The Littlefield Rhyolite and associated mafic lavas: Bimodal volcanism of the Columbia River magmatic province, with constraints on age and storage sites of Grande Ronde Basalt magmas

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ABSTRACT

We present data that distinguishes the long-known Littlefield Rhyolite of eastern Oregon (northwestern United States) into two distinct, voluminous, Snake River-type, high-temperature rhyolite lava packages that erupted in short sequence over <100 k.y., with minimum volumes of 100 and 150 km³ respectively, contemporaneous with flood basalt volcanism of the Grande Ronde Basalt phase of the Columbia River Basalt Group. Contemporaneity of rhyolites with flood basalts is exceptionally demonstrated within the Malheur Gorge by intercalated mafic units belonging to the Grande Ronde Basalt that are stratigraphically constrained by underlying and overlying Littlefield Rhyolite flows, and the underlying Dinner Creek Tuff (unit 1). Our new ages of 16.11 Ma and 16.02 Ma for the lower and upper Littlefield Rhyolite, respectively, provide a narrow age constraint on the controversial lower age of Grande Ronde Basalt volcanism. Petrological data on local, intercalated Fe-rich andesitic (icelanditic) lavas provide further evidence for coeval existence of rhyolitic and mafic magmas, and additionally provide location evidence for storage sites of Grande Ronde Basalt magmas. Based on these data in addition to similar data on the nearby Dinner Creek Tuff rhyolite center, as well as the locations of other rhyolite centers that fall within the same period of intense rhyolite volcanism of ca. 16.1 Ma, we infer that Grande Ronde Basalt crustal magma reservoirs were widespread in this area of eastern Oregon. We further infer that the main eruptions of stored flood basalt magmas followed the magmas’ lateral transport from these reservoirs to the well-known dike swarms located at the periphery of the rhyolite distribution area where local eruptions of rhyolites are notably absent. Our study highlights the interplay of mafic and crustally derived rhyolite magmas, with implications for other continental flood basalt provinces that are less well preserved than the Columbia River Basalt province.

INTRODUCTION

During the middle Miocene, voluminous tholeiitic flood basalts of the Columbia River Basalt Group (CRBG) erupted from fissures in eastern Oregon, eastern Washington, and western Idaho (northwestern United States; Reidel et al., 1989; Camp et al., 2003, 2017; Camp and Ross, 2009). The onset of flood basalt volcanism is currently placed at 16.8 Ma (Camp et al., 2013; Barry et al., 2013). Widespread eruptions of rhyolite tuffs and lavas from vents in eastern Oregon, northern Nevada, and southwestern Idaho accompanied the most voluminous phase of CRBG volcanism (e.g., Coble and Mahood, 2012; Streck et al., 2015; Ferns et al., 2017; Henry et al., 2017) (Fig. 1). While numerous causes have been proposed, many researchers currently favor that impingement of a mantle plume associated with the Yellowstone hotspot generated this enormous magmatic pulse (e.g., Pierce and Morgan, 2009, and references therein). Although the basaltic component of the bimodal magmatic activity of the CRBG has received considerable attention, the silicic phase has until recently received considerably less attention (Cummings et al., 2000; Coble and Mahood, 2012; Streck et al., 2015; Mahood and Benson, 2016; Henry et al., 2017; Webb, 2017). The greater Malheur Gorge area of eastern Oregon (Fig. 2) contains important intercalated stratigraphy of main-phase CRBG lavas that have been geochemically and petrographically correlated with the Steens, Imnaha, and Grande Ronde Basalts (Binger, 1997; Lees, 1994; Camp et al., 2003; Hooper et al., 2002), and recently with Picture Gorge Basalt lavas (Cahoon and Streck, 2013). Throughout the Malheur Gorge, units that erupted in the north (Imnaha and Grande Ronde Basalts) and northwest (Picture Gorge Basalt) interfinger with lavas that erupted in the south (Steens Basalt), providing the stratigraphic basis for including the Steens Basalt into the CRBG as the oldest unit (V. Camp, 2016, personal commun.). The Malheur Gorge area is also one of the few...
Figure 1. Regional overview map of southeast Oregon (northwestern United States) showing rhyolites of this study in relation to other mid-Miocene rhyolites and mid-Miocene mafic lavas of the Columbia River Basalt Group (CRBG). Mapped units are as follows: LFR—undifferentiated Littlefield Rhyolite; rCM—rhyolite of Cottonwood Mountain, including rhyolite of Bully Creek canyon; MMr—middle Miocene rhyolites; CRBG—Columbia River Basalt Group. Dashed polygon encompasses the Oregon-Idaho graben (OIG), after Cummings et al. (2000); 87Sr/86Sr lines of 0.704 and 0.706 are from Pierce and Morgan (2009) and demarcate relatively younger accreted terranes to the west and relatively older cratonic crust to the east. Inset shows map extent and schematic location of major CRBG dike swarms that erupted main-phase CRBG lavas as follows: S—Steens dike swarm; M—Monument dike swarm; CJ—Chief Joseph dike swarm. Compiled geological mapping database is from the Oregon Department of Geology and Mineral Industries (Ma et al., 2009). Map datum and projection are North American Datum of 1983 (NAD83), Oregon Statewide Lambert.
Figure 2. Overview map showing the extent of major stratigraphic units exposed in the Malheur Gorge (eastern Oregon). Stratigraphic units, from youngest to oldest, are as follows: LFR—undifferentiated Littlefield Rhyolite; HCB—Hunter Creek Basalt; rCM—rhyolite of Cottonwood Mountain, including rhyolite of Bully Creek canyon; DIT—Dinner Creek Tuff (unit 1); bMG—basalt of Malheur Gorge; Tr—stratigraphically isolated units that Kittleman et al. (1965) originally mapped as belonging to the Littlefield Rhyolite. Regional features are as follows: AC—Alder Creek canyon; BC—Bully Creek canyon; PC—Pole Creek; CM—Cottonwood Mountain; LR—Littlefield Ranch; MG—Malheur Gorge. Vent locations are as follows: VB—Hunter Creek Basalt vents; VR—lower Littlefield Rhyolite and rhyolite of Cottonwood Mountain vents. Mapping below latitude 44°N is from a compiled geological mapping database from the Oregon Department of Geology and Mineral Industries (Ma et al., 2009); above 44°N, from unpublished mapping by James Evans (1994, personal commun.), digitized by Mark Ferns. Map datum and projection are North American Datum of 1983 (NAD83), Oregon Statewide Lambert.
Stratigraphic transects were performed at three areas of interest distributed within the mapped areal extent of the Littlefield Rhyolite. The primary transects were performed within the eastern extent of the Malheur Gorge, at the historical settlement of Namorf, where mid-Miocene volcanic stratigraphy is spectacularly exposed. Additional transects were performed toward the northern and southern mapped extents of the Littlefield Rhyolite. The northern transects were performed across a relatively broad geographical area north of the Malheur Gorge and southwest of the historical town of Westfall. The southern transect was performed at Alder Creek (Fig. 2).

