49	0.04	97.00
003_g3	74.5	0.20	13.29	2.98	0.02	0.04	0.81	4.38	3.71	0.03	96.43
003_g4	74.5	0.21	13.12	2.77	0.09	0.03	0.75	5.04	3.42	0.00	97.04
003_g5	74.8	0.19	13.33	2.81	0.00	0.03	0.74	4.62	3.41	0.00	96.60
003_g6	75.0	0.23	13.20	2.44	0.01	0.03	0.61	4.71	3.68	0.04	98.15
003_g7	74.9	0.22	13.37	2.15	0.03	0.03	0.74	4.72	3.76	0.01	96.97
003_g8	75.0	0.18	13.38	2.14	0.00	0.02	0.56	4.82	3.80	0.00	97.18
003_g9	74.9	0.20	13.32	2.32	0.07	0.01	0.67	4.68	3.76	0.00	96.45
003_g11	75.2	0.20	13.23	2.30	0.04	0.02	0.65	4.91	3.36	0.00	96.88
003_g12	74.2	0.19	13.34	3.08	0.04	0.04	0.83	4.77	3.40	0.00	96.21
003_g13	74.9	0.19	13.47	2.51	0.01	0.02	0.65	4.87	3.26	0.00	96.00
003_g14	75.3	0.20	13.33	1.97	0.12	0.00	0.69	4.52	3.71	0.03	96.31
003_g15	75.3	0.19	13.29	2.07	0.00	0.01	0.62	4.61	3.81	0.01	97.03

Total* - original analysis total

EMP analysis- Hampton Tuff cont.

Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total*
003_g16	74.8	0.20	13.25	2.48	0.08	0.02	0.70	4.85	3.47	0.01	97.69
003_g17	74.7	0.20	13.18	2.69	0.05	0.03	0.69	4.89	3.49	0.00	96.93
003_g18	74.8	0.18	13.13	2.85	0.11	0.02	0.68	4.75	3.41	0.00	97.31
003_g19	74.7	0.19	13.31	2.19	0.05	0.02	0.60	4.75	4.07	0.02	97.09
003_g20	74.3	0.17	13.41	2.76	0.05	0.02	0.70	4.84	3.63	0.00	96.15
003_g21	75.4	0.19	13.41	2.18	0.03	0.03	0.56	4.48	3.67	0.00	96.38
003_T1	75.0	0.20	13.44	2.04	0.10	0.00	0.65	4.51	3.87	0.01	97.19
003_T7	75.1	0.19	13.16	2.32	0.04	0.03	0.86	4.55	3.69	0.01	98.16
003_T8	74.1	0.19	13.45	2.98	0.11	0.03	0.96	4.53	3.54	0.00	95.95
003_T10	75.2	0.20	13.31	1.92	0.05	0.03	1.18	3.62	4.38	0.01	95.79
003_T15	75.5	0.19	13.13	2.43	0.02	0.01	0.61	4.73	3.30	0.03	97.03
006_g1	74.8	0.20	13.03	2.77	0.12	0.04	1.02	4.78	3.10	0.00	99.62
006_g2	74.9	0.21	12.97	2.83	0.13	0.03	0.91	4.85	3.06	0.00	99.21
006_g7	75.4	0.20	13.04	2.59	0.09	0.02	0.89	4.86	2.85	0.00	99.50
006_T1	76.5	0.20	12.56	2.34	0.00	0.02	0.58	4.28	3.42	0.00	98.59
0037b_g2	74.1	0.19	13.17	2.65	0.05	0.02	1.29	4.33	4.14	0.02	97.08
0037b_g3	74.5	0.21	13.37	2.58	0.10	0.03	1.25	4.44	3.45	0.03	96.36
0037b_g4	74.4	0.18	13.17	2.65	0.11	0.02	1.28	4.60	3.55	0.01	96.89
0037b_g5	74.1	0.21	13.27	2.69	0.07	0.04	1.21	4.23	4.15	0.00	96.59
0037b_g6	74.1	0.21	13.39	2.62	0.06	0.03	1.18	4.66	3.67	0.02	96.77
0037b_g7	74.2	0.20	13.31	2.74	0.08	0.04	1.25	4.44	3.69	0.01	96.06
0037b_g8	74.7	0.19	13.21	2.43	0.09	0.03	1.22	4.34	3.72	0.00	95.65
0037b_g9	73.8	0.18	13.44	2.78	0.08	0.03	1.20	4.74	3.71	0.00	95.47
0037b_g11	75.0	0.20	13.06	2.54	0.10	0.03	1.28	4.33	3.39	0.04	97.49

