Voluminous and compositionally diverse, middle Miocene Strawberry Volcanics of NE Oregon: Magmatism cogenetic with flood basalts of the Columbia River Basalt Group

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ABSTRACT

The mid-Miocene Strawberry volcanic field of northeastern Oregon is an example of intracontinental flood volcanism that produced lavas of both tholeiitic and calc-alkaline compositions derived by open-system processes. Until now, these dominantly calc-alkaline lavas have not been considered to have a petrogenetic origin similar to that of the flood basalts of the Pacific Northwest because of their calc-alkaline composition. These lavas are situated in between and co-erupted with the dominant volcanic field of the Columbia River Basalt Group (CRBG). Due to the timing, location, and diversity of these erupted units, the Strawberry Volcanics may hold valuable information about the role of crustal modification during large magmatic events such as hotspot volcanism. The earliest eruptions of the Strawberry Volcanics began at 16.2 Ma and appear continuous to 15.3 Ma, characterized by low-silica rhyolite. High-silica, A-type rhyolite eruptions followed at 15.3 Ma. The silicic eruptions continued until 14.6 Ma, with an estimated total volume up to ~100 km³. The first eruptions of the intermediate lava flows occurred at 15.6 Ma and continued with both tholeiitic and calc-alkaline, and transitional, lavas until 12.5 Ma. Volume estimates of the intermediate lavas are ~1100 km³. The mafic lavas are sparse (~2% of total volume) and are distributed throughout the upper sequences, and they appear to be near last to arrive at the surface. Herein, we show that the Strawberry Volcanics are not only related in time and space to the Columbia River Basalt, but they also share some chemical traits, specifically to the Steens Basalt. Evidence of this similarity includes: overlapping normalized incompatible trace-element patterns, selected trace-element ratios, and radiogenic isotopes. Furthermore, we compared the Strawberry rhyolites to the other mid-Miocene rhyolites of eastern
INTRODUCTION

The name “Strawberry Volcanics” was given to a diverse group of volcanic rocks that crop out along the southeastern margin of the John Day valley of NE Oregon and that are mid-Miocene in age (Fig. 1; Thayer, 1957). Thayer (1957), Brown and Thayer (1966a, 1966b), and Robyn (1977) published the first works on the Strawberry Volcanics, providing data on their spatial extent and geologic relationships to regionally occurring, stratigraphically younger and older units, and delineating their general geochemical and petrographic characteristics. These works established the overall calc-alkaline character and prevalence of andesitic lavas of this volcanic field (Fig. 2). It was also noted that these voluminous andesites are located in an intracontinental setting and were not generated due to subduction processes (Robyn, 1979). The only subsequent work of note on the Oregon associated with the inception of the Yellowstone–Snake River Plain hotspot and found overlapping eruption ages, trace and rare earth element compositions, and “A-type” rhyolite characteristics. This research concludes that the Strawberry Volcanics were part of the regional basalt to rhyolite magmatism of the Yellowstone–Snake River Plain hotspot.

Figure 1. Regional map and simplified geologic map. (A) Location of the Strawberry Volcanics and regional lavas of the Columbia River Basalt Group: MD—Monument dikes, SD—Steens dikes, CJ—Chief Joseph dikes, SRP—Snake River Plain–Yellowstone hotspot, SV—Strawberry Volcanics, MT—Montana, NV—Nevada, OR—Oregon, UT—Utah, CA—California, ID—Idaho, WA—Washington. Dashed line outlines the Snake River Plain, and circles inside the dashed line are inferred volcanic centers. Figure of the Columbia River Basalt Group lavas is molded after Camp and Ross (2004). Solid red line outlines the area shown in B, and the dashed rectangle shows area covered in Figure 3B. (B) Simplified geologic map showing Strawberry Volcanics and bordering area. Field observation–identified volcanic centers (asterisks) and dikes (dashed lines) are included on map: SM—Strawberry Mountain, BRM—Bull Run Mountain, BV—Bear Valley, CM—Canyon Mountain, HM—High Mountain, ISM—Ironside Mountain, and LV—Logan Valley. Stars represent towns of John Day (JD), Seneca (Sen), and Unity (UN). The geological units surrounding the Strawberry Volcanics are based on Thayer (1956), Crowley (1960), Brown and Thayer (1966a, 1966b, 1977), Thayer et al. (1967), Greene et al. (1972), Robyn (1977), Brooks and Ferns (1979), Ferns et al. (1983), and Mullen (1983).
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Strawberry Volcanics after the 1950s to 1970s was that by Goles et al. (1989), who presented isotopic data for basaltic andesites of the Slide Creek member (Thayer, 1957), located in the NNE portion of the field. No other recent data exist on this enigmatic middle-Miocene calc-alkaline volcanic field, which is surrounded by the tholeiitic lavas of the Columbia River Basalt Group. However, these earlier studies have brought to light aspects that make the Strawberry Volcanics an important field to understand, including: (1) the petrogenetic evolution of a voluminous volcanic field dominated by intracontinental, calc-alkaline andesites; (2) the relationship of mafic magmas to the surrounding contemporaneous tholeiitic flood basalts of the Columbia River Basalt Group; and (3) the context of the largely unknown rhyolites of the Strawberry Volcanics compared to other mid-Miocene silicic centers associated with the inception of the Yellowstone–Snake River Plain hotspot (Fig. 3).

Lavas of the Columbia River Basalt Group have been heavily studied and have received considerable attention, but the volcanic fields spatially and temporally associated with the Columbia River basalts that erupted calc-alkaline lavas have remained relatively understudied (Hooper et al., 2002; Camp et al., 2003; Ferns and Mcclaughry, 2013). Calc-alkaline lavas associated with the Columbia River Basalt Group are generally thought to have erupted around 13.5 Ma and to mark the transition between the tholeiitic flood basalt stage and the Basin and Range extension calc-alkaline phase (Hooper et al., 2002; Camp et al., 2003; Ferns and Mcclaughry, 2013).

Figure 2. (A) Total alkali–silica diagram (Le Bas et al., 1986) with data of this study showing the compositional diversity of the volcanic suite of the Strawberry Volcanics. (B) Miyashiro (1974) tholeiitic and calc-alkaline diagram showing that mafic to intermediate compositions of the Strawberry Volcanics display both tholeiitic and calc-alkaline affinities.

Figure 3. Regional distribution of major 16–15 Ma rhyolite centers (after Streck et al., 2015, and references therein) in relation to rhyolites of the Strawberry Volcanics (in pink). DITEC—Dinner Creek Tuff eruptive center, depicting postulated source for four cooling units of the Dinner Creek Tuff (Streck et al., 2015); LOVF—Lake Owyhee volcanic field; OIG—Oregon-Idaho graben, shown by solid dashed lines (Cummings et al., 2000). Numbers are ages in Ma and are near onset of activity of select centers, except for rhyolites of the Strawberry Volcanics, for which activity period is indicated.
et al., 2003; Ferns and McCalghry, 2013). However, the studies from Brueseke and Hart (2009) showed that calc-alkaline lavas of intermediate composition from the Santa Rosa–Calico volcanic field were derived from tholeiitic magmas of Steens Basalt interacting with the crust during the main flood basalt phase of the Columbia River Basalt Group.

