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The Geology and Petrology of Enigmatic Rhyolites at
Graveyard and Gordon Buttes,
Mount Hood Quadrangle, Oregon

by

Elizabeth G. Westby

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

Master of Science
in
Geology

Thesis Committee:
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Portland State University
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Abstract

Rhyolite lava flows are found at two dome complexes at Graveyard Butte and Gordon Butte, Mount Hood Quadrangle, Oregon. At Graveyard Butte, the White River has cut a winding canyon 150 m deep, exposing at its base, a 40-meter-thick outcrop of flow-banded rhyolite (73 wt.% SiO₂, 3.67±0.01 Ma) that laterally extends along the canyon wall for about 1 km. Stratigraphically above the flow-banded rhyolite is locally-erupted iron-rich andesites (lava flows, agglutinate and other pyroclastic rocks as well as clastic debris), a rhyolitic ash-flow tuff (74 wt.% SiO₂), and the 2.77±0.36 Ma tholeiitic basalt lava flows of Juniper Flat (Sherrod and Scott, 1995). Roughly 2 km downstream, a phenocryst-poor, maroon-colored rhyolite (3.65±0.01 Ma) is visible again, forming steep canyon walls for about 1.6 km. A compositionally similar silicic unit is found 18 km to the northwest of Graveyard Butte at Gordon Butte. Exposed units along Gordon Butte's Badger Creek (3.64±0.03 Ma) and the southeastern upper slopes of Gordon Butte include rhyolite flows (69.6–72.1 wt.% SiO₂).

The rhyolite lava flows at Graveyard Butte and Gordon Butte's Badger Creek are nearly chemically indistinguishable and both contrast with the younger rhyolitic ash-flow tuff at Graveyard Butte and lava flows on Gordon Butte's Upper Slopes. The rhyolites of Graveyard Butte and Badger Creek are richer in Nb and Zr (30–40 ppm and 487–530 ppm, respectively) than the younger rhyolitic tuff and Upper Slopes flows (13–19 ppm and 235–364 ppm, respectively) and share characteristics with A-type granitoids. The rhyolite lavas are porphyritic (~7%) with the porphyroclasts comprising primarily individual feldspars (250–500 µm in length) with ragged margins, oscillatory zoning and

less commonly, spongy cores. Other phenocrystic phases include fayalitic olivine, Fe-rich clinopyroxene, and Fe-Ti oxides.

A-type-like incompatible trace-element-enriched compositions as well as mineralogical indicators suggest rhyolite lava flows at Graveyard Butte and Gordon Butte's Badger Creek are likely generated in an extensional tectonic setting. A possible geotectonic framework for generation of these rhyolite lavas is the northward propagating intra-arc rift of the Oregon Cascades.

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I. Introduction and Overview

Graveyard Butte has a very unremarkable exterior. Its low-profile is covered by pasture grass, small pine and oak, and overshadowed by the nearby folded terrane of Tygh Ridge, Mutton Mountains and Laughlin Hills (Figure 1). On clear, sunny days, Mount Hood and Mount Jefferson come into view, from their positions tucked back behind the foothills of the Cascade Range. Isolated in the middle of the flat to undulating expanse of Smock Prairie and Juniper Flat, it is difficult to discern how Graveyard Butte fits into the geologic landscape.

Figure 1. View to the southwest across the farmland of Smock Prairie with the low profile of Graveyard Butte in the middle distance and the Laughlin Hills in the background. Mount Jefferson is in the upper right.

In contrast to its plain cinder cone-like exterior (Sherrod and Scott, 1995), entry into the interior or central portion of Graveyard Butte is richly rewarding (Figure 2). The

White River has carved a 150-m-deep canyon into volcanic sediments and lava flows, and stranded paleochannels filled with cobbles high above the current water line, all within a compact area of less than 6 km².

Figure 2. View to the northwest from the south side of Graveyard Butte. The Wasco County quarry is the area in the upper left, located along the White River Crossing Road. The White River is visible in the trees at the bottom center of the image.

This study focuses on volcanism at Graveyard Butte—mapping the volcanic and sedimentary units inside the White River canyon, and conducting petrographic, geochemical and isotopic age analyses of Graveyard Butte samples. The rhyolite at Graveyard Butte is compared to rhyolite found at Gordon Butte, located 18 kilometers (km) to the west, in order to place the volcanism into a broader regional context. The intent of the research is to distinguish events at Graveyard Butte, investigate the connection between the two buttes, and propose a conceptual geotectonic framework for the evolution of magmas at Graveyard and Gordon Buttes.

II. Description of the Area

Graveyard Butte is located in what is informally known as Tygh Valley, Oregon (Figure 3).

Figure 3. Map of the area in and around Graveyard Butte. Quaternary faults indicated by dotted lines and folds indicated by solid green lines (U.S. Geological Survey and others, 2006). Basemap from ESRI. Map scale 1:320,000.

The butte is located west of the towns of Maupin and Tygh Valley, near Wamic and Pine Grove. Other nearby landforms are the Tygh Ridge anticline to the northeast, Mutton Mountains to the southeast and Mount Hood to the northwest. Gordon Butte is ~18 km northwest of Graveyard Butte; Badger Creek runs along the southern margin of Gordon Butte.

The buttes are located in a transition zone between western and eastern Oregon climates. Traveling south on Highway 26 from Government Camp, dense stands of Douglas fir give way to stunted Ponderosa pine and white oak (Figure 4). Mount Hood's lush montane ecology, supported by 91 centimeters (cm) of annual rainfall (National Oceanic and Atmospheric Administration, 2014) and several meters of snow, becomes oak, pine, sagebrush and grass covering the flat prairies around the towns of Pine Grove, Wamic and Tygh Valley. Mount Hood, at an elevation of 3,426 meters (m), creates a rain shadow on its east side, challenging local farmers and ranchers with only 45 cm of annual precipitation (Soil Survey Staff, undated).

Figure 4. Transition zone of conifer forest to pine and oak near the summit of Gordon Butte. View to the west with Mount Hood in the background; a weathered rhyolite outcrop is pictured in the foreground.

At the turn-off for the White River Crossing (near Pine Grove), the road becomes a gravel wash-board, long used by local residents. Elevated to county road status in 1913 (Marty Matherly, Public Works Director, Wasco County, personal communication, January 27, 2014), the White River Crossing Road bisects open pasture, where loess, ash and silt form a thin layer over rounded mafic cobbles. The cobbles are exposed only in knee-deep gullies where short-duration, intense rains have winnowed finer sediments. From the road, the view forward is nondescript. Although at an elevation of 707 m above sea level (ASL), the rounded profile of Graveyard Butte rises barely 90 m above the moderately undulating Smock Prairie and Juniper Flat (see Figure 1).

At the highest point on the south side of Graveyard Butte, is a small fenced-off cemetery for local families Claymier, Hix, Laughlin, Magill, McCorkle, McCubbins, and Smith. Many of the families traveled west by ox team from Missouri and Ohio in the mid-1850s, completing their journey along the local section of the Barlow Trail. They acquired 160 acre land grants and settled in the area to farm and raise livestock (Shaver *et al.*, 1905). Descendants remain in the area and features such as the Laughlin Hills, McCubbins Gulch and many of the local roads bear the names of these early pioneers. The area at and around Graveyard Butte today, is a combination of private ownership parcels used for dry-land agriculture, orchards and animal grazing, with land along the White River overseen by the Bureau of Land Management as part of the White River Wild and Scenic Area.

The southern entrance to Graveyard Butte's White River canyon first passes by an unofficial landfill, with its buck-shot washing machine, plastic detritus, and occasional animal carcass. The second, more appealing sight is inside the 150-m-deep White River canyon. The southern promontory offers a view to the west toward massive terraced basalt flows incised by the White River. Originating at the terminus of the White River Glacier on the east side of Mount Hood, the White River flows southeasterly away from the volcano. In its upper reaches, the river drops 250 m per km over its first 6 km before turning directly east at Smock Prairie. In the middle section where Graveyard Butte is located, the river drops an average of 30 m per km (Figure 5). Once the river passes the town of Tygh Valley, the lower reach drops about 15 m per km. It then joins the

Deschutes River upstream of Sherar's Falls, north of Maupin, at River Mile 47.5 (76.4 km), at an elevation of 240 m (Wasco County Comprehensive Plan, 1983).

Figure 5. View from the White River Crossing bridge looking to the southwest, upstream. Channel bar comprised of medium- to dark-gray cobbles is in the bottom center. Local volcanoclastic deposits are visible at water level to mid-way upslope in the center left of the image. A paleochannel filled with cobbles is exposed in the upper left.

From this same viewpoint looking north, are the rainbow colors of heat- and fluid-altered volcanoclastic debris (see Figure 2). The sediments were once quarried by the Wasco County Department of Public Works until the conclusion of mining activities in the 1950s (Marty Matherly, Public Works Director, Wasco County, personal communication, January 27, 2014); the county's no trespassing sign remains for target practice.

The view farthest east (Figure 6) is to warped lava flows and the entrance to a narrow 120-m-high canyon. From there, the White River emerges from its geologic meander of Graveyard Butte, through the Tygh Valley, to eventually join the Deschutes River.

Figure 6. View to the east and flow units on both sides of the White River in the canyon at Graveyard Butte. The stand of pines in the lower left is at one of five sharp bends in the river channel. The Tygh Ridge anticline is in the background, upper left.

The semi-arid climate, sparse vegetation and limited human interaction with the landscape cater to geologists. Outcrop is thin to massive, completely exposed or very nearly buried. Within the confines of Graveyard Butte are epiclastic and volcanoclastic deposits, andesite, rhyolite and basalt flows, that, collectively, represent an important part of the geologic record of this area.

III. Geologic History

Although not locally exposed, Graveyard Butte is underlain by the volcanic, volcanoclastic and sedimentary rocks of the Eocene Clarno Formation and the late-Eocene to early-Miocene John Day Formation (Beebee *et al.*, 2002; Johnson, 2011; McClaughry *et al.*, 2009; Smith, 1986).

Some of the earliest local high standing landforms may well have been the Mutton Mountains. Located to the south of Graveyard Butte, volcanism ~28-29 Ma produced this rhyolitic dome complex (Johnson, 2011). Around 15.5 Ma, Columbia River Flood Basalts flowed into the Tygh Valley, lapping onto the flanks of the Mutton Mountains (Johnson, 2011). Compression associated with tectonic plate rotation produced folds at Tygh Ridge and Mutton Mountains and deformed the Columbia River Basalts (Beebee *et al.*, 2002; Hildreth *et al.*, 2012; Smith, 1986); the most active period of folding is estimated to have occurred between 8.4–4.5 Ma (Johnson, 2011).

Sitting between the steeply dipping forelimb of the Tygh Ridge anticline to the north and the shallowly-dipping, broad backlimb of the Mutton Mountains anticline to the south, the Tygh Valley syncline is the local depositional basin for the volcanoclastic sediments of the middle-Miocene to Pliocene Tygh Valley Formation. The Tygh Valley Formation consists of weakly cemented basaltic, andesitic and pumiceous sandstone and conglomerate; tuffaceous siltstone and sandstone; tuff; pumice lapilli tuff; tuff breccia; agglomerate; and 1- to 20-m-thick lahar deposits (Farooqui *et al.*, 1981). The Formation is coeval with the Deschutes Formation and part of the larger Dalles Group (Beebee *et*

al., 2002; Farooqui *et al.*, 1981). The Dalles Group extends along the eastern margin of the Cascade Range from the Madras Basin in the south to the Columbia River in the north. The Dalles Group consists of five mid-Miocene to Pliocene age formations that overlay Columbia River Basalts (Farooqui *et al.*, 1981).

The primary source of Tygh Valley Formation sediments is to the west. The Cascade Range is a subduction-created volcanic arc that extends from northern California to southern British Columbia. Eruptions along various segments of the ancestral Cascades (also called the Western Cascades) began about 45 Ma, with a period of relative quiescence in northern Oregon until 17 Ma (du Bray and John, 2011). From 17–8 Ma, eruptions to the north and west of Graveyard and Gordon Buttes consisted of andesite (Figure 7(A)) transitioning to basalt with bimodal (basalt/dacite) association at Graveyard Butte during the 7–2 Ma time period (Figure 7(B)) (du Bray and John, 2011).