Total* - original analysis total

Potato Lake tuff											
Major elements are normalized on a volatile-free basis, with total Fe expressed as FeO*.											
Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total*
0064a_4_g1	70.85	0.46	14.20	4.03	0.21	0.28	1.09	5.00	3.71	0.09	95.98
0064a_4_g3	71.07	0.50	14.00	3.74	0.19	0.27	1.16	5.10	3.73	0.09	94.43
0064a_4_g5	70.96	0.50	14.07	3.83	0.14	0.32	1.09	4.72	4.13	0.15	96.37
0064a_4_g6	69.67	0.54	14.40	4.56	0.19	0.29	1.12	5.05	4.02	0.09	96.05
0064a_4_g8	70.10	0.52	14.51	4.15	0.15	0.29	1.21	5.26	3.66	0.08	96.71
0064a_4_g9	69.33	0.53	14.52	4.30	0.23	0.30	1.31	5.46	3.77	0.18	97.62
0064a_4_g10	74.54	0.28	13.09	2.42	0.07	0.11	0.57	5.29	3.50	0.05	97.48
0064a_4_g11	75.11	0.27	12.82	2.35	0.07	0.12	0.60	3.86	4.63	0.07	95.69
0064a_4_g12	74.32	0.27	13.01	2.37	0.08	0.12	0.63	4.72	4.36	0.02	96.59
0064a_4_g13	74.63	0.27	12.96	2.21	0.04	0.10	0.52	5.44	3.74	0.00	95.48
0064a_4_g14	74.05	0.30	13.16	2.48	0.05	0.10	0.57	4.91	4.26	0.05	96.74
0064a_4_g15	75.13	0.27	12.94	2.13	0.05	0.10	0.48	4.45	4.36	0.00	95.69
0064a_4_g20	74.98	0.26	13.12	2.32	0.07	0.09	0.50	4.58	3.93	0.04	96.42
0064a_4_g24	74.50	0.28	13.12	2.55	0.08	0.09	0.47	5.10	3.69	0.03	95.96
0064a_4_g25	75.26	0.26	12.73	2.41	0.06	0.08	0.44	5.07	3.56	0.04	96.75
0064a_4_g28	74.73	0.26	13.16	2.38	0.09	0.09	0.49	5.09	3.61	0.04	95.58
0064a_4_g29	75.20	0.26	12.71	1.95	0.05	0.09	0.48	3.75	5.41	0.02	95.54
0064a_4_g32	70.67	0.50	14.19	3.85	0.17	0.27	1.15	5.32	3.71	0.08	96.28
0064a_4_g34	70.46	0.45	14.18	4.18	0.12	0.28	1.20	5.36	3.64	0.05	97.95
0064a_4_g35	70.10	0.52	14.30	4.30	0.15	0.30	1.25	5.12	3.76	0.10	96.02
0064a_4_g36	74.64	0.27	12.98	2.21	0.10	0.09	0.52	4.13	4.95	0.02	95.06
0064a_4_g38	70.15	0.53	14.40	3.86	0.17	0.31	1.16	5.08	4.13	0.12	95.64
0064a_4_g40	70.09	0.51	14.42	3.95	0.13	0.33	1.29	5.19	3.87	0.10	97.21
0064a_4_g41	70.37	0.48	14.06	4.23	0.07	0.31	1.27	5.40	3.67	0.08	97.56
0064a_4_g42	70.70	0.53	14.11	3.93	0.20	0.31	1.22	4.70	4.14	0.07	96.79
0064a_4_g43	70.27	0.50	14.12	4.11	0.17	0.27	1.20	5.17	4.02	0.10	95.95
0064a_4_g44	70.73	0.51	14.15	4.12	0.08	0.26	1.10	4.81	4.04	0.07	95.01
0064a_4_g45	71.09	0.47	14.09	3.90	0.03	0.24	1.08	4.74	4.11	0.14	94.38
0064a_4_g46	74.87	0.27	13.06	2.30	0.00	0.11	0.51	4.80	3.96	0.03	96.15
0064a_4_g48	75.23	0.24	12.65	2.15	0.10	0.08	0.52	4.63	4.30	0.01	97.40
0064a_4_g49	75.31	0.23	12.76	2.15	0.05	0.09	0.50	4.55	4.24	0.02	97.33
Total* - original analysis total											