The goals of this paper are the following: (1) to identify lavas of the Strawberry Volcanics based on physical characteristics, mineralogy, geochemistry, and stratigraphy; (2) to reevaluate the timing and stratigraphy of the Strawberry Volcanics with 40Ar/39Ar age dates, placing particular emphasis on time and space relationships to Columbia River Basalt Group magmas as previous ages include 19.8 ± 0.38 Ma to 12.4 ± 0.41 Ma suggesting onset of magmatism of the Strawberry Volcanics occurred prior to the Columbia River Basalt Group; (3) to investigate the petrogenetic relationships of mafic magmas of the Strawberry Volcanics to surrounding Columbia River Basalt Group units; and (4) to describe the rhyolites of the Strawberry Volcanics and explore their association with other mid-Miocene rhyolites associated with the Yellowstone–Snake River Plain hotspot.

GEOLOGIC SETTING

Geologic History

The lavas of the Strawberry Volcanics are underlain by the pre-Tertiary, Paleozoic, and Mesozoic accreted terrane rocks of the Blue Mountains Province and Mesozoic sediments of the Izee terrane (Robyn, 1977; Schwartz et al., 2010; LaMaskin et al., 2011). A Paleozoic section of the Baker terrane that crops out immediately adjacent west of Strawberry Mountain, Oregon, locally known as Canyon Mountain, is a presumed ophiolite and includes mafic-ultramafic rocks, serpentinite, and chert-argillite mélangé (Himmelberg and Loney, 1980; LaMaskin et al., 2011; Gerlach et al., 1981). Fine-grained mudstone/siltstone, argillite, and limestone of the Izee terrane crop out in areas southwest of Strawberry Mountain near the town of Seneca, Oregon (Fig. 1; Brown and Thayer, 1966a, 1966b). Southwest of Strawberry Mountain, these sedimentary rocks form discontinuous units. East of Strawberry Mountain, Jurassic argillite and limestone and Cretaceous intermediate to silicic dikes and sills are exposed near Bull Run Mountain and Ironside Mountain (Fig. 1; Thayer et al., 1967).

Rocks of the Clarno and John Day Formation are exposed throughout the vicinity of the Strawberry Volcanics (Fig. 1). The Clarno Formation is composed of nonmarine volcanic and volcanioclastic units ranging from 54 to 39 Ma in age (Swanson and Robinson, 1968). These volcanic products are thought to be derived from subduction zone magmatism and are strongly calcalkaline with hydrous minerals phases (amphibole and biotite), yet some transitional tholeiitic compositions do occur (Rogers and Novitsky-Evans, 1977). The John Day Formation is composed of volcanic units ranging from silicic to intermediate tuffs, lava flows, and domes to intermediate lava flows, all ranging in age from 39 to 22 Ma (Robinson et al., 1984; McCalghry et al., 2009; Ferns and McCalghry, 2013). Within the surrounding outcrop area of the Strawberry Volcanics, exposures of John Day Formation were found to be minimal (Brown and Thayer, 1966a, 1966b).

The main outcrop area of the Strawberry Volcanics is bordered by units from the Columbia River Basalt Group: lavas of Picture Gorge Basalt to the west and northwest, lavas of the Grande Ronde Basalt to the north, lavas of the Imnaha Basalt to the east to southeast, and Steens Basalt lavas to the south (Fig. 1). The main pulse of the Columbia River Basalt Group erupted tholeiitic mafic lavas during the middle Miocene (ca. 16.7–15.6 Ma), and it is the most widespread and voluminous Cenozoic volcanic unit within the Pacific Northwest (230,000 km²; Camp and Hooper, 1981; Baksi, 1989; Camp and Ross, 2004; Barry et al., 2013; Camp et al., 2013, 2017; Reidel et al., 2013). Specifically, the ages of the Columbia River Basalt Group eruptions and duration are: Steens Basalt 16.7–16.4 Ma; Imnaha Basalt 16.7–16.0 Ma; Grande Ronde Basalt 16.0–15.6 Ma; Wanapum Basalt 16–15.4 Ma; and Saddle Mountains Basalt 14.0–5.5 Ma (Barry et al., 2013; Camp et al., 2013, 2017). Details of Columbia River Basalt Group chronology are still a topic of controversy and of ongoing research. These magmas erupted from mafic shield volcanoes and fissures that are now preserved as dike swarms (Wilcox and Fisher, 1966; Swanson et al., 1975; Brueseke et al., 2007; Bondre and Hart, 2008; Brown et al., 2014). Locations of the dikes that produced the lavas of the Columbia River Basalt Group surround the Strawberry Volcanics (Fig. 1).

Several regional felsic ignimbrites, including the Dinner Creek Tuff, ca. 16.2–14.9 Ma (Streck et al., 2015), Devine Canyon Tuff, ca. 9.7 Ma (Jordan et al., 2004), and the Rattlesnake Tuff, ca. 7.1 Ma (Streck and Grunder, 1995), reach into the area of the Strawberry Volcanics. Units of the Dinner Creek Tuff are intercalated among intermediate and silicic units of the Strawberry Volcanics and younger tuffs overlie.

METHODS

Whole-Rock Geochemistry

Major and Trace Elements

Fresh samples were selected for whole-rock major- and trace-element analysis. Sample preparation followed the analytical procedures of the Washington State University Peter Hooper GeoAnalytical laboratory following Johnson et al. (1999) for X-ray fluorescence (XRF) and inductively coupled plasma–mass spectrometry (ICP-MS) analysis. Samples were analyzed

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1GSA Data Repository Item 2018233, Appendix DR1—X-ray fluorescence and inductively coupled plasma–mass spectrometry data and Appendix DR2—Isotopes, is available at www.geosociety.org/datarepository/2018/, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.
using a ThermoARL Advant’XP+ sequential XRF spectrometer and an Agilent 7700 ICP-MS. The data provided were normalized to anhydrous values, and the total Fe content is reported as wt% FeO*.

Radiogenic Isotopes

Sr, Nd, and Pb isotopic compositions were measured on 13 samples representing mafic, intermediate, and rhyolitic compositions. Sample dissolution and chemistry were performed at the radiogenic isotope clean laboratory and analyzed using thermal ionization mass spectrometry (TIMS) at New Mexico State University, Las Cruces, New Mexico. Samples were powdered and weighed (<1 g) and digested in acid. Once completely dissolved, the solution was then run through a quartz column filled with chromatography resin. Sr isotopic ratios were fractionation-corrected using \(^{86}\text{Sr}/^{88}\text{Sr} = 0.1194\), and the NBS 987 Sr standard resulted in an average value of 0.710304 (\(n = 3\)). Nd isotopic ratios were normalized to \(^{143}\text{Nd}/^{146}\text{Nd} = 0.7219\), and results for the La Jolla and JNd-1 standards were 0.511854 (\(n = 1\)) and 0.512106 (\(n = 1\)), respectively. Pb isotopes were doped with NBS 997 Ti and normalized to \(^{205}\text{Ti}/^{203}\text{Ti} = 2.387075\). Results for NBS 981 were \(^{206}\text{Pb}/^{204}\text{Pb} = 16.932\), \(^{207}\text{Pb}/^{204}\text{Pb} = 15.486\), and \(^{208}\text{Pb}/^{204}\text{Pb} = 36.680\) (\(n = 6\)). Age corrections for Sr and Nd isotopic ratios were applied using the ratio of Rb and Sr whole-rock element concentrations.