Figure 7. Geologic maps show the distribution and composition of ancestral Cascade arc (Western Cascades) rocks emplaced at (A) 17–8 Ma, and (B) 7–2 Ma, in northern Oregon. Bimodal eruption of basalt and dacite are shown at Graveyard Butte in the 7–2 Ma time period. Modified from du Bray and John (2011).

From 5 to 3.5 Ma, the geologic record shows evidence for uplift of the Western Cascades (Sherrod and Scott, 1995). Cheney and Hayman (2007) studied deformation of gravels west of Ellensburg, Washington, to conclude that major uplift occurred around 4 Ma. Locally, to the east of Graveyard and Gordon Buttes the broad Deschutes River switched from a mostly aggrading to mostly degrading channel after 4 Ma in response to uplift (Beebee *et al.*, 2002). Moreover, the rise of the Cascades led to creation of a rain shadow, supported by work on fossil floras east of the current Cascades axis. Mustoe and Leopold (2014) concur that the Cascade Range was undergoing major uplift around 4 Ma based on the shift of plant communities in Idaho from a summer–wet and winter–mild climate, to semi-arid, after 3.4 Ma.

Tectonic plate rotation caused north-south compression to produce local and regional folding at Tygh Ridge and Mutton Mountains. The rotation also created east-west horizontal extension (Hildreth *et al.*, 2012; Wells *et al.*, 1998). As a result, the Pliocene Cascade volcanic platform sank by as much as 1.2 km in the central part of the Cascade Range between about 5 and 4 Ma, and a north-trending graben 30 km wide and 50 km long developed along the Green Ridge fault (Beebee *et al.*, 2002; Sherrod and Smith, 2000). The exact location of the northern-most extent of this rift is unknown but is assumed to have propagated northward beyond Mount Jefferson to join the Hood River fault in northern Oregon (Hildreth *et al.*, 2012). The narrow Hood River fault is a north-northwest-striking fault zone 1 to 3 km wide formed by an *en echelon* succession of normal faults that run to the Columbia River. Faulting occurred in late Pliocene or early

Quaternary time (Sherrod and Smith, 2000), cutting lavas as young as 2.9 Ma (Conrey *et al.*, 1996) (see Figure 3).

To the northwest of Graveyard Butte is Mount Hood, a stratovolcano of the High Cascades, with a modern edifice less than 500,000 years old (Scott *et al.*, 1997). This High Cascades volcano sits upon the remnants of earlier eruptive centers, such as the Sandy Glacier Volcano (~1.3 Ma); more than 45 peripheral volcanoes of Quaternary and Tertiary age surround Mount Hood on all sides (Hildreth, 2007). Over its eruptive history, Mount Hood has produced a consistent composition of andesitic domes and lava flows that has trended over the last 15,000 years to a more dacitic composition (Koleszar *et al.*, 2012). No widespread tephra fall units are known to have erupted from Mount Hood (Hildreth, 2007), although neighboring volcanoes to the north (Mount St. Helens) and the south (Mount Jefferson, Three Sisters, and Crater Lake) have had significant explosive eruptions (Conrey *et al.*, 2002; Koleszar *et al.*, 2012).

IV. Stratigraphy and Geologic Map of Graveyard Butte

Units at Graveyard Butte include rhyolite, andesite and basalt, plus thin to massive volcanoclastic and sedimentary deposits (Figure 8, Table 1).

Figure 8. View to the northwest from the south side of Graveyard Butte, with Mount Hood in the center background and Gordon Butte in the far right background. The Wasco County quarry is in the center of the image. The extent of units found in this area is indicated by dotted lines.

A. Geologic Map and Description of Rock Units

The geologic map of Graveyard Butte is provided in Figure 9, with polygons defining the lateral extent of the surficial units mapped for this study. Figure 10 includes a correlation of units and two hypothetical cross-section, A–A' and B–B', with the locations indicated on the geologic map. The description of rock units is provided in Table 1.

Geologic Map of Graveyard Butte, Oregon

Figure 9. Geologic map of Graveyard Butte, Oregon.

Figure 10. (A) Correlation of units from Graveyard Butte geologic map, (B) hypothetical cross-section for A–A', and (C) hypothetical cross section for B–B'.

Table 1. Description of Map Units at Graveyard Butte.

Unit	Description
Qal	<p>Alluvium (Holocene, Pleistocene)</p> <p>Unconsolidated fluvial deposits of volcanic origin, ranging from clay- and sand-sized to unconsolidated gravels, cobbles and boulders (gray). Includes low-relief natural levees and areas of sand and silt overwash adjacent to the White River channel. Unit likely originates on the slopes of Mount Hood at the base of the White River glacier as outwash, debris-flows and the erosional re-working of volcanoclastic deposits, or as gravels and boulders of eroded local lava flows such as the Juniper Flat basalt flow.</p>
Qc	<p>Colluvium (Holocene, Pleistocene)</p> <p>Fine-grained loess and ash forming thin soils.</p>
Ql	<p>Landslide, Debris Flow (Holocene, Pleistocene)</p> <p>Channelized flow deposits of unconsolidated, poorly sorted, rounded to sub-rounded pebbles and cobbles in a sandy matrix. Also includes massively-bedded debris flow at the base of the south side of the White River canyon along the White River channel.</p>
Qt	<p>Ash-flow Tuff (Pleistocene)</p> <p>Non-welded ash-rich pyroclastic flow deposit with ~5% tan-colored, oblate, crystal-rich pumices, 1–15 cm on longest axis, often with stretched vesicle channels, and ~2% gray subangular dense lithic fragments 1–2 cm.</p>
Tb	<p>Basalt (Pliocene)</p> <p>Basalt flows of Juniper Flat with an age of 2.77 ± 0.36 Ma (Sherrod and Scott, 1995). Color is medium gray, forming lobes 2–40 m thick with rubbly tops and bottoms and a solid center; often vesiculated in the upper part of the lobes. Identifiable by plagioclase laths to 3 mm and sparse olivine. Talus forms aprons below steep cliffs, either unvegetated or capable of supporting vegetation if unit includes colluvium. Basalt covers areas adjacent to Graveyard Butte and is channelized into the White River canyon. SiO_2 ranges from 49–50 wt.% (see Appendix D. Geochemical Data, Table 3).</p>

Table 1. Description of Map Units at Graveyard Butte.

Unit	Description
Tr	<p>Rhyolite (Pliocene)</p> <p>Rhyolite dome and lava flows in southwestern portion of canyon with an $^{40}\text{Ar}/^{39}\text{Ar}$ whole rock age of 3.67 ± 0.01 Ma. Outcrop consists of coherent blocks with fractured and weathered talus apron. Can be flow-banded. Outcrop in northeastern portion of map is massive, commonly microcrystalline and phenocryst-poor, with an $^{40}\text{Ar}/^{39}\text{Ar}$ whole rock age of 3.65 ± 0.01 Ma. SiO_2 ranges from 69–73 wt.% for both areas (see Appendix D. Geochemical Data, Table 3, Table 4, and Table 5; Appendix E. $^{40}\text{Ar}/^{39}\text{Ar}$ Age Results for Graveyard and Gordon Buttes, Table 8).</p>
Tt	<p>Volcaniclastic (Pliocene)</p> <p>Poorly to moderately indurated volcaniclastic deposits of ash (62–350 μm) and small (~1 mm) pumice and scoria (sometimes pastel pink and gray, black or red). Large scoria to 15 cm in length, with black or yellow coats over black centers. Some crystal-rich, subangular lithics to 20 cm. Brick-red agglutinate. Beds are thin to massive.</p>
Ta	<p>Andesite (Pliocene)</p> <p>Andesitic lava flows with an $^{40}\text{Ar}/^{39}\text{Ar}$ whole rock age of 3.86 ± 0.07 Ma. Flows in the western portion of the canyon are coherent, brick red and black with sparse phenocrysts, and can include medium-gray lithics. Agglutinate and scoria on southern side of canyon. In eastern portion of canyon, flows are platy. SiO_2 ranges from 56–62 wt.% (see Appendix D. Geochemical Data, Table 3, Table 4, and Table 5; Appendix E. $^{40}\text{Ar}/^{39}\text{Ar}$ Age Results for Graveyard and Gordon Buttes, Table 8).</p>

B. Descriptions of Stratigraphic Sections

Units within the White River canyon include lava flows and at least four distinctive volcanoclastic or sedimentary deposits—one at the Wasco County quarry, two in exposures along the White River Crossing Road, and one downstream of the White River Crossing bridge.

1. Wasco County Quarry Units (Tt, Tb)

The most visually dramatic depositional site is at the former Wasco County quarry (45.162514°, -121.3119429°) (Figure 11; see also Appendix B. Illustrative Stratigraphic Sections). The uppermost unit (Unit 1) consists of a plagioclase-rich basalt lava flow with about four subunits, each approximately 2 m thick. The layers have solid or vesiculated centers (vesicles are 1 millimeter (mm) to 3 cm) and frequently, rubbly flow tops and bottoms.

Figure 11. Stratigraphy of the Wasco County quarry. The upper schematic outlines the seven units visible in the lower image.

Beneath the basalt is a thin bed of sand-sized grains with minor lithics (Unit 2). A distinguishing feature of Unit 3 is its brick-red color. The unit consists of ash (~177–200 micrometers (μm)), black glassy fragments and scoria, along with angular clasts 5–20 cm

of gray or red lava. The unit has gradational contacts with upper and lower beds and coarsens upward to a layer of angular lithics before fining upward to the next contact. Unit 4 is a black, structure-less bed of sand-sized (125–350 μm) glassy, sub-rounded grains of andesitic composition (see Appendix D. Geochemical Data, Table 4, sample X-9). Unit 5 is similar to Unit 3 in its brick-red color but the ashy matrix is finer (~88–125 μm) with smaller, similarly-sized angular clasts (4–15 cm) and scoria. Clasts in the upper portion of the unit are more rounded and include black, glassy fragments. The unit is normally sorted and has a sharp contact with the lower unit. Unit 6 is fine, angular ash and lapilli. Bedding consists of scoriaceous material, glassy fragments and subrounded clasts of no more than 1 cm; the unit pinches out upslope and thickens downslope.

Unit 7 is a massive, crudely stratified bed of volcanoclastic debris with an angular unconformity to the strata above. Most distinctive is the gradational color from maroon to brick-red, orange, yellow, tan and gray, with a change in orientation from near vertical to dipping at a shallower angle. From a distance, the unit appears to have crude wavy bedding, marked by large scoria (black with yellow coats) although the layering is not pronounced at close distance. The finest dry-sieved particles (less than 0.063 mm) comprise glass shards and bubble walls, along with subhedral translucent yellow, white and dark brown minerals. Subrounded yellow pumices are included in size fractions of 0.250 mm and greater. At 0.5 mm and greater, pumices are yellow, brown, brown-green and red [scoria]. Subangular lithics are salmon-colored, gray and white, and maroon. Scoria is found in size increments from 4 mm to a few as large as 15 cm.

The base of Unit 7 is not exposed. This part of the site has been re-worked by quarry activities and the building of the White River Crossing Road. Across the road, continuing down the steep slope toward the river, rounded lenticular mounds (less than 1.5 m high) of brick-red, poorly indurated lithics and red scoria punctuate a slope of grasses and small pines. No solid outcrop was found on the lower slope below the road; the slope is being undercut by the White River.

2. Volcaniclastic Deposit Downstream of Bridge (Tt)

Downstream of the White River Crossing bridge, on the south side of the river (45.160097°, -121.3073957°), there is an exemplary exposure consisting of tuff and re-worked volcaniclastic material (Figure 12; see also Appendix B. Illustrative Stratigraphic Sections).

Figure 12. Schematic diagram and image of sedimentary units downstream of the White River Crossing bridge on the south side of the White River. Height of exposure in image is ~15 meters.

The upper unit just beneath the vegetation varies in thickness, is generally reddish to brown colored, disorganized, poorly sorted, and has a sharp contact with the lower unit. The matrix is approximately $\sim 88\text{--}177\text{ }\mu\text{m}$ and grains are angular, with some sub-rounded 3–5 mm sized yellow pumice and red scoria 0.5–1 cm in size.