A total of 57 samples of Littlefield Rhyolite units collected in the field were analyzed at Portland State University (Portland, Oregon) using a BRUKER Tracer IV-SD portable X-ray fluorescence (XRF) spectrometer (pXRF), which allowed for rapid and widespread identification of individual Littlefield Rhyolite flow units by exploiting distinct differences in Zr and Nb concentrations (see below). For details of pXRF calibrations, see Steiner et al. (2017). This allowed the identity of all sampled outcrops to be determined after each session of fieldwork, which in turn provided constant feedback to field observations, improving our understanding of the stratigraphy and distribution of these two Littlefield Rhyolite units. A subset of these samples was selected for XRF and inductively coupled plasma–mass spectrometry (ICP-MS) analysis.

Bulk rock compositions of select samples were acquired for better characterization and comparison of different units identified in the transects. Major and trace element compositions of 56 bulk samples, including a subset of Littlefield Rhyolite samples, were determined by XRF and by ICP-MS at the Washington State University GeoAnalytical Laboratory (Pullman, Washington) (Hooper et al., 1993; Knaack et al., 1994; Johnson et al., 1999).

Polished petrographic thin sections were prepared from a subset of the collected samples and analyzed using a petrographic microscope. Backscattered electron imagery and preliminary major element compositions of feldspar, pyroxene, and titanomagnetite phenocrysts, glass (groundmass), andapatite were acquired using a Zeiss Sigma VP scanning electron microscope (SEM) at Portland State University.

Major element compositions of plagioclase feldspars and pyroxenes were determined with the CAMECA SX100 electron microprobe housed at Oregon State University (OSU; Corvallis, Oregon), which was operated remotely from Portland State University. We employed an accelerating voltage of 15 kV, a focused beam of 2 μm diameter, and a beam current of 15 nA for plagioclase and 30 nA for pyroxene. For plagioclase, peak and background (expressed in the following as peak/background) counting was done as follows (in seconds): 10/5 for Na, Al, and Si; 20/10 for Ca; and 40/20 for K, Fe, and Mg. For pyroxene, count times were as follows: 10/5 for Na, Mg, Si, Fe, and Ca; and 30/15 for Al, Ti, Mn, Cr, and Ni. Natural mineral standards were used for calibration and were monitored during each session.

Single-crystal laser-fusion ⁴⁰Ar/³⁹Ar ages were determined on plagioclase separates from two samples of the upper Littlefield Rhyolite, three samples of the lower Littlefield Rhyolite, one sample of the rhyolite of Bully Creek canyon (Brooks and O’Brien, 1992a, 1992b, and one sample of the rhyolite of Cottonwood Mountain (Cummings et al., 2000; Hooper et al., 2002). Analyses were performed at the New Mexico Geochronology Research Laboratory at New Mexico Tech (Socorro, New Mexico). Plagioclase feldspar separates were prepared from ground and sieved rhyolite samples by hand picking followed by etching in dilute hydrofluoric acid. Particular attention was paid to select plagioclase crystals with minimal amounts of melt inclusions. Plagioclase separates and Fish Canyon Tuff sanidine monitors were irradiated in vacuo in machined aluminum trays at the U.S. Geological Survey TRIGA reactor (Denver, Colorado). Following initial experiments that yielded flat age spectra for plagioclase from representative samples, between 13 and 16 single plagioclase feldspar crystals from each sample were fused by CO₂ laser and analyzed using a Thermo Argus VI mass spectrometer in multicollector mode. Weighted-mean ages were calculated for each sample after eliminating analyses with low-precision or ages significantly outside the main population of ages (i.e., ages forming distinct peaks when displayed on an age-probability diagram). Quoted uncertainties include uncertainties in J-factor determination but exclude uncertainties in decay constants and monitor age. All resulting age calculations are determined relative to the Fish Canyon Tuff sanidine monitor age of 28.201 Ma (Jourdan and Renne, 2007; Kuiper et al., 2008).

### GEOLOGICAL SETTING AND BACKGROUND

**Main phase of the Columbia River Basalt Group (CRBG)**

The main phase of the Columbia River Basalt Group (CRBG), including the Steens, Imnaha, Picture Gorge, and Grande Ronde Basalts, erupted between ca. 16.8 and ca. 15.9 Ma from a series of dikes associated with the Steens, Chief Joseph, and Monument dike swarms (Fig. 1) (Camp and Ross, 2004; Camp et al., 2003; Wolff et al., 2008; Barry et al., 2013; Wolf and Ramos, 2013; Mahood and Benson, 2016). Volumetric estimates for main-phase CRBG units are 31,800 km³ for the Steens Basalt, 11,000 km³ for the Imnaha Basalt, 2500 km³ for the Picture Gorge Basalt, and 150,000 km³ for the Grande Ronde Basalt (Reidel and Tolan, 2013; Reidel et al., 2013; Camp et al., 2013). The current understanding is that main-phase CRBG volcanism began in southeastern Oregon with fissure eruptions of the lower Steens Basalt, followed by the more-voluminous upper Steens Basalt. Upper Steens Basalt eruptions were contemporaneous with the
initial outpourings of the Imnaha Basalt from the Chief Joseph dike swarm in the north (Barry et al., 2013; Camp and Ross, 2004; Camp et al., 2003; Wolff and Ramos, 2008; Ramos et al., 2013). The Grande Ronde Basalt began to erupt from the Chief Joseph dike swarm after the onset of Imnaha eruptions, while the Picture Gorge Basalt, commonly viewed as being coeval to the Grande Ronde Basalt, erupted from the Monument dike swarm to the southwest of the Chief Joseph dike swarm (Fig. 1). Details of the timing of all main-phase CRBG units are still a matter of ongoing research. For recent examples, Barry et al. (2013) suggested that the Grande Ronde Basalt erupted between 16.0 and 15.6 Ma, while slightly older ages of ca. 16.5–15.9 Ma have been argued for by Jarboe et al. (2010), Baksi (2013), and Wolff and Ramos (2013).