\(^{40}\text{Ar}/^{39}\text{Ar} Geochronology

The \(^{40}\text{Ar}/^{39}\text{Ar} geochronology was conducted at the Argon Geochronology Research Laboratory, Oregon State University (OSU), Corvallis, Oregon, on a total of 15 samples: 10 groundmass concentrates, three plagioclase separates, one biotite, and one glass sample. All samples were loaded in quartz vials with small quantities of mineral monitor FCT-3 (28.030 ± 0.003 Ma; Renne et al., 1998) and irradiated at the OSU TRIGA research reactor. Obtained ages were later recalculated using a Fish Canyon Tuff (FCT) age of 28.201 Ma (Kuiper et al., 2008). All samples were analyzed by the furnace incremental heating age spectrum method using a Mass Analyzer Products (MAP) Model 215-50 mass spectrometer and analyzing between eight and 12 heating steps (Table 1). Further details of the analytical procedures are described in Duncan and Keller (2004). All new age data cited in the text are quoted at 2\(\sigma\) (Table 1).

RADIOMETRIC AGES

Previous Ages of Strawberry Volcanics

Robyn (1977) determined a 7-m.y.-long activity period for the Strawberry Volcanics, from 19.8 ± 0.38 Ma (2\(\sigma\)) to 12.4 ± 0.41 Ma (2\(\sigma\)), based on six K/Ar age dates. Of the ages reported by Robyn (1977), a single basalt lava at 14.9 ± 0.85 Ma (2\(\sigma\)) and a basaltic andesite at 12.4 ± 0.41 (2\(\sigma\)) Ma conform best with our geochronological study of the Strawberry Volcanics. On the other hand, the oldest ages of 19.8 ± 0.38 Ma, 19.1 ± 0.65 Ma, and
18.1 ± 0.50 Ma (2σ) that Robyn (1977) reported for lava flows are significantly older than any of our ages. Field and lithological characteristics make these units very unlike any other units of the Strawberry Volcanics. They are dacitic in composition and contain large phenocrysts of plagioclase (~1–3 cm) and amphibole, which matches up with units from the John Day Formation described earlier herein much better.

Summary of New 40Ar/39Ar Results

New 40Ar/39Ar ages from this investigation indicate that basaltic andesite to rhyolite lavas of the Strawberry Volcanics erupted from 16.16 ± 0.17 Ma to 12.52 ± 0.12 Ma (Fig. 4; Table 1) (cf. Steiner and Streck, 2013). Rhyolites yielded the oldest ages, ranging from 16.16 ± 0.17 Ma to 14.70 ± 0.13 Ma, which is consistent with stratigraphic field observations described next (Fig. 4; Table 1). Among intermediate lavas, those of calc-alkaline affinity erupted over the longest duration, as indicated by ages ranging from 15.59 ± 0.36 Ma to 12.52 ± 0.12 Ma (Fig. 4; Table 1). The tholeiitic lavas produced a slightly narrower range of ages of 15.57 ± 0.16 Ma to 13.53 ± 0.24 Ma. This may not be significant, but what is clear is that tholeiitic and calc-alkaline volcanism were coeval (Fig. 4; Table 1). One basalt sample yielded an age of 12.61 ± 0.08 Ma (Fig. 4; Table 1). Other basalts are intercalated near the middle of a stratigraphic sequence of lava flows at Strawberry Mountain and thus have ages within the range of intermediate lavas.

STRATIGRAPHY AND ERUPTIVE UNITS

Rhyolite Volcanism

Rhyolites of the Strawberry Volcanics, hereafter named Strawberry rhyolites, erupted as lava domes and coulees, and fallout and ash-flow tuffs. Rhyolites are generally located in the lower part of the stratigraphy, sitting on top of Izee terrane sediments or between both calc-alkaline and tholeiitic intermediate lavas (Fig. 4). Where the rhyolites are in direct contact with the intermediate lavas, there is no evidence of a significant time gap (e.g., paleosol or unconformities). Dikes of mafic to intermediate composition crosscut these rhyolite lavas and tuffs. Phenocrysts are mostly plagioclase and quartz and occasionally biotite and amphibole. Microphenocrysts are rare (<1%) but are seen on occasion and include plagioclase, quartz, and minor pyroxene, and accessory minerals include zircon and apatite. These lavas are often devitrified or include obsidian bands between devitrified sections. Ash-flow tuffs and fallout deposits, associated with vents proximal to this location, are dispersed throughout the area and intercalated among rhyolitic lavas or are stratigraphically younger. The volume is difficult to estimate because of outcrop exposure, erosion, and the expected variability in thicknesses of domes and rhyolite flows at emplacement. Nevertheless, we estimated a total erupted rhyolite volume of between 40 and 100 km³.

Strawberry rhyolites range from ~70 to 78 wt% SiO₂ and are peraluminous (which is likely a feature of postemplacement alkali mobility) to mildly peralkaline (Fig. 5). Major elements follow typical trends with silica enrichment, such as decreasing CaO, FeO*, and Al₂O₃, and trace-element concentrations vary most in Sr (9–250 ppm), Zr (66–450 ppm), Ti (300–3500 ppm), and Ba (350–1630 ppm; Table 2). We normalized our data to upper-crust values and the rhyolites plot around 1, indicating a similar composition but with pronounced depletions in Sr, P, and Ti (Fig. 6).

Basaltic to Intermediate Lava Flows

The Strawberry Volcanics primarily consist of lava flows of basaltic andesite and andesite composition (Fig. 2) that cover 3600 km² of the Malheur National Forest and Strawberry Mountain Wilderness (Fig. 1). The best exposures of these lava flows are found in the vicinity of Strawberry Mountain proper, a glacially carved mountain with a maximum elevation of ~3000 m, for which the Strawberry Volcanics were named (Fig. 1). Within this mountain range, the total thickness of numerous basaltic andesite and andesite lava flows is uniformly ~1000 m. Across this range, individual lava flows show constant thicknesses of ~5–10 m, with little columnar jointing, but instead display a thin (tens of centimeters), platy appearance. Volume estimates can be conservatively calculated by using the volume of a cone, assuming that the lava thicknesses decrease from Strawberry Mountain toward the outer edges of the volcanic field. If we use a radius of 32 km and a thickness of 1 km, the result is ~1100 km³, which is likely an underestimate given our approximation.