Unit 2 bedding is poorly indurated and wavy, comprised of ash and lapilli. The lapilli is muted or pastel shades of brown, red, and gray. Clasts are red scoria granules, some with hot red to orange interiors, angular to subrounded, frequently to 2 cm, and very angular clasts of nonvesiculated aphyric red lava. The matrix is a creamy-yellow ash ($\sim 90\text{ }\mu\text{m}$).

Unit 3 is crystal-lithic coarse volcanic sandstone. The bedding is massive and grading is uncertain due to limited access and cliff-like exposure. The matrix is of two sizes; one is $88\text{--}177\text{ }\mu\text{m}$ (average) with some fragments even finer, and the second is coarse 1–2 mm rounded to subangular grains. Clasts include red scoria in the upper 0.6 m of the unit, and small yellow pumices throughout.

Units 4 through 6 consist of thin beds of fine volcanic sandstone. Unit 4 is comprised of angular grains up $\sim 125\text{ }\mu\text{m}$ in size with sharp, planar, parallel or irregular fining up sequences. The crystal-lithic sandstone is poorly indurated and can include flattened pumice up to 1 cm in length, and red spherical scoria to $\sim 4\text{ mm}$. Unit 5 is poorly indurated volcanic sandstone with a matrix grain size of $\sim 88\text{ }\mu\text{m}$ and spherical yellow pumice and red scoria to 1 mm. Unit 6 is composed of angular creamy-yellow ash of $\sim 125\text{ }\mu\text{m}$. Clasts are red scoria from 3 mm to 6 cm and yellowish-green, crystal-

rich pumice from 3 mm to 1 cm. Bedding is wavy and fines upward for a sharp contact with the upper unit.

Unit 7 is a white to greenish-white bed that is poorly indurated with wavy contacts. The grain size is $\sim 62\ \mu\text{m}$ and particles are angular. Unit 8 consists of a thin sequence of coarse crystals, fine ash and coarse crystals, before fining upward. The grain size is $\sim 62\ \mu\text{m}$ with flattened glassy fiamme to $\sim 1\ \text{cm}$ in length. Unit 9 is at the river level and a shelf is observed extending below the water level. The grain size is $\sim 88\ \mu\text{m}$ and grains are angular to subangular. Clasts include a few red scoria of $\sim 2\ \text{cm}$ or less and some yellow to greenish-yellow pumice.

3. Ash-flow Tuff Near Quarry (Qt)

The non-welded ash-flow tuff is located along the White River Crossing Road near the top of the north side of the White River canyon (45.162374° , -121.3091732°) (Figure 13). The tuff exposure is $\sim 8\ \text{m}$ in thickness and the base of the tuff is concealed. The matrix consists of cream-colored ash, translucent crystals ($125\text{--}177\ \mu\text{m}$), and subrounded pumices ($1\text{--}15\ \text{cm}$ on the longest side) with stretched vesicle channels. The deposit includes small gray or red angular lithics ($1\text{--}2\ \text{cm}$). The ash-flow tuff is cut (with sharp contacts) by a paleochannel of rounded cobbles. Other tuff units are found at similar elevations exposed along primitive roads in the White River canyon ($\sim 540\ \text{m ASL}$), but none are as laterally extensive as this unit along the White River Crossing Road.

Figure 13. View to the northeast from the White River Crossing Road and ash-flow tuff. Person at left of image (1.7 m tall for scale) is examining a channel cut filled with rounded cobbles.

4. Fluvially-transported Deposits (Qal, Ql)

The White River canyon has several exposed paleochannels, now stranded high above water line. Channels range in size from as little as 8 m to as much as 100 m (see example in Figure 14, located at 45.159202°, -121.3119644°, east of the White River Crossing bridge). The channels are flat-bottomed to arcuate, filled with rounded to subrounded medium-gray cobbles, some of which are 15 cm or larger. The mafic cobbles are commonly vesiculated and plagioclase-rich.

Figure 14. (A) Upper image shows wide view of White River Canyon (looking east or downstream); (B) magnified section of image with dashed line and annotation showing the base of a paleochannel with rounded cobbles cutting into volcaniclastic sediment. The White River Crossing bridge is in the bottom center.

A debris flow fills a paleochannel carved into volcanoclastic sediment (45.159885°, -121.3076692°) downstream of the White River Crossing bridge (Figure 15). The bed is chaotic, poorly sorted, brownish in color, consisting of lenticular, poorly indurated clumps of sand-sized particles and larger angular blocks. The steep exposure precluded careful study, but chunks collected below the deposit are similar to Units 3 and 4 at the Wasco County quarry (see Figure 11).

Figure 15. Debris flow in upper left, carved into volcanoclastic sediment. The paleochannel is approximately 5 m above the modern-day river channel.

5. Soils (Qc)

Soils in and around Graveyard Butte include: (1) the Bakeoven-Watama complex, formed from loess, volcanic ash, and residuum weathered from basalt; (2)

Hesslan and Hesslan-Skyline complex, comprised of volcanic ash and colluvium derived from sediments and sandstone; (3) Wamic loam and Wamic-Skyline complex, formed from alluvium or colluvium derived from basalt or andesite overlain by volcanic ash and loess; and (4) Watama-Wapinitia silt loams comprised of loess and volcanic ash. Soil depths to bedrock are generally 30 cm to no more than 152 cm, depending on location (Soil Survey Staff, undated).

V. Petrography of Graveyard Butte Units

A. Rhyolites

Graveyard Butte rhyolites (see, for example, samples WR13 (Table 3), S6-13 and X3 (Table 4)) are variably porphyritic, with crystal abundances from 3% to 7%. The crystal assemblage contains plagioclase, clinopyroxene (Figure 16), fayalitic olivine (Figure 17), quartz, ilmenite, magnetite and accessory phase zircon and apatite (see also Appendix C. Energy Dispersive Spectra (EDS)).

Figure 16. Backscatter electron micrograph of sample S6-13, with clinopyroxene and Fe-Ti oxide.

Figure 17. Backscatter electron micrograph of sample S6-13, a flow-banded rhyolite, with Na-rich plagioclase, fayalitic olivine, Fe-Ti oxide and zircon.

The subhedral plagioclase is blocky to rectangular with irregular edges characterized by new mineral overgrowths; some phenocrysts display a wormy interior. Twin margins are commonly blurred. The subhedral clinopyroxene is fractured and embayed and the fayalitic olivine is subrounded (Figure 17). The quartz is subhedral and frequently observed under microscope with undulose extinction. The samples include Fe-Ti oxides (~45 μm) and sample S6-13 contains zircon (~37 μm). Sample X3 includes a mafic enclave with plagioclase and clinopyroxene, similar to that observed in basalt sample WR11 (Figure 18, see also Figure 19). Small phenocrysts line the elongated vesicles that define flow-banding.

Figure 18. Representative examples of Graveyard Butte rhyolite crystal assemblages: (A) sample WR13 show feldspar with ragged margins (magnification 5x); (B) sample S6-13 clinopyroxene (brown) and plagioclase (magnification 10x); (C) sample X3 crystal clot (magnification 10x); (D) sample X3 includes a mafic enclave (magnification 10x). All images under cross-polarized light.

B. Basalts

The basalt (sample WR11 (Table 3)) texture is equigranular to glomeroporphyritic, with plagioclase feldspar, Mg-rich olivine, clinopyroxene phenocrysts and microphenocrysts in an intersertal to intergranular groundmass. The plagioclase is commonly found as subhedral laths 900-1300 μm . The plagioclase is polysynthetic twinned, commonly with blurred margins between twins. Edges can include embayments creating a ragged appearance. Some have a sieved or spongy interior. The

plagioclase can be zoned, with an exterior higher in sodium as confirmed with EDS (Figure 19, see also Appendix C. Energy Dispersive Spectra).

Figure 19. Sample WR11 as viewed (A) under petrographic microscope with crossed-polarized light, and (B) as an annotated backscatter electron micrograph.

The olivines are 200–600 μm , subhedral to anhedral and fractured (Figure 19).

The olivines are commonly surrounded by pyroxene and oxides; Fe-Ti oxides can occur at rim margins. Subhedral clinopyroxene are rounded, 400–800 μm , and typically occur with olivine. Secondary minerals include zeolite (~20–30 μm subhedral clinoptilite) and Fe-Ti oxides.

C. Andesites

In hand samples, the andesites are commonly glassy (black or red) with less than 5% phenocrysts. Primary minerals include plagioclase feldspar (labradorite), clinopyroxene and Fe-Ti oxides. The larger plagioclase phenocrysts are subhedral (~350 μm) with poly-synthetic twins or two to four Carlsbad twins. All edges, including the short edge, can include embayments. The intermediate-sized plagioclase (~125 μm) is subhedral with sharp long margins and edges. Also observed are plagioclase microlaths that show some alignment on the long edges (Figure 20). The smaller plagioclase (~42 μm) has higher calcium interiors and more sodic rims (see Appendix C. Energy Dispersive Spectra). The Fe-Ti oxides are subhedral, up to 400 μm in length. The rock sample includes a rounded melt inclusion with labradorite, clinopyroxene and oxides (Figure 21).

Figure 20. Illustrative examples of Graveyard Butte andesites: (A) sample S12-6 (magnification 10x); (B) sample S12-6 (magnification 5x) (C) sample S12-6 vein (magnification 5x); (D) sample V1 (magnification 2.5x). All images under cross-polarized light.

Figure 21. Sample V1 includes a rounded melt inclusion, with zoned plagioclase, clinopyroxene and oxides.

VI. Geochemical Classification and Composition of Graveyard Butte Units with Comparison to Gordon Butte

Selected samples were prepared for bulk geochemical analysis (see Appendix A. Methods, for sample processing and analytical procedures), including rocks from Gordon Butte. Gordon Butte is the closest source of silicic rocks to Graveyard Butte (Sherrod and Scott, 1995), some 18 km distant. A comparison of geochemical data from both buttes provides the means to analyze trends and consider regional influences on magma compositions.

Lavas at Gordon Butte were sampled at several locations—one along Badger Creek and a second group of samples were taken at various locations from the butte's Upper Slopes (Figure 22).

Figure 22. Map of Gordon Butte rhyolite sample locations at Badger Creek and Upper Slopes. Basemap from ESRI. Map scale is 1:30,000.

Rhyolite sample locations at Graveyard Butte were in the western canyon, central canyon or quarry, and eastern canyon (Figure 23). Figure 9 shows the sample locations of the andesites and basalts.

Figure 23. Sample locations for Graveyard Butte include the western canyon, central canyon or quarry and eastern canyon. Basemap from ESRI. Map scale is 1:30,000.

As shown in Figure 24, the igneous rocks at Graveyard Butte are basalt, basaltic andesite, andesite, trachyandesite, and rhyolite (see data in Appendix D. Geochemical Data, Table 3, Table 4, and Table 5). The samples collected at Gordon Butte are exclusively rhyolite (see Appendix D. Geochemical Data, Table 6). The rhyolite ranges from 69.01 to 74.08 wt.% SiO_2 , the basalt ranges from 49.5 to 50.1 wt.% SiO_2 with Mg numbers that range from 49.1 to 54.5, and the andesites range from 56.9 to 62.4 wt.% SiO_2 .

Figure 24. Classification of 40 geochemical samples from Graveyard Butte (solid symbols) and Gordon Butte (open red squares with cross). The data consists of four basalts, nine andesites, six trachyandesites, and 21 rhyolites. All samples are subalkaline/tholeiitic. Total Alkalis-silica classification after LeBas *et al.*, 1986; alkaline, subalkaline/tholeiitic fields after Cox *et al.*, 1979.

The rhyolite samples are tholeiitic in character, while andesites and basalts plot along the border of the tholeiitic and calc-alkaline trend (Figure 25(A)). The rhyolite shows variability in the total iron (FeO_t) to magnesium (Mg) ratio compared to the andesites and basalts. The rhyolites are high-potassium (K), while andesites and basalts (with the exception of one sample) are within the medium-K range (Figure 25(B)).