HP-91-9 - Buckaroo Lake Tuff											
Data are not normalized											
Sample	SiO ₂	TiO ₂	Al ₂ O ₃	FeO*	MnO	MgO	CaO	Na ₂ O	K ₂ O	P ₂ O ₅	Total
HP-91-9_g1	53.70	2.50	15.60	9.70	0.18	3.42	8.52	5.00	0.25	1.41	100.40
HP-91-9_g2	51.80	2.80	14.90	12.20	0.28	4.21	8.44	4.80	0.38	1.39	101.30
HP-91-9_g3	52.40	2.60	14.80	11.00	0.22	3.98	8.17	5.00	0.20	1.37	99.90
HP-91-9_g4	52.30	2.70	15.00	11.70	0.24	3.91	7.85	4.80	0.47	1.44	100.40
HP-91-9_g5	51.50	2.90	14.60	11.90	0.28	4.49	8.28	5.00	0.41	1.34	101.00
HP-91-9_g6	52.10	2.80	14.50	11.40	0.21	4.26	8.38	5.00	0.25	1.24	100.30
HP-91-9_g7	54.00	2.50	15.60	10.60	0.25	3.73	7.75	5.30	0.26	1.15	101.30
HP-91-9_g8	54.00	2.60	14.60	11.00	0.22	3.91	7.64	4.90	0.59	1.22	100.80
HP-91-9_g9	57.80	1.80	14.90	7.50	0.19	2.54	4.50	4.80	3.30	0.84	98.30
HP-91-9_g10	51.90	2.20	14.30	10.50	0.29	3.43	6.65	3.20	2.40	1.09	96.40
HP-91-9_g11	50.10	2.60	14.10	11.00	0.20	4.33	8.84	3.50	2.10	1.54	98.60
HP-91-9_g12	53.90	2.20	14.40	10.70	0.09	3.46	6.67	3.60	2.40	1.24	99.20
HP-91-9_g13	52.00	2.80	14.20	12.70	0.23	4.38	7.86	4.70	0.28	1.56	100.80
HP-91-9_g14	53.10	2.60	14.90	11.40	0.22	3.97	8.04	4.70	0.19	1.36	100.70
HP-91-9_g15	52.50	2.90	14.40	12.10	0.32	4.49	7.78	4.60	0.23	1.32	100.70
HP-91-9_g16	52.10	2.70	15.10	11.50	0.27	3.86	8.24	4.60	0.19	1.27	99.90
HP-91-9_g17	53.60	2.50	14.80	10.70	0.22	3.73	7.50	5.00	0.37	1.19	99.60
HP-91-9_g18	51.40	2.70	14.70	12.10	0.27	4.25	8.16	4.60	0.23	1.48	100.10
HP-91-9_g19	53.20	2.40	15.90	10.00	0.24	3.31	8.32	4.90	0.35	1.49	100.30
HP-91-9_g20	71.50	0.30	13.90	2.20	0.12	0.07	0.36	5.30	3.40	0.00	97.20
HP-91-9_g21	70.30	0.30	13.60	2.80	0.05	0.16	0.44	4.90	4.10	0.06	97.00
HP-91-9_g22	70.50	0.30	13.70	3.40	0.12	0.20	0.37	5.00	4.10	0.06	97.90
HP-91-9_g23	52.60	2.60	14.50	11.30	0.25	4.02	8.04	4.90	0.28	1.30	100.00
HP-91-9_g24	51.40	2.80	14.80	11.30	0.26	4.09	8.20	5.00	0.23	1.45	99.70
HP-91-9_g25	52.00	2.70	14.60	11.70	0.23	4.10	8.22	4.50	0.60	1.44	100.40
HP-91-9_g26	70.70	0.40	13.80	2.50	0.17	0.30	0.63	4.90	4.70	0.12	98.30
HP-91-9_g27	67.20	0.60	13.50	4.40	0.19	0.80	1.78	4.60	3.80	0.29	97.50
HP-91-9_g28	67.50	0.70	13.80	3.60	0.27	0.87	1.89	4.80	4.00	0.19	97.70
HP-91-9_g29	66.20	0.70	13.60	4.80	0.16	0.77	1.73	4.40	4.20	0.28	96.90
HP-91-9_g30	67.40	0.50	13.60	3.60	0.16	0.50	0.97	4.60	4.50	0.10	95.90
HP-91-9_g32	65.50	0.80	13.60	4.90	0.17	1.13	2.65	4.40	4.30	0.32	97.90
HP-91-9_g33	68.30	0.70	14.00	2.50	0.10	0.64	1.24	5.00	3.40	0.15	96.10
HP-91-9_g34	60.60	1.70	14.20	8.20	0.28	2.51	5.19	5.00	1.80	0.83	100.60
HP-91-9_g35	69.80	0.60	13.80	3.00	0.06	0.53	1.19	5.30	3.10	0.19	97.60
HP-91-9_g36	61.30	1.60	14.50	7.40	0.18	2.26	4.95	5.80	0.80	0.74	99.70
HP-91-9_g37	60.70	1.60	14.20	7.20	0.22	2.40	5.80	6.00	0.70	0.90	99.80
HP-91-9_g39	71.10	0.30	13.50	2.10	0.11	0.19	0.53	5.10	4.10	0.04	97.20