Calc-Alkaline Intermediate Volcanism (15.60–12.5 Ma)

The oldest (15.59 ± 0.36 Ma) intermediate lava of the Strawberry Volcanics is a calc-alkaline basaltic andesite, and the youngest (12.52 ± 0.12 Ma) is an andesite vent plug located at High Mountain (Table 1; Fig. 2). We base the calc-alkaline definition on discrimination schemes by Miyashiro (1974) and Arculus (2003). These lavas range in SiO₂ (wt%) from 52.7% to 64.5% and generally form linear or collinear trends with typical increases or decreases as silica increases from basaltic andesite to dacite in major elements (Fig. 2). Al₂O₃ ranges from 16.0 to 17.9 wt%, and MgO and FeO* decrease with increased silica, ranging from 6.2 to 2.0 wt% and 9.2 to 5.2 wt%, respectively (Fig. 7). These lavas display little to no increase in FeO*/MgO ratios toward higher SiO₂ contents (Fig. 2). Incompatible elements behave variably within the calc-alkaline suite of the Strawberry Volcanics from basaltic andesite to dacite (Fig. 7; Table 3). Trace elements that increase include Rb, Ba, Pb, and U, but all other trace elements, including rare earth elements (REEs) are nearly constant or slightly decrease with increasing SiO₂ content (Fig. 7; Table 3).

Calc-alkaline lava flows vary from aphyric to phenocryst-poor to containing 30% phenocrysts. The typical calc-alkaline lava type is aphyric or contains <5% phenocrysts. The aphyric-type
Figure 4. Fence diagrams for the Strawberry Volcanics. Sections are labeled A–H and can be correlated to locations on inset map. Ages of specific units are labeled to the right of the diagram. All ages in black are from this study. Ages in red are for rhyolitic units of the Dinner Creek Tuff (Streck et al., 2015 and unpublished) and previously dated Strawberry units (Robyn, 1977). Numbers on left of diagram are elevations in meters. CRBG—Columbia River Basalt Group.
flows are best exposed along the lower section below 2000 m in the cirque walls of Strawberry Mountain near Strawberry Lake. The calc-alkaline lavas that show greater amounts of phenocrysts have glomerocrysts consisting of small (1–2 mm) plagioclase, pyroxene, and minor olivine and oxides. The more phenocryst-rich calc-alkaline lavas are dispersed throughout the Strawberry Mountain vicinity.

Numerous dikes are exposed throughout the Strawberry volcanic field and appear to be the main conduit system for magma extrusion at the surface through fissures or small-scale central vent volcanoes (Fig. 1; Steiner and Streck, 2013). These dikes are often represented by topographic highs and crosscut lava flows of the Strawberry Volcanics and associated terranes (Fig. 1). Most dikes strike NNW-SSE, similar to dikes of the nearby (~40 km) Monument dike swarm, which gave rise to the Picture Gorge Basalt unit of the Columbia River Basalt Group (Fruchter and Baldwin, 1975; Thayer, 1957). Dikes within the Strawberry volcanic field are clearly part of the Strawberry Volcanics and not the Monument dike swarm, based on geochemical and petrographic similarities to the lavas of the Strawberry Volcanics. Several dikes form a radial pattern around a central vent at Baldy Mountain, located in the north-central area of the Strawberry Volcanics (Fig. 1), despite that depictions of the Monument Dike Swarm typically include those. Some vent site lavas have microplutonic textures (e.g., the micro-norite dikes and plugs of Strawberry Mountain and High Mountain) and were previously thought to be a feature related to a long-lived, stratovolcanic edifice that supplied the lavas for the Strawberry Volcanics (Robyn, 1977). There is no evidence for large single composite volcanoes, such as thickening of lava flows away from the vent locations throughout the Strawberry Volcanics. Rather, we see lava flows extend in uniform thicknesses for tens of kilometers away from the vent typical of shield volcanoes or lava flow fields.

**Tholeiitic Basalt and Intermediate Volcanism (15.60–13.50 Ma)**

The tholeiitic lavas of the Strawberry Volcanics are geochemically similar to the calc-alkaline lavas and comprise compositions ranging from basalt to andesite with SiO₂ ranging from 47.5 to 60.4 wt% (Fig. 2). These lavas are relatively high in Al₂O₃ (15.4–18.2 wt%), and they vary in MgO (2.6–7.2 wt%; Fig. 7; Table 3). Incompatible element ranges are comparable to the rhyolites, suggesting a similar source region.
Voluminous and compositionally diverse, middle Miocene Strawberry Volcanics of NE Oregon to calc-alkaline lavas, although high field strength elements (HFSes) and REEs tend to be higher in more-evolved tholeiitic compositions (e.g., Figs. 7 and 8; Table 3). Normalized incompatible trace-element patterns indicate distinct spikes at Ba and Pb, and occasionally Ta and Nb have small troughs relative to neighboring elements (Fig. 8).

| TABLE 2. STRAWBERRY MOUNTAIN RHYOLITES |
|------------------------------------------|
| AS-SV- 66 144 151 173 263 175 63 133 190 98 60 179 37 |
| Major oxides measured by X-ray fluorescence (wt% normalized) |
| SiO₂ | 69.85 | 72.99 | 73.19 | 73.33 | 74.62 | 75.44 | 76.80 | 76.88 | 76.93 | 76.97 | 77.71 | 78.45 | 78.72 |
| TiO₂ | 0.59 | 0.35 | 0.35 | 0.27 | 0.26 | 0.21 | 0.26 | 0.21 | 0.06 | 0.05 | 0.19 | 0.09 | 0.10 | 0.15 | 0.14 |
| Al₂O₃ | 15.17 | 15.00 | 14.57 | 14.24 | 12.98 | 12.96 | 13.20 | 13.35 | 12.66 | 13.16 | 12.40 | 12.36 | 11.64 |
| FeO* | 3.46 | 2.29 | 2.23 | 2.02 | 1.97 | 1.89 | 1.90 | 1.98 | 0.80 | 0.78 | 1.19 | 0.93 | 0.85 | 0.30 | 0.84 |
| MgO | 0.04 | 0.04 | 0.05 | 0.05 | 0.05 | 0.02 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.04 | 0.00 | 0.00 |
| MnO | 0.53 | 0.25 | 0.23 | 0.57 | 0.72 | 0.00 | 0.03 | 0.02 | 0.13 | 0.08 | 0.08 | 0.00 | 0.00 | 0.00 |
| CaO | 2.70 | 2.03 | 1.99 | 2.21 | 1.77 | 0.06 | 0.53 | 0.52 | 0.81 | 0.69 | 0.68 | 0.45 | 0.06 |
| Na₂O | 4.45 | 3.53 | 3.86 | 3.28 | 3.27 | 5.20 | 3.93 | 3.52 | 4.12 | 3.37 | 3.76 | 3.99 | 4.28 |
| K₂O | 3.07 | 3.47 | 3.42 | 3.96 | 4.83 | 3.91 | 4.69 | 4.37 | 4.28 | 4.25 |
| P₂O₅ | 0.15 | 0.05 | 0.10 | 0.08 | 0.05 | 0.03 | 0.01 | 0.01 | 0.02 | 0.02 | 0.02 | 0.05 | 0.00 |
| Pre-normalized total | 98.37 | 95.01 | 98.09 | 95.79 | 97.05 | 98.66 | 99.51 | 95.33 | 98.60 | 95.33 | 99.42 | 99.01 | 98.84 |