(B)

Figure 25. (A) Rhyolites show variability in $\text{FeO}_t / \text{MgO}$ (FeO_t is total Fe) compared to andesites and basalts; samples plot almost exclusively in the tholeiitic field (boundaries from LeBas *et al.*, 1986). (B) Rhyolites are high-K, while andesites and basalts (with one exception) are medium-K (suite boundaries from Ewart, 1982).

The rhyolites from Graveyard Butte (with the exception of the ash-flow tuff) and Gordon Butte's Badger Creek have distinctly higher concentrations of high field strength elements (HFSE) such as zirconium (Zr) (Figure 26) and lower concentrations of fluid-mobile elements like strontium (Sr) (Figure 27), than samples from Gordon Butte's Upper Slopes and the ash-flow tuff.

Figure 26. Comparison of Zr versus SiO₂ by location (symbols as in Figure 24). Two sample locations are distinguished for Gordon Butte (Badger Creek and Upper Slopes) and six for Graveyard Butte (E Canyon, W Canyon, Central Canyon, Quarry, Above Quarry, and Tuff). For the rhyolites, the Badger Creek and most Graveyard Butte samples have higher Zr than the Upper Slopes and Tuff.

Figure 27. Comparison of Sr versus SiO₂ by location (symbols as in Figure 24, locations described in Figure 26). For the rhyolites, the Badger Creek and most Graveyard Butte samples have lower Sr concentrations than the Upper Slopes and Tuff.

As shown in Figure 28, the Graveyard Butte and Badger Creek rhyolites show more enriched concentrations in light rare earth elements (LREE or La–Sm in Figure 28) than heavy rare earth elements (HREE or Tb–Lu in Figure 28) and depletion in Europium (Eu). The Gordon Butte Upper Slopes samples in comparison, are less enriched in all of these elements.

Figure 28. Primitive mantle normalized incompatible trace element pattern for rhyolite samples of Graveyard Butte (filled squares) and Gordon Butte (unfilled squares with cross). The Graveyard and Badger Creek samples have higher concentrations of LREE and HREE than those from Gordon Butte's Upper Slopes. C1 Chondrite normalizing values from McDonough and Sun (1995).

The basalts are enriched in the fluid-mobile elements barium (Ba) and Sr, with enrichment in uranium (U) and lead (Pb) and depleted in thorium (Th) and Nb relative to primitive mantle compositions (Figure 29).

Figure 29. Primitive mantle normalized incompatible trace element pattern for basalt samples shows enrichment in Ba, U, K, Pb and Sr. Primitive mantle normalizing values from Sun and McDonough (1989).

With few exceptions, the andesites are enriched in Ba, U, K, and Pb, and depleted in Nb, phosphorus (P) and titanium (Ti) (see Figure 30); two andesite samples (samples S6-10U and CC16) are distinctly lower in abundance of all these elements.

Figure 30. Primitive mantle normalized incompatible element pattern for andesite samples shows enrichment in Ba, U, K, Pb and Sr, with depletions in Nb, Ce, P and Ti. The two samples with distinctly lower values are S6-10U and CC16. Primitive mantle normalizing values from Sun and McDonough (1989).

VII. Isotopic Analyses of Rhyolites and Andesite

A. $^{40}\text{Ar}/^{39}\text{Ar}$ Age Analyses

The $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology method was used to determine ages of two rhyolite samples from Graveyard Butte (X3, CC14), one rhyolite sample at Gordon Butte (sample GB4-3) and one andesite sample at Graveyard Butte (sample S12-6) (see Appendix A. Methods, for description of processing techniques and analytical procedures). Samples X3 and GB4-3 analyses included both feldspar crystals and groundmass, feldspar was used for sample CC14 and groundmass was used for the crystal-poor sample (CC14) from Graveyard Butte's eastern canyon (see Appendix E. $^{40}\text{Ar}/^{39}\text{Ar}$ Age Results for Graveyard and Gordon Buttes).

Argon release spectra are shown in Figure 31. The Graveyard Butte quarry sample X3 is slightly younger (3.67 ± 0.01 Ma) than its groundmass (3.71 ± 0.01 Ma). The same holds true for the rhyolite of Gordon Butte's Badger Creek (GB4-3) with a feldspar date of 3.64 ± 0.03 Ma and groundmass date of 3.70 ± 0.01 Ma. Sample CC14 is representative of the rhyolite in the eastern White River canyon and has a date of 3.65 ± 0.01 Ma. Sample S12-6 is from an andesite outcrop at the southwestern portion of the White River canyon, with a date of 3.86 ± 0.07 Ma. The ages described in this research are from the weighted plateau (Figure 31).

Figure 31. $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for (A, B) Graveyard Butte rhyolite, (C) Graveyard Butte andesite and (D) Gordon Butte rhyolite. Ages from the weighted plateau.

B. $^{87}\text{Sr}/^{86}\text{Sr}$ Analyses

Strontium analyses was conducted for two samples at Graveyard Butte—a rhyolite and andesite. The Graveyard Butte quarry rhyolite sample X3 (feldspar) has an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.703431, with an error of 0.000011. The Graveyard Butte andesite sample S12-6 from the southwestern portion of the White River canyon (groundmass) has an $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of 0.703268, with an error of 0.000011.

VIII. Discussion

In summary, the field, petrographic, geochemical and isotopic analyses of Graveyard Butte with a comparison to Gordon Butte point to the following conclusions: (1) the rhyolite at Graveyard Butte is an endogenous dome (cryptodome) deforming the overlying andesite lavas and pyroclastic deposits; (2) the geochemical and mineralogical analyses of the rhyolitic rocks at Graveyard Butte and Gordon Butte's Badger Creek indicate they represent hot, dry, ferroan magmas similar to A-type or anorogenic rhyolites associated with intra-arc rifting or within plate tectonic settings; (3) a possible geotectonic setting is the opening of the intra-arc Cascade graben; and (4) the rhyolite of Gordon Butte's Upper Slopes rhyolite and the Graveyard Butte ash-flow tuff shows affinities with the younger volcanic arc magmas. The evidence is discussed in greater detail below.

A. Field Evidence for an Endogenous Rhyolitic Dome and Flow at Graveyard Butte

Clearly visible above the quarry and slightly to the west, the andesite outcrop is deformed. The andesite is faulted, with the A' block thrust over the A" (Figure 32). The movement is consistent with the upward rise of rhyolitic magma.

Figure 32. The upward rise of the rhyolitic magma (bottom left of image) produced the thrust fault in the overlying andesitic unit. As shown, the andesite of the A' block is thrust over the A".

As shown in Figure 32 and Figure 33, the rhyolite behind the red carapace is brecciated (lower center and lower left of images). Rhyolitic outcrop also includes coherent—albeit segmented flow (bottom far left of Figure 33, and Figure 34).

Figure 33. The rhyolite to the west of the Wasco County quarry is brecciated (as viewed behind the red carapace) but also includes a segmented, coherent flow (to the far left of image).

(A)

(B)

Figure 34. Examples of unbrecciated, coherent rhyolitic flow in the western canyon: (A) is a flow and doming feature (geochemical sample CC3); and (B) is flow-banded rhyolite.

Evidence of the doming effect is visible in the volcaniclastic debris of the Wasco County quarry (map unit Tt). An angular unconformity exists between the bottom-most unit (see Figure 11, Unit 7) and the strata above. A reasonable scenario for the formation of the unconformity is shown in Figure 35. Initially, the volcaniclastic debris of Unit 7

would have been laid down relatively flat, given the uniform thickness of the unit. The rising magmatic intrusion would have bent the volcanoclastic package and tilted the entire unit upward by approximately 18° (Figure 35). Subsequent volcanic events would have shed debris that was deposited along the slope of the tilted bed. The unit directly on top of Unit 7 (see Figure 11, Unit 6) pinches out upslope and thickens downslope, consistent with deposition on an incline. Moreover, Unit 6 comprises ash and lapilli, indicating that mild explosive activity could have accompanied a rhyolitic lava flow (Figure 34) after the dome was emplaced.

Figure 35. Deposition and evolution sequence of units at the Wasco County quarry, with focus on changes to Unit 7. The initial position of the volcanoclastic unit is nearly horizontal. The rising rhyolitic magma bends and tilts the volcanoclastic package, with subsequent deposition of volcanoclastic debris down the inclined slope. Hydrothermal fluids and vapor produce the color gradations. The image to the right is provided for visual reference.

One of the most visually-striking features in the quarry is the color change in Unit 7, from maroon to brick-red, orange, yellow, tan and gray (see Figure 35). As the magma was rising, it came into contact with meteoric water along its margins. The hydrothermal fluids and vapor interacted with the volcanoclastic layers of Unit 7 near the dome margin, producing the color gradations. The darkest red or maroon color is the contact with the intrusion (Figure 36). The maroon carapace itself is slightly indurated volcanoclastic material of the same type and composition as Unit 7 (see Appendix D. Geochemical Data, Table 4, samples S6-9 and X7b).

Figure 36. Dark-red or maroon is a color tracer for the contact between the rhyolitic intrusion and volcanoclastic debris of the quarry's Unit 7. The light-gray, brecciated rhyolite is visible in the upper right of the image behind the red-maroon carapace, and as the gray-pink surface in the middle left of the image.

Finally, the timing of a later rhyolitic dome emplacement is consistent with the acquired age data. Sample X3 is flow-banded rhyolite from the quarry with a slightly younger (3.67 ± 0.01 Ma) age than the andesite outcrop (sample S12-6) from the southwestern portion of the White River canyon (3.86 ± 0.07 Ma) (see Figure 31). This is what would be expected from the emplacement of an endogenous dome and flow subsequent to the eruption of andesitic lavas.

B. Graveyard Butte and Badger Creek are A-Type Rhyolitic Magmas

In the mid-1970s, a classification was established for characterizing the source of granitoid suites. Chappell and White published geochemical characteristics for those derived from igneous, meta-igneous (I-type) or metasedimentary sources (S-type) (Eby, 1990). The work was refined by White in 1979 to include a classification for the melted subducted oceanic crust or overlying mantle (M-type) (Eby, 1990). Loiselle and Wones added the A-type, linking geochemical affinities with the tectonic environment in which they are typically found (Eby, 1990).

The A-type granitoids—and their eruptive equivalents rhyolites, can be distinguished based on chemical characteristics (Eby, 1990). Compared to other rhyolites, A-types typically have high FeO/MgO and $\text{K}_2\text{O}+\text{Na}_2\text{O}$ and low CaO and Al_2O_3 (Eby, 1990), high abundances of HFSE (*i.e.*, Zr, Nb, Y, cerium (Ce), Ti, but not Eu) (Dyhr *et al.*, 2013; Eby, 1990), low Ba, Sr (Dyhr *et al.*, 2013; Whalen, 1987), are water-poor and halogen-rich (Eby, 1990). In primitive mantle normalized plots they generally show significant enrichment in cesium (Cs) and rubidium (Rb), significant depletion in

Ba, Sr, Eu, Ti, and P, no or minimal Nb, and tantalum (Ta) depletion (Eby, 1990). In chondrite normalized REE plots, the A-type signatures are variable, from relatively flat patterns with large negative Eu anomalies to more LREE enriched patterns with relatively small Eu anomalies. In most cases, the isotopic data indicate mantle involvement (Eby, 1990).

Minerals in A-type granitoids are commonly quartz+fayalite $\pm$ Fe-rich pyroxenes $\pm$ Fe oxides (Bonin, 2007; Eby, 1990). Small volumes of fluorine-bearing hydrous minerals can be present, such as amphibole and mica (Bonin, 2007; McCurry *et al.*, 2008). As shown in Section V. Petrography of Graveyard Butte Units, the presence of Fe-clinopyroxene and fayalitic olivine along with the absence of hydrous phenocrysts in Graveyard Butte rhyolites are consistent with the A-type classification.

Most rhyolites at Graveyard Butte (with the exception of the ash-flow tuff) and Gordon Butte's Badger Creek are within the ranges proposed by Eby (1990) and Bonin (2007) for A-type granitoids generated in a Within Plate tectonic environment (Table 2). The ash-flow tuff and rhyolites of Gordon Butte's Upper Slopes share similarities in major oxides but differences appear in trace element concentrations. These rhyolites, with greater abundances of fluid-mobile trace elements and lesser amounts of HFSE, are more aligned with silicic magmas generated at or near a cooler, more fluid-rich subduction-generated volcanic arc.