Appendix IV – Incremental heating analyses – Hampton Tuff

Incremental Heating		36Ar(a) [fA]	37Ar(ca) [fA]	38Ar(cl) [fA]	39Ar(k) [fA]	40Ar(r) [fA]	Age $\pm 2\sigma$ (Ma)	40Ar(r) (%)	39Ar(k) (%)	K/Ca $\pm 2\sigma$
14D10292	1.7 %	0.0526884	1.1250	0.0000000	0.39149	0.63439	5.26 $\pm$ 5.27	3.91	0.08	0.150 $\pm$ 0.070
14D10294	1.9 %	0.0054243	1.4837	0.0000000	0.38651	0.60832	5.11 $\pm$ 4.60	27.49	0.08	0.112 $\pm$ 0.043
14D10295	2.1 %	0.0027889	1.5619	0.0045308	0.37803	0.61360	5.27 $\pm$ 4.60	42.64	0.08	0.104 $\pm$ 0.039
14D10297	2.5 %	0.0149464	3.7771	0.0000000	1.22036	1.47867	3.94 $\pm$ 1.44	25.06	0.26	0.139 $\pm$ 0.020
14D10298	2.9 %	0.0031065	3.8587	0.0000000	1.27793	1.44941	3.68 $\pm$ 1.34	61.10	0.27	0.142 $\pm$ 0.019
14D10300	3.1 %	0.0061137	7.1455	0.0000000	2.13980	2.62432	3.98 $\pm$ 0.83	59.12	0.45	0.129 $\pm$ 0.010
14D10301	3.6 %	0.0050325	8.3383	0.0003730	2.71107	3.24703	3.89 $\pm$ 0.65	68.44	0.57	0.140 $\pm$ 0.010
14D10303	4.2 %	0.0095852	25.0319	0.0000000	7.29294	8.90484	3.97 $\pm$ 0.25	75.69	1.55	0.125 $\pm$ 0.003
14D10304	4.8 %	0.0669100	21.5911	0.0000000	6.31294	10.73351	5.52 $\pm$ 0.34	35.16	1.34	0.126 $\pm$ 0.003
14D10306	5.6 %	0.0047987	43.0956	0.0000000	12.89943	15.43918	3.89 $\pm$ 0.14	91.32	2.73	0.129 $\pm$ 0.002
14D10307	6.4 %	0.0121999	73.3260	0.0000000	21.72784	26.00918	3.89 $\pm$ 0.09	87.58	4.60	0.127 $\pm$ 0.001
14D10309	7.4 %	0.0051067	115.4788	0.0000000	33.99231	41.16765	3.93 $\pm$ 0.06	96.17	7.20	0.127 $\pm$ 0.001
14D10310	8.4 %	0.0084760	159.0521	0.0000000	46.95768	55.80592	3.86 $\pm$ 0.04	95.41	9.95	0.127 $\pm$ 0.001
14D10312	9.4 %	0.0062095	171.6927	0.0000000	49.87930	59.95857	3.90 $\pm$ 0.04	96.73	10.57	0.125 $\pm$ 0.001
14D10313	10.4 %	0.0059954	172.5469	0.0122590	50.01494	59.61242	3.87 $\pm$ 0.04	96.81	10.60	0.125 $\pm$ 0.001
14D10315	11.4 %	0.0056137	175.9212	0.0000000	51.46313	61.45262	3.88 $\pm$ 0.04	97.07	10.91	0.126 $\pm$ 0.001
14D10316	12.7 %	0.0056743	160.3213	0.0443887	46.85831	55.81685	3.87 $\pm$ 0.04	96.78	9.93	0.126 $\pm$ 0.001
14D10318	14.2 %	0.0263232	150.7943	0.0000000	45.31767	54.32906	3.89 $\pm$ 0.05	87.23	9.60	0.129 $\pm$ 0.001
14D10319	16.2 %	0.0457348	99.3336	0.0774363	30.82351	37.13467	3.91 $\pm$ 0.07	73.15	6.53	0.133 $\pm$ 0.001
14D10321	18.2 %	0.0043992	71.2818	0.0000000	21.58250	25.89449	3.90 $\pm$ 0.09	94.93	4.57	0.130 $\pm$ 0.001
14D10322	21.2 %	0.0060312	61.0204	0.0000000	18.02441	21.99047	3.96 $\pm$ 0.10	92.24	3.82	0.127 $\pm$ 0.001
14D10324	22.3 %	0.0092509	68.6171	0.0733983	20.20864	24.39718	3.92 $\pm$ 0.09	89.67	4.28	0.127 $\pm$ 0.001
Σ		0.3124094	1596.3949	0.2123862	471.86075	569.30237				

Information on Analysis	Results	40(r)/39(k) $\pm 2\sigma$	Age $\pm 2\sigma$ (Ma)	MSWD	39Ar(k) (%,n)	K/Ca $\pm 2\sigma$
Sample = HJS-HTP-006-2012	Age Plateau	1.19726 $\pm$ 0.00464	3.89 $\pm$ 0.02	0.56	98.66	0.127 $\pm$ 0.001
Material = Plagioclase		$\pm$ 0.39%	$\pm$ 0.44%	94%	21	
Location = Deschuttes			Full External Error $\pm$ 0.09	1.63	2 σ Confidence Limit	
Analyst = Dan Miggins			Analytical Error $\pm$ 0.02	1.0000	Error Magnification	
Project = OREGON SANVILLE (14-0)	Total Fusion Age	1.20651 $\pm$ 0.00589	3.92 $\pm$ 0.02		22	0.127 $\pm$ 0.000
Mass Discrimination Law = LIN		$\pm$ 0.49%	$\pm$ 0.53%			
Irradiation = 14-OSU-01			Full External Error $\pm$ 0.09			
J = 0.00179800 $\pm$ 0.00000185			Analytical Error $\pm$ 0.02			
FCT-NM = 28.201 $\pm$ 0.023 Ma						