Trace elements (ppm), measured by inductively coupled plasma–mass spectrometry:

| Ni | 3.4 | 3 | 2.5 | 4.5 | 0.40 | 3.4 | 1.9 | 1.5 | 3 | 2.3 | 0.8 | 3.4 | 1.3 |
| Cr | 4.7 | 4.6 | 5.4 | 6.7 | 29.1 | 29.1 | 29.2 | 29.2 | 29.2 | 29.2 | 29.2 | 29.2 | 29.2 |
| V | 43.1 | 25 | 29.8 | 27.1 | 35.91 | 4.2 | 1.2 | 2.7 | 1.9 | 2.7 | 3.6 |
| Ga | 17.4 | 14.6 | 15.7 | 15.5 | 14.86 | 24.7 | 17.9 | 17 | 14.4 | 16.7 | 13.7 | 16 |
| Cu | 5.3 | 2.8 | 7.2 | 6.4 | 9.18 | 1.8 | 0.4 | 2.7 | 0.4 | 1.1 | 0.5 |
| Zn | 63.4 | 43.4 | 48.5 | 42.1 | 35.11 | 132.7 | 34.0 | 38.7 | 35.2 | 34.2 | 25.4 | 21.2 | 41.3 |

Trace elements (ppm), measured by inductively coupled plasma–mass spectrometry:

| Sc | 10.1 | 6.6 | 5.8 | 6.2 | 7.3 | 1.7 | 4.4 | 5.3 | 4.7 | 4.4 | 3.6 | 5.3 | 2.8 |
| Ta | 236 | 172 | 171 | 139 | 109 | 448 | 81 | 71 | 176 | 97 | 102 | 220 | 451 |

Tholeiitic lavas of both basaltic and andesitic composition are dispersed throughout the stratigraphy of the Strawberry Volcanics (Fig. 4). Lavas with tholeiitic affinity are minor in volume relative to calc-alkaline lavas. Tholeiitic intermediate lavas are phenocryst poor (<10%), similar to the phenocryst-poor calc-alkaline lavas in textures and modal mineral abundances, making
them essentially indistinguishable in the field. The vents for tholeiitic lavas are assumed to have been similar to those for calc-alkaline lavas. Tholeiitic basalt lavas tend to be more massive and cohesive in texture and lack the platy texture of the calc-alkaline lava flows. These tholeiitic basalts have vesicles and commonly display diktytaxitic texture. Several tholeiitic basalts are located in the Strawberry Mountain cirque walls and can be distinguished from the calc-alkaline and tholeiitic intermediate lavas by an ophitic texture (Table 3). Tholeiitic basalt to andesitic lavas are distributed throughout the Strawberry Volcanics and are associated with nearby vent structures (e.g., dikes), which were identified at Strawberry Mountain proper and south to southwest of this range and east, near the town of Unity, Oregon (Fig. 1).

Tholeiitic basalt lava flows are characterized by the presence of plagioclase, clinopyroxene, olivine, and Fe-Ti oxide. The most prevalent petrographic texture of the basalt lavas is the ophitic texture. Plagioclase is the main mineral phase, with a modal abundance of ~60%, and it ranges in size from <1 mm to 2 mm and is often tabular and euhedral. Oikocrysts of clinopyroxene (augite) are the sole pyroxene phase present, and they have a modal abundance of ~30%, ranging in size from 1 mm to 3 mm. Small olivine phenocrysts (~1 mm in size) account for up to 7%. Acicular Fe-Ti oxides are ~.05 mm in length and account for ~3% of the total visible crystals. Minor amounts of glass occupy the interstitial zones between crystal laths. Neither obvious disequilibria of phenocrystic phases are evident nor do any xenoliths or glomerocrysts occur in thin sections of tholeiitic samples.

Intermediate lavas of tholeiitic composition are largely phenocryst-poor lavas. Groundmass crystals consist of plagioclase (65% modal abundance) + clinopyroxene (30% modal abundance) + oxides (≤3% modal abundance) and ± olivine (≤2% modal abundance). Groundmass textures can vary and can include ophitic texture, much like the basalts, but minerals are smaller in size (<1 mm). When phenocrysts do occur they include plagioclase, clinopyroxene, or olivine, or a combination of all three, never exceeding >10% by volume. Plagioclase phenocrysts can be ~2 mm in length and are often anhedral to subhedral, zoned, and with sieved and resorbed textures. When present, clinopyroxene and olivine phenocrysts range in size from 1 to 2 mm.

DISCUSSION

Synopsis of Emplacement History of the Strawberry Volcanics

The Strawberry Volcanics, spanning the compositional range from basalt to rhyolite, have an eruption history that lasted 4 m.y. The first eruption of the Strawberry Volcanics, located in the south, occurred at 16.2 Ma with rhyolite lavas and domes. Succeeding eruptions of calc-alkaline and tholeiitic intermediate lavas started at ca. 15.6 Ma. Activity continued with eruptions of dominantly intermediate calc-alkaline lavas, accompanied by tholeiitic basalt and intermediate tholeiitic lavas. Eruptions of rhyolite near the northwestern margin of Strawberry Mountain began at 15.3 Ma and continued up to 14.8 Ma. These eruptions produced aphyric lavas forming domes and minor pyroclastic events. During this time, eruptions at the early southernmost rhyolite field continued and appear to cease at 14.7 Ma. Low-volume, mafic tholeiitic eruptions appear sporadically throughout the volcanic field. The youngest intermediate lava flow with tholeiitic affinity is 13.5 Ma, and we take this as the time when tholeiitic volcanism
ceased. Tholeiitic volcanism was likely superseded by eruptions of calc-alkaline lavas, which possibly erupted last at 13.8 Ma, as suggested by our current age data. However, an intrusive calc-alkaline micro-norite dike at Strawberry Mountain was dated at 12.5 Ma, but it is unclear if any lava flows were produced at the surface (Table 1).

Relationships of Mafic Strawberry Volcanics to Flood Basalt Magmatism of the Columbia River Basalt Group

The close temporal and spatial relationships between the Strawberry Volcanics and units of the Columbia River Basalt Group invite the question as to the extent to which there is a petrogenetic relationship, despite the predominantly calc-alkaline nature of the Strawberry Volcanics (Fig. 1). New ages presented herein demonstrate that silicic and mafic to intermediate magmatism of the Strawberry Volcanics was ongoing during the eruptions of the Columbia River Basalt Group (Table 1; Jarboe et al., 2008; Barry et al., 2013; Camp et al., 2013, 2017). Field evidence has shown that the eruption style of the mafic to intermediate lavas of the Strawberry Volcanics is akin to the eruptions of the Columbia River Basalt Group. Despite our noted compositional differences (i.e., calc-alkaline) compared to Columbia River Basalt Group magmas, eruptions of Strawberry Volcanics were fed from dikes leading to fissure eruptions at the surface. In fact, a number of authors (e.g., Camp and Ross, 2004; Brueseke and Hart., 2009) have shown on maps that the Monument dike swarm of the Columbia River Basalt Group reaches into the area of the Strawberry Volcanics (Fig. 1). It is our conclusion, based on geochemical data and geographical location, that these mapped dikes are in fact dikes of the Strawberry Volcanics. Next, we will discuss the geochemistry of mafic lavas (≤56 SiO₂ wt%) of the Strawberry Volcanics with regard to differences with and similarities to the various units of the Columbia River Basalt Group.