Compositionally and texturally, the Grande Ronde Basalt stands out relative to the rest of the main-phase CRBG units by being mostly fine-grained, aphyric, iron-rich basaltic andesites and andesites. Other CRBG units are plagioclase-phyric basalts, while lavas of the Steens Basalt are noteworthy for carrying plagioclase megacrysts. Subtle major and trace elemental and isotopic variations between major CRBG units have been explained by varying amounts of melts derived from (1) deeper oceanic island basalt-like mantle sources, (2) shallower, mid-ocean-ridge basalt-like sources, and (3) sources variably overprinted by subduction fluids, with the addition of some crustal overprint (Carlson, 1984; Carlson and Hart, 1988; Carlson et al., 1981; Camp, 2013; Camp and Ross, 2004; Wolff et al., 2008; Ramos and Wolff, 2013). Credible models for evolved, trace element– and isotopically enriched magmas of the Grande Ronde Basalt involve open-system processing of Imnaha-type basalt magmas with old cratonic crust (Wolff et al., 2008) along the western craton boundary which runs north-south along the Oregon-Idaho state border, as defined by the 0.704 and 0.706 $^{187}$Sr/$^{186}$Sr line (Fig. 1) (e.g., Pierce and Morgan, 2009).

**Malheur Gorge: Crossroad for Main-Stage CRBG Units**

The Malheur Gorge is located approximately midway between the Steens and Chief Joseph dike swarms. Mafic lavas correlative with the Steens, Imnaha, Picture Gorge, and Grande Ronde Basalts of the CRBG are intercalated in the gorge.

Many of the units of Malheur Gorge were first named by Kittleman et al. (1965, 1967), who grouped and divided units based on physical characteristics and perceived stratigraphic position. The basal unit in the gorge is the "unnamed igneous complex" of Kittleman et al. (1965), now more commonly referred to as the basalt of Malheur Gorge (Evans, 1990), and is part of the western tholeiitic lavas of Ferns et al. (1993a). The basalt of Malheur Gorge is as much as 1100 m thick in the Malheur Gorge (Binger, 1997; Cummings et al., 2003; Hooper et al., 2002). Lees (1994) divided the basalt of Malheur Gorge into two formations based upon petrography and geochemistry. The Pole Creek formation is the lowest exposed series of stratigraphic units and is made up of notably coarse-grained and plagioclase-phyric (20%-40%) basalt lavas. Units in the lower part of the Pole Creek formation have been correlated with lavas of the Steens Basalt (Binger, 1997; Lees, 1994; Hooper et al., 2002; Camp et al., 2003) and typically weather to form dark-brown, coarse-grained, sand- and gravel-sized colluvium. Lavas in the upper part of the Pole Creek formation are moderately to sparsely phytic, and more closely resemble lavas of the Imnaha Basalt (Lees, 1994; Camp et al., 2003). The Birch Creek formation (Lees, 1994) overlies the Pole Creek formation and is made up of lavas that are typically aphyric and commonly contain interstitial glass. Birch Creek lavas are correlative with lavas of the Grande Ronde Basalt (Binger, 1997; Lees, 1994; Hooper et al., 2002; Camp et al., 2003; Reidel and Tolan, 2013). Work by Binger (1997) and Lees (1994) suggests that the basalt of Malheur Gorge stratigraphy is dominated by Pole Creek lavas in the south, while Birch Creek lavas become more prevalent to the north and northeast, in the areas surrounding Brogan, Oregon (Figs. 1, 2).

Kittleman et al. (1965, 1967) described a bimodal sequence of units that overlie their "unnamed igneous complex" along the Malheur River that are collectively included in the Hog Creek formation of Lees (1994). The base of the Hog Creek formation is defined by the Dinner Creek Tuff (Lees, 1994; Hooper et al., 2002). This widespread rhyolite ignimbrite is overlain by the blocky-weathering Hunter Creek Basalt, which is in turn overlain by the large-volume rhyolite lavas of the Littlefield Rhyolite (Kittleman et al., 1965, 1967; Lees, 1994; Cummings et al., 2000; Hooper et al., 2002). The Hunter Creek Basalt is made up of Fe-rich basaltic-andesite to andesite lavas and proximal vent deposits correlative with the Grande Ronde Basalt (cf. Reidel and Tolan, 2013), representing the late-stage eruption of tholeiitic volcanism within the Malheur Gorge area (Ferns and McClauwthy, 2013; Webb, 2017). Lavas of the Birch Creek formation and the Hunter Creek Basalt are distinguished solely stratigraphically, with the Hunter Creek Basalt overliving and Birch Creek lavas underlyng the Dinner Creek Tuff, which is a well-defined, laterally continuous, cliff-forming marker bed.

**LITTLEFIELD RHYOLITE**

Prior Work

The Littlefield Rhyolite is a series of large, areally extensive rhyolite lavas that resemble the large rhyolite lavas of the Snake River Plain (central Idaho) as described by Bonnichsen and Kaufman (1987). It is named after Littlefield Ranch (historical), located in the vicinity of the designated type section near the far southern extent of this widely distributed unit (Fig. 2) (Kittleman et al., 1965, 1967). Kittleman et al. (1967) included a number of rhyolite exposures within their Littlefield Rhyolite that have since been mapped as separate units, including the rhyolite at Stockade Mountain, rhyolite at Star Mountain, rhyolite of Dry Creek, and the upper ferrolatite lavas of Ferns et al. (1993a, 1993b) (Fig. 2).

Kittleman et al. (1965, 1967) described the Littlefield Rhyolite to be stratigraphically above the Hunter Creek Basalt. Later workers discovered a lithologically similar and voluminous rhyolite beneath the Hunter Creek Basalt at...
Cottonwood Mountain (Fig. 2) (Brooks and O’Brien, 1992a, 1992b; mapping by J. Evans, 1994, personal commun., Hope Butte and Swede Flat 7.5’ quadrangles). Rhyolite lavas beneath the Hunter Creek Basalt have been referred to as the rhyolite of Bully Creek canyon (Brooks and O’Brien, 1992a, 1992b), the rhyolite of Cottonwood Mountain (Evans, 1994, unpublished mapping, Hope Butte and Swede Flat 7.5’ quadrangles; Hooper et al., 2002; Cummings et al., 2000), and as the lower Littlefield Rhyolite (Lees, 1994). The underlying rhyolite was included under the same name as the Littlefield Rhyolite because both rhyolites are lithologically indistinguishable and the lower unit had been misidentified and mapped as Littlefield Rhyolite in many areas. Rhyolite exposures at Cottonwood Mountain are geographically isolated from units exposed in the south by basin development and the deposition of younger units (Fig. 2), and this disconnection has led to different stratigraphic assessments of the rhyolite of Cottonwood Mountain. Hooper et al. (2002) described the rhyolite of Cottonwood Mountain as typically underlying, though sometimes overlying, the Hunter Creek Basalt. In contrast, Cummings et al. (2000) described the rhyolite of Cottonwood Mountain as only underlying the Hunter Creek Basalt. While upper and lower rhyolite units are physically indistinguishable, they are geochemically distinct (e.g., Ferns and O’Brien, 1992a; Lees, 1994) (see below). The difficulties in distinguishing the upper and lower Littlefield Rhyolites were likely aggravated by the fact that the two units were not observed together in sequence with the Hunter Creek Basalt intercalated (see Stratigraphy of the Littlefield Rhyolite and Intercalated Units below).