Table 2. Example of geochemical characteristics for A-type granitoids in samples with SiO₂ of ~70 wt.% (Bonin, 2007; Eby, 1990) compared to rhyolites at Graveyard and Gordon Buttes.

	SiO ₂ (wt.%)	Na ₂ O + K ₂ O (wt.%)	CaO (wt.%)	FeO / MgO (wt.%)	Zr + Nb + Ce + Y (ppm)	Y + Nb (ppm)	Yb + Ta (ppm)
Expected range for A-type		7-11%	<1.8%	8 to 80%	>350 ppm	>50 ppm for Within Plate	>6 ppm for Ocean Ridge
Graveyard Butte							
CC3	72.6	9.0	1.0	20.8	678.2	83.9	7.3
CC7	73.0	9.0	1.0	29.5	672.9	84.3	7.3
S12_1L	72.9	9.1	0.9	28.8	652.3	76.4	6.6
S12_2	72.8	9.0	0.8	14.4	653.7	79.9	6.7
S6_12	73.1	9.1	0.8	26.3	669.4	83.5	7.1
S6_13	73.2	9.0	0.8	18.1	669.7	85.2	7.3
WR13	73.2	9.2	0.6	31.4	661.1	81.2	--
X3	73.0	9.1	1.0	35.8	674.9	82.8	7.0
Graveyard Butte Eastern Canyon							
CC13	69.0	8.3	2.1	7.4	578.6	73.0	6.0
CC14	69.6	8.4	2.1	6.2	593.3	76.1	6.5
Gordon Butte Badger Creek							
GB4_3	72.1	9.3	0.6	39.7	666.8	86.4	7.3
GB5a	71.3	9.3	1.1	35.9	699.4	97.0	8.1
GB5b	70.0	9.2	1.1	53.4	720.0	95.9	8.0
GB10	72.0	9.2	0.7	30.7	669.5	93.2	--
Graveyard Butte Ash-flow Tuff							
STR11_6	74.1	8.0	1.3	7.5	314.5	32.5	--
Gordon Butte Upper Slopes							
GB1_3	71.5	7.8	1.2	25.0	408.6	35.8	3.5
GB2	70.1	8.2	1.6	22.3	450.8	49.2	4.4
GB3	71.8	7.4	0.8	52.2	428.7	36.9	3.9
GB6	70.1	8.1	1.5	7.8	475.3	43.6	4.1
GB7	69.6	8.1	1.9	6.0	483.6	54.0	4.8

The samples retain the same affinity groupings (*e.g.*, Graveyard Butte–Badger Creek, Ash-flow Tuff–Upper Slopes) on multiple geochemical diagrams. As shown in Figure 37, the rhyolite of Graveyard Butte and Gordon Butte’s Badger Creek are higher in alkalis, lower in CaO, with greater abundance of HFSE and lower fluid-mobile trace

elements. Gordon Butte's Upper Slopes and the ash-flow tuff of Graveyard Butte have greater concentrations of the more fluid-mobile elements. The two samples from Graveyard Butte's Eastern Canyon can plot with one group or the other, or between the two groups.

Figure 37. Geochemical diagrams demonstrate that Graveyard Butte and Badger Creek rhyolites have greater abundances of HFSE such as (A) Ta and Tb, and (B) Zr, are (C) lower in fluid-mobile elements such as Sr, and (D) have a lower Ce concentration, than Graveyard Butte ash-flow Tuff and rhyolites of Gordon Butte's Upper Slopes.

In Figure 38, the samples with greater abundances of incompatible trace elements are from Graveyard Butte and Gordon Butte's Badger Creek. For comparison, the Graveyard Butte andesites are shown, along with dacite samples from Mill Creek Butte (6.2 ± 1.3 Ma (Sherrod and Scott, 1995)). Mill Creek Butte is part of the Western Cascades-era subduction volcanism, located ~25 km north of Gordon Butte. As demonstrated, the pattern for the volcanic arc is less enriched in trace elements with no Eu anomaly. The Gordon Butte Upper Slopes rhyolites, although showing an Eu anomaly, are similarly, less enriched.

Figure 38. Incompatible trace element diagram shows Graveyard Butte and Gordon Butte Badger Creek rhyolites with greater abundances compared to Gordon Butte Upper Slopes rhyolite and Mill Creek Butte, a Western Cascades-era subduction-generated dacite.

Lavas of Graveyard and Gordon Buttes can be further characterized using two indices: (1) an Fe-index that reflects magma differentiation history; and (2) a modified alkali-lime index reflecting abundance and composition of the feldspar (Frost and Frost,

2008) (Figure 39). Magmas derived from subduction systems are generally characterized as calc-alkaline, magnesian, oxidized, wet and cool, with liquidus temperatures less than 850°C (Christiansen *et al.*, 2008). Christiansen *et al.*, (2008) contrasts this with the rhyolites of intraplate settings, which are alkaline to calc-alkaline, ferroan, reduced, dry, and hot (830–1,050°C). Frost and Frost (2001) posit that the combination of ferroan with modified alkali lime index for alkali-calcic rhyolitic samples indicate an A-type or anorogenic granitoid, often associated with rifting tectonic environments or within plate settings. As shown in Figure 39, the Tuff and Upper Slopes plot within the ferroan field but are borderline calc-alkalic and alkali-calcic, whereas the rhyolite of Graveyard Butte and Badger Creek consistently plot in fields diagnostic of the A-types.

(A)

(B)

Figure 39. Lavas of Graveyard and Gordon Buttes characterized in (A) using the Fe-index, and (B) the modified alkali-lime index (fields after Frost and Frost, 2008). Rhyolites are ferroan and primarily alkalic-calcic, consistent with A-type granitoid geochemistry (Frost and Frost, 2001).

To broaden the scope of the geochemical comparison beyond Graveyard and Gordon Buttes, a dataset was assembled for archetypal lavas in and around the Pacific Northwest. Data was gathered for the silicic rocks of the Eastern Snake River Plain (southern Idaho), John Day and Clarno Formations as a proxy for within plate silicic volcanism (Bonnichsen *et al.*, 1994, McClaughry *et al.*, 2009); South Sister, Newberry as a proxy for young back-arc High Cascades lavas (Fierstein *et al.*, 2011; MacLeod *et al.*, 1995); Western Cascades as a proxy for ancestral subduction-related volcanism (du Bray and John, 2011); nearby dacites from Mount Hood as a proxy for modern-day subduction volcanics (Conrey, unpublished); and other Tygh Valley samples such as the rhyolites of Mutton Mountains (Johnson, 2011) (Figure 40).

(A)

(B)

Figure 40. Comparison of regional rock samples to Graveyard Butte rhyolites and andesites, and Gordon Butte rhyolites, (A) Nb versus SiO₂, and (B) Y versus Nb. Data from Bonnicksen *et al.*, 1994, McClaughry *et al.*, 2009, Fierstein *et al.*, 2011, MacLeod *et al.*, 1995, du Bray and John,

2011, Conrey, unpublished, Johnson, 2011 and Appendix D. Geochemical Data, Table 3, Table 4, Table 5, Table 6, and Table 7).

The results show geochemical affinities among lavas generated in specific settings. The Graveyard Butte ash-flow Tuff and Gordon Butte Upper Slopes flow show an affinity with South Sister, Newberry, High Cascades and Western Cascades magma generation settings. The rhyolite from Badger Creek is similar to Eastern Snake River Plain and Graveyard Butte rhyolites show some affinities to the Eastern Snake River Plain although some Graveyard Butte rhyolites are transitional, between the Eastern Snake River Plain and Western Cascades proxies (Figure 40).

The Eastern Snake River Plain is characterized by McCurry *et al.*, (2008) as a post-hotspot, basalt-dominated volcanic field intruded, interlayered or overlain by cryptodomes, domes and flows of intermediate lavas and high-silica A-type rhyolite. McCurry *et al.*, 's (2008) physical model for the generation of rhyolite in this setting is the fractional crystallization of a basaltic trachyandesite parent magma (~55% SiO₂) with only a trace (<1%) of crustal assimilation (McCurry *et al.*, 2008). The lack of crustal assimilation suggests a relatively rapid transit of magma to the surface.

Graveyard Butte rhyolite sample X3 has an ⁸⁷Sr / ⁸⁶Sr ratio of 0.703431 and the andesite sample has an ⁸⁷Sr / ⁸⁶Sr ratio of 0.703268. Similar ratios are found south of Graveyard Butte at Mt. Jefferson, where ratios of rhyodacites are 0.70325–0.70343 (Conrey, *et al.*, 2001). Conrey, *et al.* (2001) indicate that the rhyodacite with the ⁸⁷Sr / ⁸⁶Sr ratios around 0.7033 are likely generated through partial melting of the crust at depths of 25–35 km and temperatures of 850–1100°C. To obtain these temperatures,

Conrey, *et al.*, (2001) suggest that intra-arc rifting played a major role in developing a hot mafic underplate; rifting could have also provided a more rapid pathway for magma to the surface.

C. Tectonic Connection

A-type granitoids/rhyolites are associated with extensional tectonic environments such as rift zones (back arc, island arc) or within plate (hot spot) continental settings (Eby, 1990; Frost *et al.*, 2001). As shown in Figure 41, Gordon Butte lies just to the east of the Hood River fault, which was active by at least 2.9 Ma (Conrey *et al.*, 1996). South of the Hood River fault is the Warm Springs fault is a 30-km-wide zone of mostly west-dipping, north-striking normal faults that offset early Pleistocene, Pliocene, and Miocene volcanic rocks and sediments (Personius *et al.*, 2003). To the south of the Warm Springs fault, is the Green Ridge fault that offsets upper Miocene (5.27 ± 0.04 Ma) volcanic rocks of the Deschutes Formation (Personius *et al.*, 2003). The timing of the activity along these faults (5.27–2.9 Ma) encompasses the time period for volcanic activity at the Graveyard Butte quarry (3.67 ± 0.01 Ma), eastern canyon (3.65 ± 0.01 Ma), and Gordon Butte's Badger Creek (3.64 ± 0.03 Ma). A possible geotectonic framework for the generation of these ~3.6 Ma rhyolite lavas is the northward-propagating intra-arc rift of the Oregon Cascades.

Figure 41. Regional map of central and northern Oregon with folds (solid green lines) and faults (dotted lines) (U.S. Geological Survey and others, 2006). Basemap by ESRI. Map scale 1:750,000.

IX. Conclusions

The Tygh Valley area is largely undifferentiated, in part due to the voluminous (~2.77 Ma) basalt flows that created the relatively flat expanses of present-day Juniper Flat and Smock Prairie, hiding what lies beneath. Geologic maps have identified units at Graveyard and Gordon Buttes as Tertiary (7–2 my) andesitic to rhyolitic dome fields, near-vent breccia and pyroclastic rocks (du Bray and John, 2011; Sherrod and Smith, 2000). This research builds on that work with new insights into the geologic evolution of the area.

Two different types of rhyolites can be distinguished at Graveyard and Gordon Buttes. One type is represented by the Graveyard Butte ash-flow tuff and rhyolites of Gordon Butte's upper slopes that are lower in Nb (13–19 ppm) and Ta (1.34–1.49 ppm) and richer in Sr (97–211 ppm). Generation of these magmas is consistent with a volcanic arc setting. The second is the rhyolite lava flows at Graveyard Butte and at Gordon Butte's Badger Creek (Nb from 30–40 ppm; Ta from 2.1–2.6 ppm; Sr from 72–94 ppm). Incompatible trace-element-enriched compositions and mineralogical indicators show that these magmas are A-type rhyolites that are likely generated in an extensional setting. A possible geotectonic framework for generation of these rhyolite lavas is the northward propagating intra-arc rift of the Oregon Cascades.

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Appendix A. Methods

Thirty-one days were spent in the field over the course of two summers (2012-2013). In addition to mapping Graveyard Butte, exploratory and sample collection trips were made to Gordon Butte, Badger Creek, Hootnanny Point, Keeps Mill, McCubbins Gulch, and in the Bureau of Land Management's White River Wild and Scenic areas.