Figure 7. Diagrams of select major and trace elements versus SiO₂ for basaltic to intermediate composition lavas. Major elements are MgO, FeO, and Al₂O₃ (A–C), and trace elements include Rb, Ba, La, Nb, and Zr (D–H).
TABLE 3. GEOCHEMICAL DATA FOR BASALT TO ANDESITE FROM STRAWBERRY VOLCANICS

| Major oxides measured by X-ray fluorescence (wt% normalized) | Basalt Group lavas, specifically with the Steens and Imnaha Basalt Group lavas, and Basalt Group lavas, specifically with the Steens and Imnaha Basalt Group lavas. We used the data of Wolff et al. (2008) as representative of the Columbia River Basalt Group magmas. Comparison of major-element compositions shows overlap of the basalt lavas of the Strawberry Volcanics with Columbia River Basalt Group lavas, specifically with the Steens and Imnaha Basalts (Fig. 9). The higher SiO₂ (52–56 wt%) lavas of the Strawberry Volcanics lie within the general trend of the Columbia River Basalt Group lavas in some elements, but they also trend away toward increased silica in other elements. They overlap with the Grande Ronde Basalt in MgO, CaO, and TiO₂ contents but diverge.

| AS-SV-287 | 109 | 11 | 217 | 15 | 16 | 17 | 285b | 39b | 233 | 32 | 283 | 156 | 181 |
| Major oxides measured by X-ray fluorescence (wt% normalized) | Basalt Group lavas, specifically with the Steens and Imnaha Basalt Group lavas, and Basalt Group lavas, specifically with the Steens and Imnaha Basalt Group lavas. We used the data of Wolff et al. (2008) as representative of the Columbia River Basalt Group magmas. Comparison of major-element compositions shows overlap of the basalt lavas of the Strawberry Volcanics with Columbia River Basalt Group lavas, specifically with the Steens and Imnaha Basalts (Fig. 9). The higher SiO₂ (52–56 wt%) lavas of the Strawberry Volcanics lie within the general trend of the Columbia River Basalt Group lavas in some elements, but they also trend away toward increased silica in other elements. They overlap with the Grande Ronde Basalt in MgO, CaO, and TiO₂ contents but diverge.

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| Trace elements (ppm), measured by inductively coupled plasma–mass spectrometry | Basalt Group lavas, specifically with the Steens and Imnaha Basalt Group lavas, and Basalt Group lavas, specifically with the Steens and Imnaha Basalt Group lavas. We used the data of Wolff et al. (2008) as representative of the Columbia River Basalt Group magmas. Comparison of major-element compositions shows overlap of the basalt lavas of the Strawberry Volcanics with Columbia River Basalt Group lavas, specifically with the Steens and Imnaha Basalts (Fig. 9). The higher SiO₂ (52–56 wt%) lavas of the Strawberry Volcanics lie within the general trend of the Columbia River Basalt Group lavas in some elements, but they also trend away toward increased silica in other elements. They overlap with the Grande Ronde Basalt in MgO, CaO, and TiO₂ contents but diverge.

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Figure 8. (A) Primitive mantle normalized trace element. (B) Chondrite diagram for the calc-alkaline and tholeiitic suite of lavas analyzed. Normalization values are from Sun and McDonough (1989) and McDonough and Sun (1995), respectively.

Figure 9. Major-element geochemistry of lavas with ≤56 wt% SiO₂ from the Strawberry Volcanics in comparison to Columbia River Basalt Group lavas. Basalts of the Strawberry Volcanics overlap mostly with the Steens Basalt lavas and with Picture Gorge Basalt lavas while basaltic andesites and andesites mostly define their own space. Geochemical data from the Columbia River Basalt Group are from Wolff et al. (2008).
in Al₂O₃, FeO*, and P₂O₅ contents, with notably higher Al and P and lower Fe concentrations (Fig. 9). This suggests that crustal evolution does have a significant impact on magmas within the basaltic andesites, although incompatible trace elements may be less affected than major elements and compatible trace elements.

On normalized incompatible trace-element diagrams and REE diagrams, the greatest overlap in terms of overall pattern with the lavas of the Strawberry Volcanics is observed with samples of Steens and Imnaha Basalts, as all samples of the Strawberry Volcanics are within the same range (Fig. 10). However, when compared with the average Steens Basalt pattern (or Imnaha Basalt), the Strawberry Volcanics have distinct Zr-Hf and Ti depletions, whereas average Steens Basalt has only a minor depletion in Zr-Hf, and none in Ti, and Imnaha Basalt does not have any of these depletions (Fig. 10). Another difference is that some samples of the Strawberry Volcanics are enriched in P, which could be due to select enrichment during crustal assimilation (Streck and Grunder, 2012). Significant overlap of elemental ranges occurs with the Strawberry Volcanics and Imnaha and Grande Ronde lavas, yet some elements also fall out of the range compared to Steens Basalt (Fig. 10). For example, the Strawberry Volcanics are enriched in Ba, Nb, Sr, and P, and enriched in the light (L) REEs (La through Nd) relative to the Imnaha Basalt (Fig. 10). Compared to the Grande Ronde Basalt, the Strawberry Volcanics are enriched in Nb, Sr, and P, but are significantly lower in Rb, Th, and U (Fig. 10). Samples of the Strawberry Volcanics are distinctly different from Picture Gorge Basalt in most elements from Rb to Eu, but Picture Gorge Basalt interestingly shows the same Ti troughs as samples of the Strawberry Volcanics (Fig. 10).

Diagrams using incompatible trace element ratios (e.g., Ba/Zr, La/Y, U/Nb) show that the overlap of Strawberry Volcanics samples with Steens Basalt is again greater than with other groups (Fig. 11), and that magmas of the Strawberry Volcanics are clearly offset from magmas of the Grande Ronde and Picture Gorge Basalts in plots of U/Nb or La/Y, respectively (Fig. 11).

Figure 10. Primitive mantle normalized trace-element and chondrite normalized REE (rare earth element) diagrams (insets) comparing the mafic (≤ 54 SiO₂ wt%) tholeiitic and calc-alkaline lavas of the Strawberry Volcanics (black lines) with lavas of the Columbia River Basalt Group. For the Columbia River Basalt Group units, the transparent color indicates the unit range and the solid colored line is the unit average. The Strawberry Volcanics mostly overlap with the Steens and Imnaha samples. Normalization values are the same as in Figure 8.
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Whole-rock radiogenic isotopic data for samples of the Strawberry Volcanics show that the Strawberry Volcanics overlap with the Columbia River Basalt Group but also define their own isotopic space between these groups (Fig. 12; Table 4). Initial Sr isotopic data of the Strawberry Volcanics show a strong similarity to Imnaha Basalt and some minor overlap with the Steens Basalt and Picture Gorge Basalt groups. Initial Nd isotopic values of Strawberry Volcanics are also similar to Imnaha and Grande Ronde Basalts, while 206Pb/204Pb value data are particularly distinct, with much lower values than Imnaha Basalt and some overlap with the other Columbia River Basalt Group (Fig. 12). On the other hand, Strawberry Volcanics overlap with the Grande Ronde lavas in Pb isotopic ratios (Fig. 12) and plot between the three mantle components proposed to be involved in the Columbia River Basalt Group plume (Carlson, 1984). The trend of intermediate samples away from the basalt may reflect a more complicated process of assimilating country rock. This, however, will be the focus of another paper.