Ages of Littlefield Rhyolite Units

Age analyses performed by prior investigators collectively present a broad range of ages (14.6–17.9 Ma) with large analytical errors and that are stratigraphically inconsistent (Fig. 3; Table 5 in Supplemental Material) (Fiebelkorn et al., 1983; Lees, 1994; Hooper et al., 2002; Hess, 2014). This was likely influenced by the relatively low concentrations of potassium within plagioclase feldspar phenocrysts, and possibly due to excess 40Ar captured in melt inclusions in plagioclase, which are abundant in both rhyolites. New dates presented below indicate that the upper and lower Littlefield Rhyolites were likely younger than the ages of prior studies and 40Ar/39Ar data of samples of this study, respectively.

In this study, single-crystal 40Ar/39Ar ages were obtained from three samples of the lower Littlefield Rhyolite, two samples of the upper Littlefield Rhyolite, and one sample each of the rhyolite of Cottonwood Mountain and the rhyolite of Bully Creek canyon. Except for one sample of the lower Littlefield Rhyolite that was dated twice producing unacceptable large errors of ±170 k.y. and ±190 k.y., all other ages were sufficiently precise, with 2σ errors of ±40 k.y. or ±60 k.y. (Table 1; Fig. 3; Table S2 [footnote 1]).

Samples of the lower Littlefield Rhyolite yielded ages of 16.09 ± 0.04 Ma and 16.13 ± 0.08 Ma, and samples of the upper Littlefield Rhyolite yielded ages of 15.98 ± 0.06 Ma and 16.05 ± 0.04 Ma. Based on the average value of each pair of dates, our preferred ages are 16.11 Ma for the lower Littlefield Rhyolite and 16.02 Ma for the upper Littlefield Rhyolite (Fig. 3). This is significantly older than the age of 15.3 Ma recommended by Hooper et al. (2002) and settles the uncertainty on the age of the Littlefield Rhyolite units that has persisted until now, causing others to speculate whether they are even late Miocene in age (cf. Benson and Mahood, 2016). The new ages of the lower and upper Littlefield Rhyolite at historical Namorf are consistent both with the age of the underlying Dinner Creek Tuff (unit 1; Streck et al., 2015), which has been dated at 16.15 Ma and with our radiometric ages of 16.10 ± 0.06 Ma and 16.17 ± 0.06 Ma for lower Littlefield Rhyolite exposures along Bully Creek canyon and on Cottonwood Mountain, respectively.

Petrology of the Littlefield Rhyolite Units

The lower and upper Littlefield Rhyolite units are lithologically indistinguishable in the field and can be subdivided only by stratigraphic position in the Malheur Gorge (see below). On the other hand, major and trace elemental compositions, isotopic and petrographic data, and 40Ar/39Ar ages are distinct between these rhyolites. Both rhyolites are low-silica, Fe-rich rhyolites. Upper Littlefield Rhyolite samples have A-type rhyolite affinities (i.e., Fe-rich pyroxene, high contents of high field strength elements) while samples of lower Littlefield Rhyolite straddle the boundary of A-type and I&S-type silicic magmas, being A-type with regard to Zr concentrations and I&S-type with regard to Zn concentrations (cf. Whalen et al., 1987) (Fig. 4; Table 2; Table S3 [footnote 1]). All samples of both rhyolites fall within a narrow silica range of 71.3–72.6 wt%,
with most clustering at the middle of the range and at nearly the same Al₂O₃ content of ~12.6 wt%. In contrast, there are distinct compositional differences in FeO* (total Fe calculated as FeO) and TiO₂, and subtle differences in MgO, CaO, P₂O₅, and possibly Na₂O (Fig. 4; Table 2; Table S3 [footnote 1]). The upper Littlefield Rhyolite is relatively higher in Fe, Ti, and Na but relatively lower in Mg, Ca, and P. A notable feature of both rhyolites is the high FeO* of ~4 wt% in the lower Littlefield Rhyolite and ~5 wt% in the upper Littlefield Rhyolite, which are on the high end of FeO* for Oregon rhyolites as well as rhyolites from the neighboring Snake River Plain–Yellowstone association (cf. Streck, 2014). Trace element contents are distinctly different between the two rhyolites, with the upper Littlefield Rhyolite being generally more enriched, with the exception of Rb, U, Th, and Sr (Figs. 4, 5; Table S3 [footnote 1]). In addition, the lower and upper Littlefield Rhyolite have distinct isotopic compositions (e.g., ⁸⁷Sr/⁸⁶Sr of 0.7070 and 0.7055, respectively) (Lees, 1994; Hess, 2014).

Both the lower and upper Littlefield Rhyolite units are porphyritic, containing ~8%–12% phenocrysts or glomerocrysts composed of plagioclase feldspar, a single pyroxene, microphenocrysts or inclusions of Fe-Ti oxides, and accessory apatite. Plagioclase phenocrysts range from subhedral to euhedral, and many contain abundant melt inclusions. Pyroxene and Fe-Ti oxides are mostly euhedral. Plagioclase feldspar in the lower Littlefield Rhyolite is andesine (Or₅–₄₃, An₁₆–₃₉, Ab₇₁–₆₆) (Fig. 6; Table S4 [footnote 1]), while in the upper Littlefield Rhyolite it is oligoclase (Or₁₄–₃₉, An₁₆–₃₉, Ab₇₁–₆₆) (Fig. 6; Table S4 [footnote 1]). Pyroxene compositions are also distinct; the lower Littlefield Rhyolite contains pigeonite (Wo₁₁–₄₅, En₅₃–₇₃, Fs₅₃–₇₃) (Wo—wollastonite, En—enstatite, and Fs—ferrosilite component), while the upper Littlefield Rhyolite contains Fe-rich augite (ferrohedenbergite) (Wo₄₃–₄₇, En₆₃–₇₃, Fs₅₂–₅₇) (Fig. 6; Table S4 [footnote 1]). Fe-Ti oxide compositions are overlapping, but the upper Littlefield Rhyolite contains ilmenite in addition to titanomagnetite, while the lower Littlefield Rhyolite contains titanomagnetites that are mostly overlapping in the lower Ti–higher Fe range. The lower Littlefield Rhyolite in the Malheur Gorge shows a close correspondence with rhyolite lavas exposed at Cottonwood Mountain and in Bully Creek canyon to the northwest (Figs. 4, 5).