At Graveyard Butte, field work consisted of mapping the extents of geologic units and collecting rock and sediment samples for later analyses. Samples were labeled with a unique identifier and notations were made regarding locations and other site information in a field notebook. All geographic data were collected using a Garmin *etrex* Vista handheld GPS unit and plotted on 1:12,000 scale topographic map (Wamic quadrangle) using a mapping grid. The geologic map was prepared using ArcGIS software.

Rock samples from Graveyard and Gordon Buttes, McCubbins Gulch, Hootnanny Point and Mill Creek that were selected for major and trace element analysis were individually machine-chipped into a size fraction of approximately 0.5 cm, using facilities at Portland State University. At the GeoAnalytical Laboratory of Washington State University (Pullman, Washington), approximately 120 g from each of the crushed samples were ground into powder using a tungsten carbide ring mill. A flux agent (dilithium tetraborate) was added to 3.5 g of the rock powder on a 1:1 ratio. The rock-flux was well-mixed, transferred to a carbon crucible, placed in a 1000°C oven and fused into a glass bead. For X-ray fluorescence spectrometer (XRF) analysis, the glass bead was re-ground into a powder and re-fused. For inductively-coupled plasma mass spectrometry (ICP-MS) analysis, 2 g of the flux was added to 2 g of rock power, mixed and fused into

a glass bead. The glass bead was re-ground into a powder using a steel bowl. The XRF and ICP-MS analyses were conducted by personnel at the WSU GeoAnalytical Laboratory. Geochemical analyses were prepared using GCDKit (Janoušek *et al.*, 2006), written for R statistical and computing software.

Billets were cut and sent to a local petrographic company for completed thin sections. Petrographic analysis was conducted at Portland State University. The thin sections were carbon-coated using the sputter coater and scanning electron microscope micrographs were collected using an Aspex Express located in the petrology laboratory at the U.S. Geological Survey-Cascades Volcano Observatory (Vancouver, Washington). Images were processed using Perception software.

Age dating experiments were conducted at facilities located in Oregon State University's College of Earth, Ocean and Atmospheric Sciences (Corvallis, Oregon). Samples selected for age analyses were individually machine-chipped into fragments of less than 1 mm. The samples were sieved into size fractions of 106–250 μm , and 250–500 μm in an effort to obtain the largest crystals; crystalline groundmass was also sampled when too few crystals were found. Using a Frantz Isodynamic Separator, the non-magnetic portion of the sieved sample was collected; a binocular microscope was used to examine the grains to confirm the presence of feldspar. The sample was leached with acid (HF) to remove quartz and other rock fragments and placed into packets for irradiation; the groundmass sample was not leached. The samples, along with Fish Creek Tuff biotite (28.030 ± 0.003 Ma used for sample S12-6; 28.030 ± 0.571 Ma used for

samples CC14, GB4-3 and X3) as a neutron-flux monitor, were packed into vials and irradiated at the OSU research reactor. Analyses were conducted using the MAP215-50 single-collector mass spectrometer, and later, by the automated ARGUS VI multi-collector. The results were analyzed using the ArArCalc software developed by OSU's Dr. Anthony Koppers (Koppers, 1998).

Strontium isotope analysis was conducted by Portland State University graduate student Emily Jenkins Hess using facilities at New Mexico State University.

Appendix B. Illustrative Stratigraphic Sections

Representative stratigraphic section of sedimentary units in the Wasco County quarry by depth (m) from the surface (see Figure 11).

Depth (m)	Unit	Clay	Silt	Sand	Gravel	Description	
				vf f m c vc	g p c b		
0.50	Unit 1						Unit 1 (0.00m to 1.50m) Reworked lapilli in uppermost unit below vegetation (thickness varies). Bedding: overall reddish/brown color, disorganized, poorly sorted, poorly indurated, sharp contact with lower unit. Matrix: 88 to ~177 µm, angular; clasts are yellow low sphericity pumices from 3-5 mm; some red high sphericity scoria 0.5-1 cm.
1.00							
1.50							
2.00	Unit 2						Unit 2 (1.50m to 3.90m) Wavy-bedded lapilli, clast-supported, poorly indurated. Bedding: muted brown, red, gray lapilli with thin laminae of creamy yellow ash. Matrix: fine, ~90 µm, angular, no individual mineral grains; clasts are red scoria granules, some with hot red/orange interiors, angular to subround, frequently to 2 cm. Also very angular clasts of nonvesiculated aphyric red lava with some [few] to 10 cm.
2.50							
3.00							
3.50							
4.00							
4.50	Unit 3						Unit 3 (3.90m to 7.50m) Crystal-lithic coarse volcanic sandstone. Bedding: massive, grading uncertain (access difficult), poorly indurated. Matrix: two sizes, 88-177 µm and coarser 1-2 mm. Some red scoria in upper 0.6 m, small oblate yellow pumices throughout.
5.00							
5.50							
6.00							
6.50							
7.00							
7.50							
8.00	Unit 4						Unit 4 (7.50m to 8.40m) Fine volcanic sandstone. Bedding: sharp, planar, parallel or irregular sequences, fining up. Crystal-lithic sandstone layered (sharp contact) with crystal-poor sandstone, poorly indurated. Matrix: to ~125 µm, angular; clasts are spherical yellow pumice or red scoria to 1 mm. Some beds have flattened pumice to 1 cm, red scoria are spherical ~4 mm.
8.50	Unit 5						Unit 5 (8.40m to 8.70m) Very fine volcanic sandstone. Bedding: gradational contacts with layer above, poorly indurated. Matrix: to ~88 µm; clasts are spherical yellow pumices to 1 mm, red scoria of similar size.
9.00	Unit 6						Unit 6 (8.70m to 8.90m) Lapilli tuff. Bedding: creamy yellow overall, wavy, sharp contact, fining up. Matrix: ~125 µm, angular (low sphericity); clasts are red scoria from 3 mm to 6 cm; yellow (greenish cash) crystal-rich pumice from 3 mm to 1 cm.
9.50	Unit 7						Unit 7 (8.90m to 9.00m) Tuff. Bedding: white overall with (sometimes) slight greenish cast, poorly indurated and crumbles under firm pressure, sharp, wavy contacts. Matrix: ~62 µm, angular.
10.00	Unit 8						Unit 8 (9.00m to 9.30m) Tuffaceous. Bedding: multiple laminae, gradational contacts, coarse crystals > fine ash > coarse crystals. Matrix: ~62 µm and thin, ash lenses; clasts include flattened black fiammae to ~1 cm.
10.50	Unit 9						Unit 9 (9.30m to 11.10m) Tuff, argillaceous, volcanic. Unit at river level and shelf observed under water (unit is thicker than indicated). Bedding: creamy white, sometimes with a greenish cast, poorly indurated, comes off in soft chunks or sheets. Matrix: ~88 µm, angular to subangular; clasts are few red angular scoria ~2 cm or less; some yellow pumice with greenish cast.
11.00							

Appendix C. Energy Dispersive Spectra

Rhyolite (sample S6-13)

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Sample S6-13

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Basalt (sample WR11)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.4 mm spot size = 38.9%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.1%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.1%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.1%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.1%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.1%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.1%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.1%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.9%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.9%

Andesites (sample V1)

USGS CVO ASPEX EXpress

12/26/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.9%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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02:31:41 PM

accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 36.5%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 36.5%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 36.5%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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02:39:44 PM

accelerating voltage = 20.0 kV working distance = 17.7 mm spot size = 36.5%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 36.5%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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02:43:38 PM

accelerating voltage = 20.0 kV working distance = 17.7 mm spot size = 36.5%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.1%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.7 mm spot size = 38.1%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.1%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.1%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.5 mm spot size = 38.1%

Andesite (sample S12-6A)

USGS CVO ASPEX EXpress

12/27/2013

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accelerating voltage = 20.0 kV working distance = 17.6 mm spot size = 38.1%

Appendix D. Geochemical Data

Table 3. Whole-rock geochemical analyses of rocks from Graveyard Butte's western and central canyon.

Area	Graveyard Butte Western Canyon						Graveyard Butte Central Canyon				
Sample	CC3	CC6	CC7	CC16	WR11	S12-1L	S12-2	S12-3	S12-5	S12-6	WR13
Latitude	45.1591	45.1555	45.1551	45.1646	45.1513	45.1576	45.1579	45.1580	45.1561	45.1561	45.1560
Longitude	-121.3157	-121.3195	-121.3194	-121.3051	-121.3231	-121.3118	-121.3119	-121.3118	-121.3135	-121.3135	-121.3160
Age (Ma)										3.86±0.07	
Normalized Major Elements (Weight %)											
SiO ₂	72.61	49.51	72.97	56.98	50.17	72.93	72.83	62.61	61.29	62.17	73.17
TiO ₂	0.267	1.507	0.238	1.232	1.395	0.240	0.278	1.271	1.290	1.292	0.242
Al ₂ O ₃	13.72	16.96	13.63	18.59	17.78	13.63	13.68	15.91	15.96	16.08	13.77
FeO*	3.12	11.21	2.95	6.80	10.01	2.88	3.02	6.66	6.95	6.88	2.83
MnO	0.089	0.175	0.084	0.131	0.166	0.077	0.092	0.155	0.134	0.123	0.083
MgO	0.15	7.23	0.10	3.17	6.74	0.10	0.21	1.45	2.15	1.52	0.09
CaO	0.99	9.81	0.98	7.09	9.53	0.92	0.84	4.65	5.07	4.81	0.63
Na ₂ O	5.17	3.06	5.03	4.13	3.29	5.37	5.28	4.82	4.77	4.68	5.38
K ₂ O	3.84	0.37	3.99	1.55	0.64	3.77	3.72	2.09	2.02	2.08	3.78
P ₂ O ₅	0.037	0.176	0.029	0.329	0.266	0.092	0.053	0.376	0.367	0.359	0.035
Pre-normalized	99.03	99.77	97.76	99.34	100.35	98.91	99.14	97.62	99.36	98.15	99.00
Normalized	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
XRF (ppm)											
Ni	3	128	0	34	75	0	1	5	4	6	3
Cr	3	228	2	30	127	3	2	1	1	1	2
Sc	7	27	6	16	28	6	7	15	17	16	6
V	8	202	5	152	166	3	13	99	103	127	7
Ba	705	106	701	463	191	706	712	595	465	486	724
Rb	90	5	88	21	7	86	82	41	41	38	85

Table 3. Whole-rock geochemical analyses of rocks from Graveyard Butte's western and central canyon.

Area	Graveyard Butte Western Canyon						Graveyard Butte Central Canyon				
Sample	CC3	CC6	CC7	CC16	WR11	S12-1L	S12-2	S12-3	S12-5	S12-6	WR13
Sr	78	306	72	866	524	78	93	484	481	477	75
Zr	495	92	491	181	141	490	486	282	283	285	491
Y	54	24	56	22	27	47	51	50	43	40	49
Nb	32.8	7.3	32.2	11.3	9.7	32.8	32.2	20.3	20.1	19.9	32.5
Ga	23	19	22	21	19	23	23	22	23	21	23
Cu	8	58	5	49	37	6	9	22	26	65	7
Zn	110	98	104	77	87	99	104	100	103	145	104
Pb	20	1	13	5	4	12	9	6	8	7	6
La	47	7	43	27	11	32	41	43	36	33	46
Ce	88	18	92	60	31	79	83	69	64	67	89
Th	11	1	11	4	1	10	11	7	6	6	11
Nd	44	12	45	30	19	35	44	43	43	39	43
U	4	0	4	1	1	3	3	1	1	1	3
ICP-MS (ppm)											
La	44.68	7.22	44.59	26.63	13.68	34.34	43.92	40.64	35.83	34.22	
Ce	92.38	16.36	92.77	57.31	31.60	80.05	86.53	66.66	64.58	63.85	
Pr	11.56	2.47	11.38	7.59	4.33	9.02	11.10	9.77	10.06	9.52	
Nd	45.21	11.80	44.58	30.82	18.97	35.36	43.58	41.02	42.21	39.40	
Sm	10.35	3.50	10.28	6.04	4.48	8.34	9.91	9.00	9.80	8.96	
Eu	1.79	1.33	1.72	1.80	1.60	1.75	1.83	2.42	2.55	2.48	
Gd	9.78	4.19	9.82	5.23	4.78	7.98	9.33	9.45	9.27	8.80	
Tb	1.68	0.71	1.67	0.78	0.80	1.38	1.55	1.45	1.45	1.32	
Dy	10.21	4.56	10.21	4.34	5.04	8.67	9.50	8.55	8.53	7.78	
Ho	2.07	0.91	2.05	0.82	1.04	1.75	1.89	1.71	1.64	1.51	
Er	5.54	2.47	5.66	2.15	2.75	4.80	5.17	4.52	4.27	3.98	
Tm	0.80	0.34	0.83	0.29	0.40	0.71	0.74	0.63	0.60	0.56	

Table 3. Whole-rock geochemical analyses of rocks from Graveyard Butte's western and central canyon.