Incremental Heating		36Ar(a) [fA]	37Ar(ca) [fA]	38Ar(cl) [fA]	39Ar(k) [fA]	40Ar(r) [fA]	Age $\pm 2\sigma$ (Ma)	40Ar(r) (%)	39Ar(k) (%)	K/Ca $\pm 2\sigma$
14D10353	1.7 %	0.0067830	1.9574	0.0411991	1.36875	1.18892	2.79 ± 1.27	37.17	0.25	0.301 ± 0.077
14D10355	1.9 %	0.0027346	1.9753	0.0119358	1.25035	1.15688	2.98 ± 1.33	58.73	0.23	0.272 ± 0.071
14D10356	2.1 %	0.0031778	2.2961	0.0287877	1.31618	1.15276	2.82 ± 1.28	54.98	0.24	0.246 ± 0.052
14D10358	2.5 %	0.0072704	2.8352	0.0154697	1.49886	1.59864	3.43 ± 1.14	42.60	0.27	0.227 ± 0.040
14D10359	2.9 %	0.0043883	9.0427	0.0377369	4.10929	4.52409	3.54 ± 0.41	77.51	0.75	0.195 ± 0.011
14D10361	3.1 %	0.0035002	6.8221	0.0153680	3.05874	3.26344	3.43 ± 0.55	75.73	0.56	0.193 ± 0.015
14D10362	3.6 %	0.0014384	6.5477	0.0000068	2.93648	3.70390	4.06 ± 0.57	89.46	0.53	0.193 ± 0.015
14D10364	4.2 %	0.0024183	19.6497	0.0919544	7.68677	9.42485	3.94 ± 0.22	92.68	1.40	0.168 ± 0.005
14D10365	4.8 %	0.0031906	22.6709	0.0814254	8.55902	10.30339	3.87 ± 0.20	91.35	1.56	0.162 ± 0.004
14D10367	5.6 %	0.0033774	44.1006	0.0740455	15.75675	18.84697	3.85 ± 0.11	94.68	2.87	0.154 ± 0.002
14D10368	6.4 %	0.0029149	74.0634	0.0077065	25.40613	30.97530	3.92 ± 0.07	97.00	4.62	0.148 ± 0.001
14D10370	7.4 %	0.0038861	112.7333	0.0347663	38.06302	46.60167	3.94 ± 0.05	97.30	6.92	0.145 ± 0.001
14D10371	8.4 %	0.0033968	142.1295	0.0000000	46.96330	57.14841	3.91 ± 0.04	97.97	8.54	0.142 ± 0.001
14D10373	9.4 %	0.0051781	146.6061	0.0000000	50.39393	61.32900	3.91 ± 0.04	97.27	9.16	0.148 ± 0.001
14D10374	10.4 %	0.0044262	166.7995	0.0138469	54.16834	65.72388	3.90 ± 0.04	97.75	9.85	0.140 ± 0.001
14D10376	11.4 %	0.0676340	146.1556	0.0000000	47.08513	57.14307	3.90 ± 0.05	73.92	8.56	0.139 ± 0.001
14D10377	12.7 %	0.0040391	167.2331	0.0000000	53.51986	64.82742	3.90 ± 0.04	97.89	9.73	0.138 ± 0.001
14D10379	14.2 %	0.0037532	139.2084	0.0001340	45.11232	54.87353	3.91 ± 0.04	97.72	8.20	0.139 ± 0.001
14D10380	16.2 %	0.0044211	134.0492	0.0000000	42.62464	51.75830	3.91 ± 0.05	97.24	7.75	0.137 ± 0.001
14D10382	18.2 %	0.0102820	78.4431	0.0435122	24.37681	29.86144	3.94 ± 0.08	90.51	4.43	0.134 ± 0.001
14D10383	21.2 %	0.0172423	165.5081	0.0153207	54.42384	66.03700	3.90 ± 0.04	92.57	9.90	0.141 ± 0.001
14D10385	22.3 %	0.0123319	59.8594	0.0255261	20.29308	25.27669	4.01 ± 0.09	87.17	3.69	0.146 ± 0.002
Σ		0.1777846	1650.6863	0.5387419	549.97158	666.71952				

Information on Analysis	Results	40(r)/39(k) $\pm 2\sigma$	Age $\pm 2\sigma$ (Ma)	MSWD	39Ar(k) (%,n)	K/Ca $\pm 2\sigma$
Sample = HJS-HTP-0020-0913 Material = Plagioclase Location = Deschuttes Analyst = Dan Miggins Project = OREGON SANVILLE (14-0' Mass Discrimination Law = LIN Irradiation = 14-OSU-01 J = 0.00178054 $\pm$ 0.00000182 FCT-NM = 28.201 $\pm$ 0.023 Ma	Age Plateau	1.21594 $\pm$ 0.00410 $\pm$ 0.34%	3.91 $\pm$ 0.02 $\pm$ 0.39% Full External Error $\pm$ 0.09 Analytical Error $\pm$ 0.01	0.61 87% 1.73 1.0000	97.71 16 2 σ Confidence Limit Error Magnification	0.141 $\pm$ 0.003
	Total Fusion Age	1.21228 $\pm$ 0.00496 $\pm$ 0.41%	3.90 $\pm$ 0.02 $\pm$ 0.46% Full External Error $\pm$ 0.09 Analytical Error $\pm$ 0.02		22	0.143 $\pm$ 0.000