### Lithology of the Littlefield Rhyolite Units

Upper and lower flow sections of the lower Littlefield Rhyolite form a glassy, black to dark-gray vitrophyre, encasing dense, lithoidal, platy-jointed cores with sparse, flow-aligned bands of ~1-cm-diameter spherulites. Atypical exposures observed within the Malheur Gorge display steeply ramped and chaotic flow banding. Uncommonly observed masses of rhyolite autobrecchia do not clearly appear to coincide with flow contacts. Weathered surfaces of dense, devitrified rhyolite are brownish red to brownish orange in color. Incipiently devitrified petrographic samples in some cases contain microspherulites that do not appear to be aligned along flow bands.

Lower flow sections of the upper Littlefield Rhyolite alternate between thick zones of basal autobrecchia, glassy to incipiently devitrified columnar jointed rhyolite, or glassy basal vitrophyre that forms a sharper lower contact. Autobrecchia is composed of equant clasts of vitrophyre within a fine-grained matrix. Light-gray devitrified rhyolite is commonly observed as talus, uncommonly preserved in outcrop, and is presumably remnants from the now-eroded upper section of the flow. Weathered surfaces of lithoidal rhyolite are typically brick red to brownish red in color. In contrast to the lower Littlefield Rhyolite, flow banding is rarely observed.

### Table 1. Summary of Single-Crystal Laser-Fusion ⁴⁰Ar/³⁹Ar Ages of Littlefield Rhyolite Units

| Sample number | Age type | Age (Ma) | Error (±2σ) (m.y.) | n/ν | MSWD |
|---------------|----------|----------|-------------------|-----|------|
| Upper Littlefield Rhyolite | | | | | |
| BW-14-40 | Weighted mean | 15.98 | ± 0.06 | 13/14 | 4.5 |
| BW-14-67 | Weighted mean | 16.05 | ± 0.04 | 12/15 | 4.4 |
| Lower Littlefield Rhyolite | | | | | |
| BW-14-29 | Weighted mean | 16.09 | ± 0.04 | 14/14 | 1.8 |
| BW-14-19 | Weighted mean | 16.13 | ± 0.06 | 13/15 | 2.5 |
| BW-13-02 | Plateau | 15.95 | ± 0.17 | 5/5 | 0.6 |
| BW-13-02 | Weighted mean | 16.10 | ± 0.19 | 8/8 | 0.4 |
| Rhyolite of Bully Creek Canyon | | | | | |
| EJ-12-17 | Weighted mean | 16.10 | ± 0.06 | 13/17 | 6.4 |
| Rhyolite of Cottonwood Mountain | | | | | |
| MS-12-31 | Weighted mean | 16.17 | ± 0.06 | 12/16 | 3.2 |

Notes: Material is plagioclase for all samples. n/ν—number of analyses used to compute age / total analyses; MSWD—mean square of weighted deviates.
*Sample is from a lower Littlefield Rhyolite dike.
†Repeat analysis. Both analyses were rejected because of the large uncertainty relative to other analyzed samples.
HUNTER CREEK BASALT AND BIRCH CREEK LAVAS

The Hunter Creek Basalt is distinguished from the Birch Creek formation solely on the basis of stratigraphic position. The Hunter Creek Basalt overlies, and Birch Creek lavas immediately underlie, the Dinner Creek Tuff.

Hunter Creek Basalt

Lavas of the Hunter Creek Basalt are typically hackly jointed, black or dark-gray, tholeiitic basaltic andesite (~54–56 wt% SiO₂), rather than true basalts as the formal name suggests (Fig. 7). Hunter Creek lavas commonly weather to form steep, talus-dominated slopes. Although uncommonly observed, some Hunter Creek Basalt lavas are icelandites (i.e., Fe-rich andesite; cf. Carmichael, 1964), with SiO₂ concentrations >57–63 wt% (Cummings et al., 2000; Ferns and Mcclaughey, 2013). The aphanitic-textured groundmass of the Hunter Creek Basalt is composed of feldspar, magnetite, clinopyroxene, and interstitial glass. Phenocrysts are exceedingly rare, but if present consist of small plagioclase (<1 mm) and clinopyroxene (<0.2 mm) crystals.

Hunter Creek Basalt samples show small major element variations over the SiO₂ range from 54 to 57 wt%. The most evident changes are that FeO* decreases from above 13.6 to 10.7 wt%, MgO decreases from 3.5 to 3.0 wt%, and K₂O increases from 1.5 to 2.3 wt%. CaO and P₂O₅ indicate a smaller decrease and increase, respectively. The remaining major elements indicate nearly constant concentrations, with Al₂O₃ at ~13.6 wt%, TiO₂ at ~2.4 wt%, and Na₂O at ~3.3 wt%. Trace element compositions of basaltic andesitic Hunter Creek Basalt appear to be constrained within a limited range of compositions throughout the distribution of the unit, without a strong correlation with SiO₂ or other major element contents. One notable exception is Ba, which ranges between ~600 and 1300 ppm and generally increases with silica and decreases with FeO.

Icelandite of Alder Creek

The relative distribution of basaltic andesite versus icelandite within the Hunter Creek Basalt stratigraphic interval is currently not known, but icelandites are more rarely observed. One icelandite that occurs in the southern outcrop area of the Littlefield Rhyolite, within Alder Creek canyon, is here informally designated the icelandite of Alder Creek (Fig. 2). The icelandite of Alder Creek (~63 wt% SiO₂; Table 2; Table S3 [footnote 1]) lies within the Hunter Creek Basalt stratigraphic interval in the southern transect in Alder Creek canyon. The icelandite lava is markedly platy jointed and is geochemically distinct from samples of common Hunter Creek Basalt (Figs. 4, 7), with uniformly higher concentrations of incompatible trace elements and lower concentrations of compatible elements like Sr, P, and Ti (Fig. 7). On the other hand, the icelandite of Alder Creek is petrographically similar to common Hunter Creek Basalt lavas, having aphanitic texture containing groundmass feldspar, magnetite, clinopyroxene, and interstitial glass with occasional phenocrysts of plagioclase (~3 mm).
### TABLE 2. AVERAGE COMPOSITIONS (±1σ) OF RHYOLITE AND GRANDE RONDE BASALT LAVAS AND RESULTS OF MIXING MODEL