Area	Graveyard Butte Western Canyon					Graveyard Butte Central Canyon					
Sample	CC3	CC6	CC7	CC16	WR11	S12-1L	S12-2	S12-3	S12-5	S12-6	WR13
Yb	5.15	2.08	5.18	1.81	2.44	4.50	4.64	3.73	3.70	3.33	
Lu	0.78	0.33	0.81	0.28	0.38	0.69	0.72	0.58	0.55	0.51	
Ba	711	100	708	453	188	721	718	585	462	480	
Th	11.17	0.64	10.90	3.95	1.42	10.94	10.69	5.86	5.93	5.97	
Nb	31.82	5.93	31.03	9.74	8.06	31.49	30.85	18.49	18.36	18.70	
Y	52.06	23.33	53.28	21.46	25.67	44.89	49.06	49.12	42.59	39.19	
Hf	12.77	2.36	12.46	4.48	3.32	12.50	12.21	6.82	6.95	7.00	
Ta	2.17	0.38	2.13	0.65	0.51	2.14	2.08	1.22	1.22	1.25	
U	3.13	0.26	3.27	1.15	0.43	3.25	2.67	1.80	1.73	1.75	
Pb	18.35	0.86	11.34	4.98	2.60	11.62	9.08	5.41	9.15	6.24	
Rb	87.3	4.3	85.6	19.5	6.5	85.5	81.8	40.1	39.5	38.2	
Cs	2.43	0.12	2.98	0.24	0.11	2.66	1.21	0.90	1.17	0.71	
Sr	81	308	72	852	528	79	94	481	479	476	
Sc	6.3	27.6	5.7	15.3	28.1	5.9	6.4	15.9	16.7	16.6	
Zr	502	89	496	174	135	496	487	276	278	281	

Table 4. Whole-rock geochemical analyses of rocks from Graveyard Butte quarry.

Area	Quarry									
Sample	S6-9	S6-10U	S6-11	S6-12	S6-13	S6-15	V1	X3	X7b	X-9
Latitude	45.1624	45.1623	45.1627	45.1614	45.1625	45.1623	45.1623	45.1624	45.1624	45.1624
Longitude	-121.313	-121.3154	-121.3142	-121.3143	-121.3119	-121.3137	-121.3137	-121.3134	-121.3134	-121.3133
Age (Ma)	3.67±0.01									
Normalized Major Elements (Weight %)										
SiO ₂	60.18	59.55	62.34	73.10	73.19	61.08	61.71	72.98	62.47	54.11
TiO ₂	1.386	0.857	1.203	0.241	0.243	1.303	1.255	0.238	1.221	1.365
Al ₂ O ₃	16.07	18.57	15.78	13.64	13.59	15.88	15.79	13.60	15.86	18.33
FeO*	7.58	5.78	6.60	2.89	2.90	7.19	6.80	2.86	6.68	8.88
MnO	0.137	0.096	0.134	0.082	0.080	0.134	0.134	0.084	0.125	0.144
MgO	2.40	3.39	1.86	0.11	0.16	2.29	2.12	0.08	1.73	4.87
CaO	5.64	6.51	4.66	0.79	0.79	5.28	4.97	1.02	4.64	8.01
Na ₂ O	4.47	4.05	4.82	5.30	5.27	4.45	4.79	5.36	4.65	3.13
K ₂ O	1.78	1.06	2.21	3.81	3.75	2.04	2.08	3.76	2.27	0.86
P ₂ O ₅	0.347	0.148	0.386	0.042	0.031	0.347	0.360	0.032	0.350	0.296
Pre-normalized	99.50	99.63	99.21	98.86	98.82	98.29	99.97	99.31	99.32	97.61
Normalized	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
XRF (ppm)										
Ni	10	33	3	2	9	6	5	2	6	71
Cr	7	26	2	2	2	3	0	3	1	103
Sc	19	16	16	6	7	16	17	6	16	22
V	117	129	75	10	38	123	108	4	133	152
Ba	439	243	514	727	720	450	477	717	523	378
Rb	37	15	43	86	84	42	44	86	54	13

Table 4. Whole-rock geochemical analyses of rocks from Graveyard Butte quarry.

Area	Quarry									
Sample	S6-9	S6-10U	S6-11	S6-12	S6-13	S6-15	V1	X3	X7b	X-9
Sr	487	609	451	77	77	474	476	75	456	702
Zr	261	120	302	491	489	276	293	490	301	176
Y	35	14	40	54	57	35	37	52	54	24
Nb	17.9	6.5	20.9	32.1	32.0	19.2	20.6	32.3	20.2	11.6
Ga	22	21	21	24	24	21	23	24	21	20
Cu	37	55	21	8	27	21	23	6	49	48
Zn	103	63	94	103	95	99	101	95	103	90
Pb	9	4	7	11	11	7	7	9	6	5
La	28	11	32	50	42	29	33	48	36	19
Ce	63	28	68	90	90	63	65	90	63	50
Th	6	3	8	11	10	6	7	12	6	3
Nd	32	16	37	49	41	33	34	44	42	26
U	1	1	2	3	3	1	2	3	1	0
ICP-MS (ppm)										
La	28.34	12.29	32.78	49.66	43.63	29.47	31.30	45.94		
Ce	59.80	25.36	68.49	92.60	93.31	62.63	66.47	92.69		
Pr	7.71	3.52	9.00	12.57	10.97	8.06	8.52	11.63		
Nd	31.97	14.52	37.07	48.96	43.07	33.03	34.91	45.44		
Sm	7.21	3.34	8.58	11.12	9.88	7.50	7.94	10.12		
Eu	2.05	1.14	2.27	1.88	1.83	2.07	2.16	1.85		
Gd	7.18	3.18	8.20	10.16	9.57	7.24	7.54	9.59		
Tb	1.13	0.49	1.31	1.71	1.67	1.16	1.23	1.65		
Dy	6.81	2.75	7.77	10.26	10.31	6.81	7.12	9.89		
Ho	1.33	0.53	1.53	2.06	2.08	1.33	1.41	1.96		
Er	3.53	1.41	4.07	5.50	5.64	3.54	3.75	5.31		
Tm	0.49	0.19	0.58	0.79	0.83	0.50	0.53	0.78		

Table 4. Whole-rock geochemical analyses of rocks from Graveyard Butte quarry.

Area	Quarry									
Sample	S6-9	S6-10U	S6-11	S6-12	S6-13	S6-15	V1	X3	X7b	X-9
Yb	3.00	1.19	3.55	4.97	5.17	3.12	3.21	4.89		
Lu	0.47	0.18	0.55	0.74	0.79	0.48	0.49	0.77		
Ba	434	237	512	738	733	447	477	729		
Th	5.42	2.21	6.38	11.01	11.00	5.71	6.08	11.03		
Nb	16.62	5.42	19.74	31.21	31.37	17.95	19.11	31.72		
Y	34.19	13.31	38.96	52.24	53.85	34.55	35.97	51.08		
Hf	6.39	3.05	7.41	12.39	12.42	6.75	7.20	12.38		
Ta	1.11	0.38	1.31	2.11	2.13	1.21	1.30	2.13		
U	1.55	0.71	1.81	3.40	2.91	1.68	1.81	2.85		
Pb	8.22	4.23	6.88	10.33	9.39	6.04	6.43	8.08		
Rb	35.4	13.7	41.6	85.9	84.1	40.5	43.3	86.7		
Cs	1.17	0.24	0.78	2.55	1.20	1.33	1.40	1.76		
Sr	486	606	449	79	80	473	479	79		
Sc	19.2	14.7	15.8	6.1	6.2	16.9	16.0	5.9		
Zr	255	116	298	493	491	268	287	499		

Table 5. Whole-rock geochemical analyses of rocks from Graveyard Butte quarry and Eastern Canyon.

Area	Quarry								Eastern Canyon		
Sample	STR11-2a	STR11-2c	STR11-3	STR11-4b	STR11-5	STR11-6	STR11-7	STR11-8	CC13	CC14	CC15
Latitude	45.1624	45.1624	45.1624	45.1624	45.1624	45.1624	45.1624	45.1624	45.1684	45.1655	45.1692
Longitude	-121.3134	-121.3134	-121.3134	-121.3134	-121.3134	-121.3134	-121.3134	-121.3134	-121.2800	-121.2843	-121.2912
Age (Ma)										3.65±0.01	
Normalized Major Elements (Weight %):											
SiO ₂	60.92	61.36	49.94	61.06	73.27	74.08	49.5	61.46	69.01	69.57	58.72
TiO ₂	1.31	1.283	1.504	1.311	0.245	0.256	1.457	1.32	0.636	0.561	1.495
Al ₂ O ₃	15.82	15.84	17.44	15.87	13.59	13.9	18.43	16.39	14.64	14.34	16.24
FeO*	7.18	7.04	10.69	7.01	2.86	2.09	10.71	7.17	4.42	4.11	8.25
MnO	0.135	0.133	0.175	0.136	0.082	0.054	0.175	0.142	0.077	0.095	0.144
MgO	2.35	2.14	6.46	2.32	0.14	0.28	5.8	1.77	0.60	0.66	2.64
CaO	5.39	5.13	9.7	5.3	0.74	1.33	10.11	4.63	2.13	2.12	5.99
Na ₂ O	4.55	4.67	3.26	4.66	5.27	4.15	3.11	4.7	5.15	5.16	4.44
K ₂ O	2	2.06	0.58	1.98	3.78	3.82	0.49	2.07	3.18	3.24	1.64
P ₂ O ₅	0.346	0.351	0.236	0.356	0.034	0.043	0.222	0.354	0.169	0.143	0.425
Pre-normalized	97.55	98.22	99.28	98.5	98.26	90.72	98.3	98.36	98.98	99.20	100.39
Normalized	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
XRF (ppm)											
Ni	5	4	76	5	2	8	73	5	3	3	8
Cr	2	1	124	0	3	3	126	2	3	2	3
Sc	17	17	30	17	6	5	30	17	11	10	20
V	126	113	194	123	12	5	194	68	41	34	118
Ba	450	472	189	455	708	561	480	493	665	650	440
Rb	41	42	6	42	84	57	4	41	72	70	34
Sr	474	472	491	482	76	131	525	479	233	204	558
Zr	269	280	129	272	487	235	122	284	424	432	236

Table 5. Whole-rock geochemical analyses of rocks from Graveyard Butte quarry and Eastern Canyon.

Area	Quarry								Eastern Canyon		
Sample	STR11-2a	STR11-2c	STR11-3	STR11-4b	STR11-5	STR11-6	STR11-7	STR11-8	CC13	CC14	CC15
Y	35	37	27	34	56	19	27	38	48	50	32
Nb	18.8	19.5	8.2	19.4	32.1	13.5	8.2	19.5	28.4	28.6	16.6
Ga	21	21	20	21	22	16	20	22	22	22	22
Cu	26	23	46	27	7	9	49	29	13	11	43
Zn	98	95	86	100	101	42	86	96	101	87	98
Pb	6	5	4	7	10	10	2	4	9	12	5
La	31	34	11	32	45	23	13	32	43	38	26
Ce	62	66	27	62	87	47	29	69	79	84	53
Th	5	4	1	4	12	8	1	5	10	10	4
Nd	33	37	17	34	43	19	19	35	44	42	31
U	1	1	0	2	3	2	1	1	2	3	1
ICP-MS (ppm)											
La									42.52	41.05	26.12
Ce									79.78	84.69	55.26
Pr									11.28	10.57	7.31
Nd									45.00	42.12	30.94
Sm									10.14	9.60	7.13
Eu									2.11	1.95	2.12
Gd									9.38	9.28	6.84
Tb									1.57	1.56	1.08
Dy									9.20	9.35	6.25
Ho									1.80	1.88	1.23
Er									4.78	5.06	3.21
Tm									0.68	0.73	0.44
Yb									4.21	4.59	2.71
Lu									0.64	0.71	0.43

Table 5. Whole-rock geochemical analyses of rocks from Graveyard Butte quarry and Eastern Canyon.