Incremental Heating			36Ar(a) [fA]	37Ar(ca) [fA]	38Ar(cl) [fA]	39Ar(k) [fA]	40Ar(r) [fA]	Age $\pm 2\sigma$ (Ma)	40Ar(r) (%)	39Ar(k) (%)	K/Ca $\pm 2\sigma$
15D07544	1.0 %		4.94075	1.24887	0.252760	11.9695	53.2314	13.64 ± 2.54	3.57	0.55	4.12 ± 1.07
15D07546	1.3 %		6.87420	1.76771	0.322621	17.5619	22.9458	4.02 ± 2.37	1.13	0.81	4.27 ± 0.78
15D07547	1.6 %		7.54987	2.55822	0.382978	20.7095	16.9373	2.52 ± 2.21	0.77	0.95	3.48 ± 0.44
15D07549	1.9 %		7.14848	2.43379	0.451894	21.8617	24.6339	3.46 ± 1.98	1.17	1.01	3.86 ± 0.52
15D07550	2.3 %		7.36518	2.81551	0.486570	25.8709	21.1424	2.51 ± 1.73	0.98	1.19	3.95 ± 0.44
15D07552	2.8 %		8.32560	4.03528	0.757779	37.5635	40.1546	3.29 ± 1.33	1.63	1.73	4.00 ± 0.33
15D07553	3.3 %		6.97145	3.89507	0.734457	34.8220	37.6353	3.32 ± 1.22	1.82	1.60	3.84 ± 0.32
15D07555	3.9 %		8.76962	6.91308	1.311400	59.7626	70.9406	3.65 ± 0.88	2.71	2.75	3.72 ± 0.17
15D07556	4.4 %		7.66849	7.61692	1.424431	62.7656	63.0771	3.09 ± 0.74	2.75	2.89	3.54 ± 0.14
15D07558	5.0 %		7.83655	10.77338	2.181721	88.3342	105.9012	3.69 ± 0.53	4.44	4.07	3.53 ± 0.11
15D07559	5.8 %		8.15139	13.91359	2.835608	114.0507	137.0865	3.70 ± 0.43	5.47	5.25	3.52 ± 0.09
15D07561	6.6 %		8.22518	16.55187	3.453129	133.9037	151.9081	3.49 ± 0.37	5.97	6.17	3.48 ± 0.07
15D07562	7.4 %		7.71852	22.82043	4.733079	179.1145	214.5654	3.68 ± 0.26	8.72	8.25	3.38 ± 0.05
15D07564	8.4 %		10.67449	35.42723	7.331937	267.5931	326.6916	3.75 ± 0.24	9.52	12.33	3.25 ± 0.04
15D07565	9.4 %		12.88410	36.83056	7.696453	278.8334	341.5361	3.77 ± 0.28	8.35	12.85	3.26 ± 0.04
15D07567	10.4 %		13.52523	31.10892	6.434563	233.7714	297.7142	3.92 ± 0.34	7.04	10.77	3.23 ± 0.04
15D07568	11.4 %		13.92864	25.68672	5.341347	195.2648	247.0977	3.89 ± 0.42	5.75	9.00	3.27 ± 0.05
15D07570	12.4 %		19.72733	17.99785	3.771238	139.3464	9.3691	0.21 ± 0.94	0.16	6.42	3.33 ± 0.06
15D07571	13.9 %		18.12381	14.72624	3.047803	113.6079	41.6698	1.13 ± 1.04	0.78	5.23	3.32 ± 0.07
15D07573	15.4 %		23.47305	10.28386	2.232829	80.5581	20.8323	0.80 ± 1.82	0.31	3.71	3.37 ± 0.10
15D07574	17.9 %		21.28191	5.09885	1.115366	42.6358	30.1333	2.18 ± 3.18	0.49	1.96	3.60 ± 0.22
15D07576	20.5 %		11.11415	0.68248	0.263302	10.6507	101.3280	29.05 ± 6.15	3.04	0.49	6.71 ± 3.28
Σ			242.27799	275.18643	56.563264	2170.5522	2274.6006				

Information on Analysis	Results	40(r)/39(k) $\pm 2\sigma$	Age $\pm 2\sigma$ (Ma)	MSWD	39Ar(k) (%,n)	K/Ca $\pm 2\sigma$
Sample = HJS-HTR-0020 Material = Glass Location = Deschutes Formation Analyst = Dan Miggins Project = OREGON SANVILLE (14-0' Mass Discrimination Law = LIN Irradiation = 14-OSU-07 (7B33-14) J = 0.00170208 $\pm$ 0.00000150 FCT-NM = 28.201 $\pm$ 0.023 Ma	Age Plateau	1.20539 $\pm$ 0.03615 $\pm$ 3.00%	3.71 $\pm$ 0.11 $\pm$ 3.00%	0.72 77%	81.63 16	3.31 $\pm$ 0.06
		Full External Error $\pm$ 0.14 Analytical Error $\pm$ 0.11		1.73 1.0000	2 σ Confidence Limit Error Magnification	
	Total Fusion Age	1.04794 $\pm$ 0.05314 $\pm$ 5.07%	3.22 $\pm$ 0.16 $\pm$ 5.07%		22	3.39 $\pm$ 0.02
		Full External Error $\pm$ 0.18 Analytical Error $\pm$ 0.16				

Appendix V – Incremental heating analysis and single crystal total fusion analysis for the Potato Lake tuff