| Rhyolite of Cottonwood |   |   |   |   |   |   |
|------------------------|---|---|---|---|---|---|
| Unit name              | n = 5 | n = 14 | n = 8 | n = 4 | n = 13 | n = 2 |
| XRF (wt%)              | SiO₂ | TiO₂ | Al₂O₃ | MnO | MgO | CaO |
| Na₂O                  | 0.713 ± 0.006 | 0.705 ± 0.007 | 0.409 ± 0.019 | 0.17 ± 0.09 | 0.43 ± 0.03 | 0.163 ± 0.07 |
| K₂O                   | 3.63 ± 0.43 | 4.80 ± 0.12 | 5.19 ± 0.59 | 12.26 ± 0.34 | 3.11 ± 0.01 | 1.47 ± 0.04 |
| P₂O₅                  | 0.083 ± 0.014 | 0.084 ± 0.011 | 0.117 ± 0.023 | 0.214 ± 0.027 | 0.210 ± 0.001 | 0.17 ± 0.003 |
| XRF (ppm)             | Ni  | Cr  | Sc  | V | Ti | P |
| Na                    | 3 ± 1 | 2 ± 0 | 12 ± 0 | 14 ± 1 | 18 ± 1 | 8 ± 2 |
| K                     | 1 ± 1 | 3 ± 3 | 7 ± 1 | 2 ± 1 | 18 ± 0 | 2 ± 3 |
| Ca                    | 56.8 ± 0.05 | 65.29 ± 2.64 | 8.14 ± 0.64 | 1.28 ± 0.01 | 3.77 ± 0.10 | 4.3 ± 0.02 |
| Mg                    | 26.14 ± 2.32 | 63.24 ± 2.81 | 17.9 ± 0.06 | 2.60 ± 0.08 | 3.87 ± 0.06 | 1.38 ± 0.04 |
| Fe                    | 30.16 ± 1.07 | 62.59 ± 2.18 | 8.08 ± 0.26 | 1.40 ± 0.11 | 3.98 ± 0.37 | 0.62 ± 0.05 |
| CaO                   | 80.0 ± 0.02 | 80.0 ± 0.02 | 80.0 ± 0.02 | 3.2 ± 0.01 | 3.8 ± 0.01 | 80.0 ± 0.02 |
| MgO                   | 130 ± 5.59 | 161 ± 5.60 | 5.5 ± 0.51 | 0.64 ± 0.05 | 2.0 ± 0.80 | 0.62 ± 0.05 |
| NaO                   | 65 ± 4.75 | 124 ± 4.56 | 6.23 ± 0.28 | 2.31 ± 0.30 | 2.0 ± 0.60 | 9.79 ± 0.03 |
| Al₂O₃                 | 55.9 ± 5.85 | 64.65 ± 5.03 | 24.3 ± 0.15 | 14.39 ± 0.16 | 70.0 ± 0.04 | 70.0 ± 0.04 |
| MnO                   | 172 ± 6.80 | 245 ± 7.03 | 21.0 ± 0.42 | 1.78 ± 0.17 | 2.0 ± 0.80 | 1.78 ± 0.17 |
| CrO₆                  | 7.0 ± 0.10 | 11.2 ± 0.17 | 0.70 ± 0.02 | 0.60 ± 0.02 | 0.62 ± 0.02 | 0.62 ± 0.02 |
| ZnO                   | 3.4 ± 0.18 | 3.6 ± 0.26 | 3.6 ± 0.26 | 1.1 ± 0.02 | 1.1 ± 0.02 | 1.1 ± 0.02 |
| P₂O₅                  | 14.3 ± 0.47 | 24.3 ± 0.54 | 4.4 ± 0.08 | 1.2 ± 0.03 | 1.2 ± 0.03 | 1.2 ± 0.03 |
| XRF (ppm)             | Ni  | Cr  | Sc  | V | Ti | P |
| Na                    | 3 ± 1 | 2 ± 0 | 12 ± 0 | 14 ± 1 | 18 ± 1 | 8 ± 2 |
| K                     | 1 ± 1 | 3 ± 3 | 7 ± 1 | 2 ± 1 | 18 ± 0 | 2 ± 3 |
| Ca                    | 56.8 ± 0.05 | 65.29 ± 2.64 | 8.14 ± 0.64 | 1.28 ± 0.01 | 3.77 ± 0.10 | 4.3 ± 0.02 |
| Mg                    | 26.14 ± 2.32 | 63.24 ± 2.81 | 17.9 ± 0.06 | 2.60 ± 0.08 | 3.87 ± 0.06 | 1.38 ± 0.04 |
| Fe                    | 30.16 ± 1.07 | 62.59 ± 2.18 | 8.08 ± 0.26 | 1.40 ± 0.11 | 3.98 ± 0.37 | 0.62 ± 0.05 |
| CaO                   | 80.0 ± 0.02 | 80.0 ± 0.02 | 80.0 ± 0.02 | 3.2 ± 0.01 | 3.8 ± 0.01 | 80.0 ± 0.02 |
| MgO                   | 130 ± 5.59 | 161 ± 5.60 | 5.5 ± 0.51 | 0.64 ± 0.05 | 2.0 ± 0.80 | 0.62 ± 0.05 |
| NaO                   | 65 ± 4.75 | 124 ± 4.56 | 6.23 ± 0.28 | 2.31 ± 0.30 | 2.0 ± 0.60 | 9.79 ± 0.03 |
| Al₂O₃                 | 55.9 ± 5.85 | 64.65 ± 5.03 | 24.3 ± 0.15 | 14.39 ± 0.16 | 70.0 ± 0.04 | 70.0 ± 0.04 |
| MnO                   | 172 ± 6.80 | 245 ± 7.03 | 21.0 ± 0.42 | 1.78 ± 0.17 | 2.0 ± 0.80 | 1.78 ± 0.17 |
| CrO₆                  | 7.0 ± 0.10 | 11.2 ± 0.17 | 0.70 ± 0.02 | 0.60 ± 0.02 | 0.62 ± 0.02 | 0.62 ± 0.02 |
| ZnO                   | 3.4 ± 0.18 | 3.6 ± 0.26 | 3.6 ± 0.26 | 1.1 ± 0.02 | 1.1 ± 0.02 | 1.1 ± 0.02 |
| P₂O₅                  | 14.3 ± 0.47 | 24.3 ± 0.54 | 4.4 ± 0.08 | 1.2 ± 0.03 | 1.2 ± 0.03 | 1.2 ± 0.03 |

**Note:** XRF—X-ray fluorescence; ICP-MS—inductively coupled plasma—mass spectrometry. Please see the full data table in the Supplemental Material (text footnote 1).

*Total Fe calculated as FeO.

*Includes samples of rhyolite of Bully Creek canyon.
Birch Creek Lavas

Birch Creek formation samples from the Malheur Gorge area are fine grained with virtually no phenocrysts. They are lithologically indistinguishable from the stratigraphically higher Hunter Creek Basalt. Silica ranges between 53.5 wt% and 59 wt% (Fig. 7). Some lavas of the Birch Creek formation are icelanditic, with silica values up to 59 wt%. Major element variations with silica are similar to those of the Hunter Creek Basalt. Trace element contents also strongly overlap with those of the Hunter Creek Basalt (Fig. 7). Birch Creek samples have slightly lower Ba and K concentrations at a given silica content. Regardless, samples of Birch Creek lavas and the Hunter Creek Basalt appear indistinguishable in most geochemical aspects.