Area	Quarry								Eastern Canyon		
Sample	STR11-2a	STR11-2c	STR11-3	STR11-4b	STR11-5	STR11-6	STR11-7	STR11-8	CC13	CC14	CC15
Ba									664	643	427
Th									9.13	9.41	4.77
Nb									27.00	27.68	15.48
Y									45.99	48.37	31.07
Hf									10.74	10.84	5.67
Ta									1.81	1.87	1.03
U									2.77	2.84	1.12
Pb									8.52	10.98	4.43
Rb									69.1	68.4	30.9
Cs									1.19	0.66	0.54
Sr									236	207	551
Sc									9.9	9.0	19.8
Zr									426	433	228

Table 6. Whole rock geochemical analysis of rocks from Gordon Butte.

Area	Gordon Butte								
Sample	GB1-3	GB2	GB3	GB4-3	GB5a	GB5b	GB6	GB7	GB10
Latitude	45.2835	45.2983	45.2882	45.2697	45.2694	45.2694	45.2727	45.2701	45.2695
Longitude	-121.4063	-121.4269	-121.4098	-121.4409	-121.4416	-121.4416	-121.4371	-121.4298	-121.4410
Age (Ma)	3.64±0.03								
Normalized Major Elements (Weight %)									
SiO ₂	71.49	70.05	71.79	72.14	71.26	69.97	70.12	69.60	72.04
TiO ₂	0.445	0.447	0.436	0.268	0.297	0.294	0.513	0.507	0.268
Al ₂ O ₃	15.64	15.78	16.30	13.89	13.97	15.29	16.02	15.94	13.86
FeO*	3.25	3.57	3.13	3.57	3.81	3.97	3.22	3.29	3.67
MnO	0.050	0.091	0.052	0.091	0.097	0.106	0.039	0.047	0.103
MgO	0.13	0.16	0.06	0.09	0.11	0.07	0.42	0.55	0.12
CaO	1.20	1.61	0.79	0.64	1.13	1.11	1.55	1.88	0.68
Na ₂ O	4.28	5.11	3.77	5.66	5.09	4.79	4.03	4.13	5.63
K ₂ O	3.48	3.11	3.64	3.61	4.20	4.38	4.04	3.99	3.60
P ₂ O ₅	0.040	0.077	0.019	0.032	0.033	0.028	0.057	0.082	0.026
Pre-normalized	98.29	98.32	96.51	99.21	97.07	95.18	98.81	98.32	98.96
Normalized	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
XRF (ppm)									
Ni	3	2	2	2	4	2	4	6	2
Cr	3	4	3	2	3	4	5	6	2
Sc	5	8	6	6	6	6	6	7	5
V	20	18	16	3	4	2	32	28	5
Ba	650	598	549	703	690	732	635	596	702
Rb	78	71	82	78	79	72	102	98	77
Sr	140	192	98	81	75	86	189	206	82

Table 6. Whole rock geochemical analysis of rocks from Gordon Butte.

Area	Gordon Butte								
Sample	GB1-3	GB2	GB3	GB4-3	GB5a	GB5b	GB6	GB7	GB10
Zr	329	344	330	491	503	526	366	359	497
Y	21	33	22	50	60	58	29	39	54
Nb	18.0	20.8	18.4	39.6	39.4	41.3	17.4	16.9	39.7
Ga	21	22	21	25	24	26	20	20	25
Cu	12	10	10	2	4	3	7	12	3
Zn	51	82	45	115	124	128	41	45	115
Pb	9	11	8	7	11	11	10	10	6
La	31	34	29	45	48	43	38	42	33
Ce	54	70	67	89	95	93	70	64	80
Th	11	10	12	10	10	11	14	14	9
Nd	23	31	27	45	46	43	35	38	34
U	3	2	5	3	3	2	6	5	3
ICP-MS (ppm)									
La	29.52	34.00	30.51	44.26	47.54	45.45	40.25	43.14	
Ce	53.46	71.16	68.92	86.24	92.53	94.48	67.44	68.26	
Pr	6.27	8.20	7.10	11.12	11.94	11.51	9.02	10.53	
Nd	21.89	31.14	24.83	44.17	47.30	45.19	32.99	39.94	
Sm	4.28	6.70	5.06	9.94	10.70	10.38	6.41	8.11	
Eu	0.91	1.44	0.87	1.99	1.99	2.08	1.16	1.57	
Gd	3.60	6.05	3.90	9.49	10.48	10.13	5.27	7.35	
Tb	0.60	1.01	0.67	1.57	1.80	1.77	0.87	1.17	
Dy	3.66	6.01	4.07	9.69	11.24	10.85	5.22	6.94	
Ho	0.72	1.17	0.81	1.92	2.25	2.17	1.02	1.39	
Er	2.01	3.21	2.28	5.18	6.17	6.01	2.85	3.79	
Tm	0.30	0.47	0.35	0.75	0.90	0.88	0.42	0.55	
Yb	2.05	3.00	2.36	4.81	5.55	5.45	2.69	3.45	

Table 6. Whole rock geochemical analysis of rocks from Gordon Butte.

Area	Gordon Butte								
Sample	GB1-3	GB2	GB3	GB4-3	GB5a	GB5b	GB6	GB7	GB10
Lu	0.32	0.46	0.35	0.74	0.85	0.83	0.40	0.53	
Ba	646	595	551	704	694	739	637	602	
Th	11.36	9.27	11.68	9.91	10.02	10.06	13.41	12.91	
Nb	16.97	19.02	17.37	38.39	38.94	40.01	16.98	16.43	
Y	18.84	30.13	19.56	48.03	58.10	55.91	26.66	37.58	
Hf	8.28	8.39	8.38	12.30	12.63	12.98	9.51	9.27	
Ta	1.44	1.44	1.49	2.50	2.52	2.60	1.39	1.34	
U	3.30	2.74	4.07	3.00	3.02	2.90	4.14	4.18	
Pb	8.34	8.45	7.42	5.59	10.29	10.28	9.48	10.03	
Rb	76.4	69.5	80.4	77.2	77.7	69.3	100.0	96.6	
Cs	0.89	1.12	1.50	1.36	3.39	3.15	1.64	2.16	
Sr	138	190	98	82	74	87	190	211	
Sc	5.0	7.6	4.9	5.7	5.5	6.1	5.7	6.3	
Zr	319	330	323	494	510	530	364	361	

Table 7. Whole-rock geochemical analysis of Tygh Valley samples.

Area	McCubbins	Hootnanny	Mill Creek Buttes	
Sample	Gulch WWR4	Point H2	MC1	MC4
Latitude	45.1465	45.3216	45.4447	45.4417
Longitude	-121.4286	-121.3799	-121.5220	-121.5167
Normalized Major Elements (Weight %):				
SiO ₂	63.05	69.40	64.83	63.64
TiO ₂	0.822	0.492	0.652	0.698
Al ₂ O ₃	17.10	15.61	17.40	17.14
FeO*	5.32	3.64	4.03	4.57
MnO	0.103	0.081	0.077	0.083
MgO	2.32	0.47	2.08	2.84
CaO	5.04	2.09	5.57	5.96
Na ₂ O	4.18	5.17	4.12	3.99
K ₂ O	1.88	2.94	1.09	0.94
P ₂ O ₅	0.176	0.099	0.156	0.153
Pre-normalized	99.24	98.87	99.08	98.96
Normalized	100.00	100.00	100.00	100.00
XRF (ppm)				
Ni	25	4	22	38
Cr	23	2	27	51
Sc	12	8	9	13
V	105	21	69	90
Ba	408	556	242	226
Rb	28	67	23	20
Sr	564	243	770	778
Zr	205	325	142	133
Y	23	31	15	13
Nb	10.3	18.7	6.9	6.5
Ga	19	22	21	19
Cu	37	12	28	32
Zn	67	67	54	62
Pb	6	9	4	4
La	25	31	14	15
Ce	40	67	26	30
Th	4	8	4	3
Nd	23	29	16	15
U	1	3	0	1

Table 7. Whole-rock geochemical analysis of Tygh Valley samples.

Area	McCubbins	Hootnanny	Mill Creek Buttes	
Sample	Gulch WWR4	Point H2	MC1	MC4
ICP-MS (ppm)				
La	22.02	32.35	14.29	13.83
Ce	42.49	67.68	28.66	29.46
Pr	6.02	7.61	3.85	3.75
Nd	24.78	28.62	15.49	15.25
Sm	5.40	6.12	3.47	3.33
Eu	1.49	1.39	1.14	1.12
Gd	4.82	5.60	3.12	2.98
Tb	0.74	0.93	0.47	0.45
Dy	4.25	5.69	2.66	2.55
Ho	0.81	1.12	0.51	0.48
Er	2.12	3.07	1.31	1.25
Tm	0.30	0.46	0.19	0.17
Yb	1.89	2.93	1.15	1.11
Lu	0.29	0.45	0.18	0.16
Ba	405	559	238	222
Th	4.39	8.73	2.89	2.40
Nb	9.60	17.90	6.04	5.84
Y	21.86	29.25	13.25	11.95
Hf	5.11	8.15	3.49	3.30
Ta	0.72	1.34	0.46	0.44
U	1.39	2.80	0.88	0.74
Pb	5.88	7.58	3.44	3.07
Rb	27.1	66.0	23.0	19.2
Cs	0.34	1.08	0.78	0.45
Sr	557	242	771	761
Sc	11.4	7.9	9.0	11.5
Zr	199	325	135	127

Appendix E. $^{40}\text{Ar}/^{39}\text{Ar}$ Age Results for Graveyard and Gordon Buttes

Table 8. $^{40}\text{Ar}/^{39}\text{Ar}$ Age Results for Samples at Graveyard and Gordon Buttes.

Sample No.	Latitude	Longitude	Rock location / type	Material Dated	Analysis	Steps	% ^{39}Ar	K/Ca	Age $\pm 2\sigma$ (Ma)	Analysis	K/Ca	Age $\pm 2\sigma$ (Ma)
X3	45.1624	-121.3134	Graveyard Butte / rhyolite	Ground-mass	Weighted Plateau	17	50.39	0.44	3.71 $\pm$ 0.01	Total Fusion	1.55	3.72 $\pm$ 0.01
X3	45.1624	-121.3134	Graveyard Butte / rhyolite	Feldspar	Weighted Plateau	11	81.15	0.409	3.67 $\pm$ 0.01	Total Fusion	0.395	3.70 $\pm$ 0.01
CC14	45.1655	-121.2843	Graveyard Butte / rhyolite	Feldspar	Weighted Plateau	12	92.28	0.324	3.65 $\pm$ 0.01	Total Fusion	0.328	3.65 $\pm$ 0.01
S12-6	45.1561	-121.3135	Graveyard Butte / andesite	Ground-mass	Weighted Plateau	6	89.58	0.54	3.86 $\pm$ 0.07	Total Fusion	0.62	3.77 $\pm$ 0.09
GB4-3	45.2697	-121.4410	Gordon Butte / rhyolite	Ground-mass	Weighted Plateau	27	66.56	0.30	3.70 $\pm$ 0.01	Total Fusion	1.78	3.72 $\pm$ 0.01
GB4-3	45.2697	-121.4410	Gordon Butte / rhyolite	Feldspar	Weighted Plateau	18	100.00	0.302	3.64 $\pm$ 0.03	Total Fusion	0.312	3.64 $\pm$ 0.04