Incremental Heating		36Ar(a) [fA]	37Ar(ca) [fA]	38Ar(cl) [fA]	39Ar(k) [fA]	40Ar(r) [fA]	Age $\pm 2\sigma$ (Ma)	40Ar(r) (%)	39Ar(k) (%)	K/Ca $\pm 2\sigma$
15D35283	1.7 %	0.0145695	2.5769	0.0342012	2.7698	4.2199	4.65 $\pm$ 0.43	49.44	0.20	0.462 $\pm$ 0.085
15D35285	1.9 %	0.0198250	6.4995	0.0396049	6.2953	10.4423	5.06 $\pm$ 0.20	63.97	0.46	0.416 $\pm$ 0.032
15D35286	2.1 %	0.0087058	3.0477	0.0000000	2.9417	4.9528	5.13 $\pm$ 0.41	65.72	0.22	0.415 $\pm$ 0.066
15D35288	2.5 %	0.0092258	4.4722	0.0342110	4.3175	7.3347	5.18 $\pm$ 0.28	72.78	0.32	0.415 $\pm$ 0.046
15D35291	2.9 %	0.0110485	6.7069	0.0317983	6.0641	10.1084	5.08 $\pm$ 0.20	75.46	0.45	0.389 $\pm$ 0.028
15D35293	3.1 %	0.0166013	14.0252	0.0635169	11.8973	19.6987	5.05 $\pm$ 0.10	79.91	0.87	0.365 $\pm$ 0.012
15D35294	3.6 %	0.0117272	13.3822	0.0035738	11.2720	18.8680	5.10 $\pm$ 0.11	84.32	0.83	0.362 $\pm$ 0.014
15D35296	4.2 %	0.0179875	34.4455	0.0000000	27.0174	45.4662	5.13 $\pm$ 0.05	89.35	1.99	0.337 $\pm$ 0.005
15D35297	4.8 %	0.0106121	30.3723	0.0044238	23.3358	39.3053	5.14 $\pm$ 0.06	92.42	1.71	0.330 $\pm$ 0.006
15D35299	5.6 %	0.0205583	121.2439	0.0586244	89.8625	150.7807	5.12 $\pm$ 0.02	95.92	6.60	0.319 $\pm$ 0.003
15D35300	6.4 %	0.0078290	69.3279	0.0007054	51.0257	85.6872	5.12 $\pm$ 0.03	97.16	3.75	0.316 $\pm$ 0.003
15D35302	7.4 %	0.0119523	150.7701	0.0000000	110.2122	185.0555	5.12 $\pm$ 0.02	97.91	8.10	0.314 $\pm$ 0.002
15D35303	8.4 %	0.0117744	225.1359	0.0061673	163.0753	274.4156	5.13 $\pm$ 0.01	98.53	11.98	0.311 $\pm$ 0.002
15D35305	9.4 %	0.0105101	245.1427	0.0000000	177.4556	298.7230	5.13 $\pm$ 0.01	98.75	13.04	0.311 $\pm$ 0.002
15D35306	10.4 %	0.0135535	224.9561	0.0026808	161.3067	275.0681	5.20 $\pm$ 0.01	98.35	11.85	0.308 $\pm$ 0.002
15D35308	11.4 %	0.0030772	126.7932	0.0042299	89.9908	151.8452	5.14 $\pm$ 0.02	99.18	6.61	0.305 $\pm$ 0.002
15D35309	12.7 %	0.0020873	84.2671	0.0177546	59.6964	100.8712	5.15 $\pm$ 0.02	99.17	4.39	0.305 $\pm$ 0.003
15D35311	14.2 %	0.0016957	86.6661	0.0001415	59.7776	100.8692	5.14 $\pm$ 0.02	99.28	4.39	0.297 $\pm$ 0.003
15D35312	16.2 %	0.0016982	70.2023	0.0000000	48.3620	81.6039	5.14 $\pm$ 0.03	99.17	3.55	0.296 $\pm$ 0.003
15D35314	18.2 %	0.0058472	227.2410	0.0000000	158.3217	269.5736	5.19 $\pm$ 0.01	99.14	11.63	0.300 $\pm$ 0.002
15D35315	21.2 %	0.0024220	66.3797	0.0000000	47.0715	79.3585	5.14 $\pm$ 0.03	98.88	3.46	0.305 $\pm$ 0.003
15D35317	22.3 %	0.0092098	71.3994	0.0180997	48.8662	83.2075	5.19 $\pm$ 0.03	96.62	3.59	0.294 $\pm$ 0.003
Σ		0.2225176	1885.0538	0.3197335	1360.9353	2297.4556				

Information on Analysis	Results	40(r)/39(k) $\pm 2\sigma$	Age $\pm 2\sigma$ (Ma)	MSWD	39Ar(k) (%,n)	K/Ca $\pm 2\sigma$
Sample = HJS-HTP-0064C-2	Age Plateau	1.68330 $\pm$ 0.00200	5.13 $\pm$ 0.01	1.11	70.40	0.310 $\pm$ 0.005
Material = Plagioclase		$\pm$ 0.12%	$\pm$ 0.25%	34%	13	
Location = Deschuttes			Full External Error $\pm$ 0.12	1.82	2 σ Confidence Limit	
Analyst = Dan Miggins	Total Fusion Age	1.68814 $\pm$ 0.00176	5.15 $\pm$ 0.01	1.0557	22	0.310 $\pm$ 0.001
Project = OREGON SANVILLE (14-0'		$\pm$ 0.10%	$\pm$ 0.25%			
Mass Discrimination Law = LIN			Full External Error $\pm$ 0.12			
Irradiation = 15-OSU-04 (4E26-15)			Analytical Error $\pm$ 0.01			
J = 0.00168833 $\pm$ 0.00000189						
FCT-NM = 28.201 $\pm$ 0.023 Ma						