STRATIGRAPHY OF THE LITTLEFIELD RHYOLITE AND INTERCALATED UNITS

Primary Transect within the Malheur Gorge

Our primary stratigraphic transect is located at the east end of the Malheur Gorge at the historical settlement of Namorf (Figs. 2, 8; geologic map in the Supplemental Material [footnote 1]). At Namorf, a >300-m-thick stratigraphic section is exposed in cliff faces on both sides of the Malheur River, consisting mostly of rhyolitic with intercalated mafic units. Prior workers mapped
Figure 7. Variation diagrams, primitive mantle normalization plot, and C1 chondrite-normalized rare earth element diagram of samples of Hunter Creek Basalt and Birch Creek formation lavas. *FeO—total Fe calculated as FeO. Primitive mantle composition was taken from Sun and McDonough (1989) and C1 chondritic values from McDonough and Sun (1995).
the stratigraphic sequence as Littlefield Rhyolite lavas separated by a welded tuff from the underlying Hunter Creek Basalt (Kittleman et al., 1965; Ferns and O’Brien, 1992a). The underlying ignimbrite has since been identified as the Dinner Creek Tuff (unit 1) with a radiometric age of 16.16 ± 0.02 Ma. (Streck et al., 2011; Ferns and McCloudhry, 2013; Streck et al., 2015) (section 1 of Fig. 8). This correlation showed that what had been identified as the Hunter Creek Basalt at the base of the section belonged to the Birch Creek formation.

Figure 8 and the supplemental geology map (footnote 1) illustrate the volcanic stratigraphy of the Namorf location, which is dominated by lower and upper Littlefield Rhyolite lavas. The oldest exposed unit at Namorf is marked by an upper Pole Creek formation lava at the western edge of the transect, overlain by at least three Birch Creek lavas. On the east side at Namorf, only the uppermost Birch Creek formation is exposed, consisting of a pyroclastic unit and a lava (Fig. 8). Birch Creek units are overlain by a poorly exposed tuffaceous unit and the Dinner Creek Tuff, which in turn are overlain by the lower Littlefield Rhyolite. The base of the lower Littlefield Rhyolite is glassy and grades over the distance of ~1 m from porous, microbrecciated rhyolite to dense, glassy rhyolite. Although the base and upper contact of the lower Littlefield Rhyolite can be observed at Namorf, not a single section contains both, and thus total unit thickness cannot be determined. Most sections record the central to upper flow sections of the lower Littlefield Rhyolite. The thickest section is ~130 m and serves as a minimum thickness estimate. The uppermost part of the rhyolite flow is vitric and vesiculated, and commonly becomes microbrecciated approaching the upper contact without signs of weathering, suggesting rapid coverage by other units.

The lower Littlefield Rhyolite at Namorf is directly overlain by a ~45-m-thick sequence comprising seven definable units (Figs. 8, 9A, 10A, 10B). Four of these are tholeiitic and herein correlated with the Hunter Creek Basalt. The lowest unit is a laterally widespread mafic lava ~15 m thick. This basal Hunter Creek lava is overlain by a spatter deposit that thickens laterally from <2 m on the south side of the river (section 2 of Fig. 8; Figs. 9A, 10A, 10B) to ~30 m to the north across the Malheur River (section 3 of Fig. 8; Figs. 10C, 10D) where it is strongly agglutinated. The mafic spatter deposit is overlain by a thin (~0.5 m), moderately lithified, epiclastic tuff (Figs. 10A, 10B).
Figure 9. Outcrops at Namorf (Oregon).

(A) Stratigraphy of section 2 (Fig. 8) at Namorf (HCB—Hunter Creek Basalt). Photograph is looking southwest across the Malheur River at ~280 m of relief (441093 mE, 4848022 mN; datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N).

(B) Platy-jointed lower Littlefield Rhyolite on the north side of the Malheur River. Photograph is looking southwest at ~2 m tall outcropping (440052 mE, 4848486 mN; datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N).

(C) Columnar-jointed upper Littlefield Rhyolite at section 2 (Fig. 8). Photograph is looking east from section 2 (Fig. 8) (440860 mE, 4846868 mN; datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). Columns are ~30 cm in diameter.

(D) Auto breccia of the lower Littlefield Rhyolite. Photograph is looking east (440425 mE, 4847672 mN; datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). Note walking stick shown for scale.
Figure 10. Outcrops at Namorf (Oregon). (A) Lateral view along north-facing area between section 1 (left side) to section 2 (right side) (Fig. 8). Photograph is facing east from section 2 (Fig. 8) transect (440859 mE, 4846869 mN: datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). For scale, the Hunter Creek Basalt spatter is ~2 m thick. (B) Middle part of section 2 (Fig. 8). Photograph is facing southeast from section 2 (Fig. 8) transect (440890 mE, 4846857 mN: datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). For scale, the Hunter Creek Basalt spatter is ~2 m thick. (C) View of section 3 (Fig. 8), taken from the southwest. Photograph is facing northeast showing ~110 m of relief (440135 mE, 4847507 mN: datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). (D) Photograph of proximal-vent facies, consisting of welded spatter deposits (agglutinate) of Hunter Creek Basalt upsection from the lower Littlefield Rhyolite and underlying epiclastic tuff; inset shows a closeup of basaltic andesitic Hunter Creek Basalt agglutinate (at hammer) (composed of dense black glass) with a sharp contact with overlying devitrified agglutinate (above hammer). LFR—Littlefield Rhyolite; HCB—Hunter Creek Basalt. Photograph is facing north (440493 mE, 4847594 mN: datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). Note hammer for scale.
On the south side of the Malheur River, the epiclastic tuff is directly overlain by two additional Hunter Creek lavas, herein referred to as the middle and the upper Hunter Creek Basalt lavas. The ~10-m-thick middle Hunter Creek unit is marked by a red baked zone and is directly overlain by the ~17-m-thick upper Hunter Creek unit. The uppermost Hunter Creek lava is overlain by a thin (~2 m) sequence of surge deposits consisting of thinly bedded, lithified sand-sized particles with rare angular, cobble- to boulder-sized fragments. The top of the Hunter Creek section at Namorf is marked by discontinuous lenses of an indurated dacitic tuff. It appears that this dacite was a continuous layer before it got disturbed by the emplacement of the overlying upper Littlefield Rhyolite. Analytical data and discussion of the epiclastic unit and dacitic tuff can be found in Webb (2017).