To summarize, geochemical differences that exist among formal members for the Columbia River Basalt Group are greater than differences to the Strawberry Volcanics. The dominant volume of the Strawberry Volcanics is at least contemporaneous to eruptions of Wanapum Basalt units, but may even overlap in age with upper Grande Ronde Basalt lavas—this is a matter of ongoing controversy and is currently unresolved. The Strawberry Volcanics have the greatest similarity to Steens Basalt lavas with respect to trace elements but also indicate some unique geochemical features, e.g., isotopic ratios (Figs. 10, 11, and 12) that set them apart. Some of these differences may have been controlled by open-system processes as silica increased and may in turn have been partly due to the mechanisms that ultimately caused most Strawberry Volcanics to develop calc-alkaline affinity, such as melting of local basement lithologies and differentiation during assimilation and fractional crystallization processes (Brueseke and Hart, 2009; Steiner and Streck, 2013). It is surprising, however, that the Strawberry Volcanics have more trace-element commonalities with Steens Basalt than with the immediately neighboring (~40 km) Picture Gorge Basalt (Figs. 10 and 11). This may be because the Strawberry Volcanics are slightly more evolved than the Picture Gorge
Basalts. Isotopic data argue for a similar melting source to the one for Steens Basalt and Imnaha Basalt in some respect and for Picture Gorge Basalt in others, but the Strawberry Volcanics also define their own isotopic space among the Columbia River Basalt Group lavas (Fig. 12). Based on the information provided here, we propose that the mantle upwelling giving rise to Columbia River Basalt Group is also causing magmatism of the Strawberry Volcanics and that observed geochemical differences lie in melting slightly different mantle domains as well as locally driven open system processes.

Strawberry Rhyolites within the Context of the Miocene Rhyolite Flare-Up

McDermitt caldera and other rhyolitic centers, such as the Santa Rosa–Calico volcanic field and the High Rock caldera complex located near the Oregon-Nevada border, have been viewed as the first centers of rhyolitic volcanism associated with the Columbia River Basalt Group flood basalts of the Pacific Northwest starting at 16.5 Ma (Pierce and Morgan, 1992; Brueseke et al., 2008, 2014; Coble and Mahood, 2012;
TABLE 4. ISOTOPIC ANALYSIS OF MAFIC AND INTERMEDIATE LAVAS OF THE STRAWBERRY VOLCANICS (SV)

| Sample | SiO₂ (wt%) | Rb (ppm) | Sr (ppm) | 87Rb/86Sr | 87Sr/86Sr Age (Ma) | ε | Nd (ppm) | 147Sm/144Nd | 143Nd/144Nd | 143Nd/144Nd |
|--------|------------|----------|---------|-----------|-------------------|---|----------|------------|------------|------------|
| AS-SV-287* | 47.48 | 2.49 | 343.46 | 0.0210 | 0.70527 | 14.5 | 0.70526 | 8.16 | 33.29 | 0.1483 | 0.512494 | 0.512480 | -2.4 | 38.889 | 15.598 | 18.549 |
| AS-SV-11* | 50.47 | 8.67 | 527.15 | 0.0476 | 0.70452 | 14.5 | 0.70451 | 5.61 | 24.50 | 0.1386 | 0.512773 | 0.512760 | 3.0 | 38.544 | 15.593 | 18.826 |
| AS-SV-203b* | 53.30 | 14.09 | 575.28 | 0.0709 | 0.70409 | 14.5 | 0.70408 | 7.04 | 31.78 | 0.1338 | 0.512787 | 0.512774 | 3.3 | 38.549 | 15.494 | 18.844 |
| AS-SV-289 | 53.52 | 9.54 | 413.84 | 0.0667 | 0.70376 | 14.5 | 0.70375 | 4.28 | 18.35 | 0.1410 | 0.512838 | 0.512825 | 4.3 | 38.512 | 15.612 | 18.560 |
| AS-SV-39b* | 55.40 | 4.23 | 509.56 | 0.0240 | 0.70435 | 14.5 | 0.70435 | 6.67 | 29.60 | 0.1361 | 0.512822 | 0.512809 | 4.0 | 38.519 | 15.608 | 18.888 |
| AS-SV-56 | 56.68 | 22.02 | 510.95 | 0.1248 | 0.70441 | 14.5 | 0.70439 | 5.44 | 25.03 | 0.1313 | 0.512826 | 0.512814 | 4.0 | 38.474 | 15.593 | 18.855 |
| AS-SV-159c* | 57.59 | 25.39 | 435.22 | 0.1688 | 0.70392 | 15.48 | 0.70388 | 6.58 | 28.51 | 0.1395 | 0.512875 | 0.512861 | 5.0 | 38.466 | 15.600 | 18.856 |
| AS-SV-231 | 61.70 | 32.21 | 435.63 | 0.2140 | 0.70397 | 14.5 | 0.70393 | 3.90 | 18.18 | 0.1296 | 0.512839 | 0.512827 | 4.3 | 38.475 | 15.602 | 18.846 |
| AS-SV-188 | 62.64 | 37.47 | 410.48 | 0.2642 | 0.70404 | 14.5 | 0.70399 | 4.59 | 20.86 | 0.1331 | 0.512795 | 0.512783 | 3.4 | 38.501 | 15.606 | 18.875 |
| AS-SV-151 | 73.19 | 86.65 | 231.02 | 1.0857 | 0.70429 | 16.06 | 0.70405 | 3.82 | 19.62 | 0.1176 | 0.513046 | 0.513034 | 8.4 | 38.484 | 15.596 | 18.868 |
| AS-SV-179 | 78.45 | 100.42 | 45.10 | 6.4450 | 0.70583 | 15.21 | 0.70444 | 7.12 | 33.40 | 0.1390 | 0.512878 | 0.512865 | 8.3 | 38.498 | 15.593 | 18.854 |

Note: Srλ = 1.42E–11; Ndλ = 6.54E–12; (143Nd/144Nd)CHUR = 0.512638; (147Sm/144Nd)CHUR = 0.1964, where CHUR—chondritic uniform reservoir.