Plagioclase			36Ar(a) [fA]	37Ar(ca) [fA]	38Ar(cl) [fA]	39Ar(k) [fA]	40Ar(r) [fA]	Age $\pm 2\sigma$ (Ma)	40Ar(r) (%)	39Ar(k) (%)	K/Ca $\pm 2\sigma$
15D27676	18.0 %		0.0003072	7.603131	0.0000000	3.515930	6.323801	5.45 $\pm$ 0.29	101.24	7.75	0.199 $\pm$ 0.005
15D27678	18.0 %		0.0001607	5.063553	0.0191926	3.602695	6.351319	5.34 $\pm$ 0.29	99.04	7.94	0.306 $\pm$ 0.010
15D27680	18.0 %		0.0006028	6.377567	0.0155118	5.066584	8.683675	5.19 $\pm$ 0.20	97.78	11.17	0.342 $\pm$ 0.008
15D27682	18.0 %		0.0011638	5.464374	0.0000000	2.929278	4.957082	5.12 $\pm$ 0.34	93.31	6.46	0.231 $\pm$ 0.008
15D27684	18.0 %		0.0017197	2.095999	0.0000000	1.529024	2.557491	5.06 $\pm$ 0.66	83.26	3.37	0.314 $\pm$ 0.023
15D27686	18.0 %		0.0004872	6.886205	0.0204366	3.386673	5.933950	5.31 $\pm$ 0.30	97.42	7.47	0.211 $\pm$ 0.006
15D27688	18.0 %		0.0000950	2.554268	0.0000000	3.668437	6.395903	5.28 $\pm$ 0.28	100.22	8.09	0.618 $\pm$ 0.031
15D27690	18.0 %		0.0016620	2.618302	0.0000000	1.792365	3.056661	5.16 $\pm$ 0.56	85.99	3.95	0.294 $\pm$ 0.018
15D27692	18.0 %		0.0006294	2.327683	0.0000000	1.864765	3.222868	5.23 $\pm$ 0.54	94.35	4.11	0.344 $\pm$ 0.022
15D27694	18.0 %		0.0000491	2.594197	0.0151622	1.592688	2.841682	5.40 $\pm$ 0.63	100.30	3.51	0.264 $\pm$ 0.017
15D27696	18.0 %		0.0017234	3.407154	0.0000000	2.501777	4.142648	5.01 $\pm$ 0.40	88.87	5.52	0.316 $\pm$ 0.014
15D27698	18.0 %		0.0001648	1.258088	0.0136645	0.759045	1.539511	6.14 $\pm$ 1.38	103.07	1.67	0.259 $\pm$ 0.035
15D27700	18.0 %		0.0008537	3.412832	0.0000000	2.928994	4.822104	4.99 $\pm$ 0.34	94.82	6.46	0.369 $\pm$ 0.016
15D27702	18.0 %		0.0006904	1.706871	0.0277608	1.214020	1.942056	4.84 $\pm$ 0.82	90.30	2.68	0.306 $\pm$ 0.028
15D27704	18.0 %		0.0015160	3.836709	0.0000000	2.048666	3.429375	5.07 $\pm$ 0.48	88.27	4.52	0.230 $\pm$ 0.011
15D27706	18.0 %		0.0010066	2.494253	0.0060251	1.933928	3.063732	4.80 $\pm$ 0.50	90.95	4.26	0.333 $\pm$ 0.021
15D27708	18.0 %		0.0017232	2.698053	0.0000000	2.142648	3.319085	4.69 $\pm$ 0.45	86.51	4.72	0.341 $\pm$ 0.019
15D27710	18.0 %		0.0006610	1.837837	0.0000000	1.525704	2.545579	5.05 $\pm$ 0.66	92.68	3.36	0.357 $\pm$ 0.029
15D27712	18.0 %		0.0011268	1.404290	0.0167694	1.359775	2.144383	4.78 $\pm$ 0.74	86.38	3.00	0.416 $\pm$ 0.042
Σ			0.0151104	65.641367	0.1345231	45.362996	77.272903				

Information on Analysis	Results	MSWD	39Ar(k) (%,n)	K/Ca $\pm 2\sigma$
Sample = HJS-HTP-0064C-2	Single crystal total fusion	1.10	100.00	0.257 $\pm$ 0.031
Material = Albite		34%	19	
Location = Deschuttes		1.67	2 σ Confidence Limit	
Analyst = Dan Miggins		1.0486	Error Magnification	
Project = OREGON SANVILLE (14-0)				
Mass Discrimination Law = LIN				
Irradiation = 15-OSU-04 (4E27-15)				
J = 0.00167686 $\pm$ 0.00000132				
FCT-NM = 28.201 $\pm$ 0.023 Ma				