Benson et al., 2017). Recent age determinations of long-known mid-Miocene rhyolitic centers throughout eastern Oregon have yielded ages that are about as old as those along the Oregon-Nevada state boundary and that range from 16.5 to 15.9 Ma (Streck et al., 2015; Coble and Mahood, 2016; Benson and Mahood, 2016; Henry et al., 2017). These ages are from rhyolites of the Lake Owyhee volcanic field and periphery, from the Dinner Creek Tuff, and also from as far north as near Baker City (Streck et al., 2015). Strawberry rhyolites were largely unknown until recently and thus were neither included as an area of significant rhyolite volcanism nor as one of the “earliest” mid-Miocene rhyolite centers related to Columbia River Basalt volcanism, despite the K-Ar age of 17.3 ± 0.36 Ma reported by Robyn (1977). Our currently oldest age on rhyolites of the Strawberry Volcanics is 16.2 Ma (Table 1), which indicates that rhyolite activity at Strawberry Mountain indeed started at a time when Columbia River Basalt Group volcanism was ongoing (Jarboe et al., 2010; Barry et al., 2013; Camp et al., 2013, 2017). For this reason, Strawberry rhyolites also need to be included among the earliest mid-Miocene rhyolite centers that could be viewed as “plume-head”–related rhyolites. Thus, the emerging picture is that mid-Miocene rhyolite activity in eastern Oregon (east of ~119°W) started up between 16.5 and 16 Ma across a wide area. The area is bounded by the following towns: Baker City in the north, Ontario in the east, McDermitt in the south, Buchanan in the west, and John Day in the northwest (Fig. 3).

Strawberry rhyolites range from I-type to A-type rhyolites, similar to other mid-Miocene eastern Oregon rhyolites (Fig. 5; Streck, 2014). Figure 13 is a comparison of trace elements between other mid-Miocene rhyolites and Strawberry rhyolites. At low Zr (ppm) concentrations (<300 ppm), the Strawberry rhyolites have similar TiO₂ and FeO contents (wt%) and Nb and Ba (ppm) contents as those from the High Rock caldera complex (Coble and Mahood, 2016) and the McDermitt caldera (Henry et al., 2017; see Fig. 13). The Strawberry rhyolites that have high Zr (ppm) concentrations (>300) also are similar to samples of the Dinner Creek Tuff (Streck, 2014), Lake Owyhee volcanic field (Benson and Mahood, 2016), High Rock caldera complex (Coble and Mahood, 2016), and the McDermitt caldera (Henry et al., 2017) in TiO₂, FeO, Nb and Ba (ppm) contents (Fig. 13).

Models for rhyolites associated with the Columbia River Basalt Group are highly debated but, as elsewhere, are dominated by two different scenarios. In one, rhyolites were generated by partial melting of the crust (Clemens and Wall, 1984; Munksgaard, 1984; Pichavant et al., 1988a, 1988b; Gunnarsson et al., 1998; Smith et al., 2003); the second is an origin through fractional crystallization from mafic magmas (Michael, 1984; Bacon and Druitt, 1988; Mahood and Halliday, 1988; Hildreth, 1991; DePaolo et al., 1992; Hildreth and Fierstein, 2000; Lindsay et al., 2001; Clemens, 2003). Variants of the partial melting model include degrees of differentiation and/or mixing following melting of the crust. In contrast, variants of the fractional...
crystallization model involve variations in the initial composition of the parental magma that underwent differentiation (i.e., how mafic and enriched it was) to yield rhyolites. In the case of the Strawberry rhyolites, low HFSE concentrations are key factors to narrow down possible generation scenarios. All rhyolites that have lower or equal low concentrations of Nb and Ta than intermediate or basaltic Strawberry magmas could not be generated via fractional crystallization (Fig. 14). Nb and Ta behave incompatibly throughout the compositional range from basalt to rhyolite. Therefore, differentiation-dominated scenarios would inevitably raise Nb and Ta contents and would lead to concentration levels higher than values observed in the low HFSE rhyolites. The only mineral that could fractionate Nb and Ta is titanite (e.g., Rollinson, 1993), but titanite has not been observed either in andesites or in rhyolites. Furthermore, titanite is only stable in high-fO2 rhyolites and would produce high Nb/Ta values, given that partition coefficients are slightly higher in Ta, which is not seen in our data (Rollinson, 1993). The same constraint could be formulated for the trace elements Zr and Hf, but since zircon is a stable phase in more silicic magmas, it could have lowered Zr and Hf contents during a very late stage. Although a plausible scenario, it is not very likely because other trace-elemental parameters that are typically affected by differentiation processes within the rhyolitic field do not carry a strong late fractionation signal. These parameters include Ba contents and Eu/Eu*; both are still high in most rhyolites, in other words ≥1200 ppm Ba and
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≥0.4 Eu/Eu* (Table 2). This makes a partial melting model to generate many of the Strawberry rhyolites compelling. Isotopic compositions of the rhyolites vary and appear to have multiple sources, likely including pelitic rocks of the Baker terrane and the Cretaceous granodiorites (Table 4).

CONCLUSION

In this paper, we have described the various units of the Strawberry Volcanics and established the timing and duration of eruptions. The following is a summary of volcanic events:

(1) The southernmost silicic centers start erupting at 16.16 ± 0.17 Ma, producing plagioclase-rich, mostly low-silica rhyolite lava flows and lava domes, and ash-flow tuffs. High- and low-silica rhyolitic volcanism continued in this area until 14.62 ± 0.06 Ma and was co-eruptive with other phases of the Strawberry Volcanics. At 15.30 ± 0.10 Ma, the northern rhyolites erupted aphyric, peralkaline, A-type high-silica rhyolites, co-eruptive with the southern rhyolites. Activity continued here until 14.79 ± 0.12 Ma.

(2) Intermediate lavas of calc-alkaline composition began erupting through dikes starting at 15.59 ± 0.36 Ma. This activity continued to the end of the Strawberry Volcanics at 12.52 ± 0.12 Ma.

(3) Intermediate and mafic tholeiitic eruptions started at 15.57 ± 0.16 Ma. Tholeiitic intermediate compositions erupted first, co-erupting with other intermediate and silicic eruptions, and this was followed by eruptions of more mafic composition. These eruptions continued in the same style as the calc-alkaline eruptions until 12.61 ± 0.06 Ma.

We show that the intermediate and mafic eruptions of the Strawberry Volcanics co-erupted in part with the main phase of the Columbia River Basalt Group from an area surrounded by dike swarms producing Columbia River Basalt Group lavas. The mafic magmas of the Strawberry Volcanics share petrochemical signatures with lavas of the Columbia River Basalt Group, therefore strongly suggesting Columbia River Basalt Group lavas and Strawberry Volcanics had a similar petrotectonic origin. Specifically, mafic lavas of the Strawberry Volcanics are most similar in trace-element chemistry to the Steens Basalt and indicated some overlap in radiogenic isotope ratios with the Picture Gorge Basalt, but they also define their own isotopic characteristics. Toward higher silica contents, intermediate magmas of the Strawberry Volcanics appear to be increasingly a product of open-system differentiation (assimilation and fractional crystallization and magma mixing) processes that causes their compositional trends.

Our new ages on previously little known Strawberry rhyolites indicate they erupted during the height of the rhyolite flare-up coincident with Columbia River Basalt Group volcanism. These rhyolites are not fractionates of the mafic or intermediate lavas of the Strawberry Volcanics or Columbia River Basalt Group magmas, but instead appear to have been generated by partial melting of the crust. Comparison with other mid-Miocene rhyolites of Oregon that are associated with flood basalt volcanism indicates many rhyolites of the Strawberry Volcanics are less enriched in certain typically incompatibly behaving trace elements, yet also show significant compositional overlap particularly those that have A-type characteristics, which typify rhyolitic products of the Yellowstone–Snake River Plain hotspot.

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