The stacked sequence of multiple Hunter Creek Basalt units is locally confined to a ~2-km-wide section along the south side of the Malheur River at Namorf. Commonly, only a single unit is present over the wide areal extent of the Hunter Creek Basalt stratigraphic interval (Fig. 2). The upper two Hunter Creek Basalt lavas presumably represent smaller-volume eruptions from a proximal vent. On the north side of the Malheur River at Namorf (section 3 of Fig. 8), the lower Littlefield Rhyolite is overlain by the lower Hunter Creek lava followed by the thickest deposit of Hunter Creek spatter which is strongly agglutinated, forming dense vitrophyre in places (Fig. 10D). Here, the spatter deposit is interpreted to be closest to the vent as deposits are as thick as 30 m with beds dipping 20°–30° in an easterly direction (Fig. 10D). The agglutinated spatter deposits are overlain by the epiclastic tuff and, farther northward, by the upper Littlefield Rhyolite (Fig. 10D).

The upper Littlefield Rhyolite is the youngest stratigraphic unit exposed along the Namorf transect, displaying variable thicknesses of basal auto-breccia, capped by dense, glassy to incipiently devitrified, columnar-jointed rhyolite, transitioning to lithoidal, platy-jointed rhyolite (Figs. 9, 10). Recognizable flow-top features are not preserved at the upper surface of the upper Littlefield Rhyolite exposures here, indicating that the original flow package was >150 m thick.

Geological mapping by prior workers at Namorf showed ~300-m-thick undifferentiated Littlefield Rhyolite overlying the Hunter Creek Basalt, which had supported interpretations that the Littlefield Rhyolite had discontinuously “ponded” against the northwestern shoulder of the Oregon-Idaho graben (Cummings et al., 2000). This in turn had led to the implication that a period of volcanic subsidence had occurred following the emplacement of the lower mafic stratigraphic sequence and prior to emplacement of the Littlefield Rhyolite, during which time the older mafic sequence underwent normal offset faulting associated with graben development (Cummings et al., 2000). This, combined with a history of unreliable dating of the Littlefield Rhyolite, had raised doubts as to whether the Littlefield Rhyolite might be significantly younger than the underlying units (Benson and Mahood, 2016). The stratigraphy exposed at Namorf reveals no such ponding or significant disconformity of Littlefield Rhyolite units, but rather shows that the entire stratigraphic sequence underwent normal offset faulting throughout and following its emplacement. Nevertheless, the areal distribution of the lower Littlefield Rhyolite appears to have been constrained roughly along the north-trending Rhyolite fault zone, as it is not present in the stratigraphy to the west.

Mafic and Silicic Vents Observed at or near the Namorf Site

A lower Littlefield Rhyolite feeder dike follows a steeply dipping, N-NW–striking normal fault west of Namorf (Fig. 2) (Evans, 1990; Ferns and Mc-Claughry, 2013; Ferns et al., 2017, their figure 27). This dike lies within and follows the north-trending Hog Creek fault zone of Evans (1990). Geochemistry and 40Ar/39Ar dating (sample BW-14-29a, Fig. 3; Table S3 [footnote 1]) show that the dike is a lower Littlefield Rhyolite dike.

The thickest exposure of glassy Hunter Creek agglutinated spatter (vent facies) overlies the lower Littlefield Rhyolite on the north side of the Malheur River at the west end of the Namorf site (see above), in close proximity to the lower Littlefield Rhyolite dike. This localized accumulation of dipping, graded, and welded spatter is interpreted to be a proximal vent deposit.

Near the east end of the Namorf traverse, Birch Creek lavas crop out directly at highway level (section 1 of Fig. 8). Here the Birch Creek formation is composed of a lower, proximal vent–facies pyroclastic unit overlain by a lava, separated by a sharp interface. The lower pyroclastic unit is composed of coarse clast-supported blocks and vesiculated bombs as much as 30 cm in diameter. The lower pyroclastic unit in the Birch Creek formation here is also interpreted to be a proximal vent deposit.

Northern Stratigraphic Transect

The northern transect covers a relatively widely distributed area located ~10–15 km north of Namorf (Fig. 2). Stratigraphy here is exposed in a number of parallel north-south–striking faults leading to east-dipping (~5°) rotated blocks. Fault blocks here are eroding to form steep, rounded, talus-dominated hills with only limited outcrops. General stratigraphy in the tilted fault blocks consists of the lower Littlefield Rhyolite, the Hunter Creek Basalt, and the upper Littlefield Rhyolite. Softer tuffaceous sedimentary deposits in the overlying mid- to late Miocene Bull Creek Formation (not to be confused with the similar named rhyolite of Bull Creek canyon) are locally preserved within the eroded half-grabens, unconformably overlying the Littlefield Rhyolite–Hunter Creek Basalt stratigraphic package. At the very northern extent of the upper Littlefield Rhyolite, the package of units was relatively uplifted by normal faulting. Erosion led to the removal of the upper Littlefield Rhyolite and the exposure of the underlying Hunter Creek Basalt. The upper vitrophyre of the lower Littlefield Rhyolite crops out within the primary drainages where erosion of the overlying Hunter Creek Basalt has been relatively more pronounced. Thinner interbeds between units, as documented for the Namorf location, were not observed, though Brooks and O’Brien (1992b) and Evans and Binger (1999a, 1999b) described what they referred to as tuffaceous sandstone overlying Hunter Creek...
Basalt in two locations nearby. Without a thin section, the epiclastic tuff would likely be identified as being tuffaceous sandstone or tuffaceous siltstone (cf. Webb, 2017). Farther to the east, south of Cottonwood Mountain, deposits mapped by Brooks and O’Brien (1992b) form elongate, north-trending ridges marked by steeply dipping hydroclastic surge deposits interpreted by Ferns and McClaughey (2013) and Ferns et al. (2017) to be proximal vent deposits of the Hunter Creek Basalt (Fig. 2).

Southern Stratigraphic Transect in Alder Creek Canyon

The Alder Creek traverse is located ~23 km southwest of Namorf (Fig. 2). The sequence here consists of the Dinner Creek Tuff (unit 1), the Hunter Creek Basalt, a thin indurated dacite tuff, and the upper Littlefield Rhyolite (Fig. 2). The lower Littlefield Rhyolite is absent from Alder Creek canyon. Unit 1 of the Dinner Creek Tuff at Alder Creek is relatively thin (1.5 m) and only incipiently welded. Hunter Creek Basalt lava above the Dinner Creek Tuff is a high-silica variant herein referred to as the icelandite of Alder Creek (~63 wt% SiO2). The base of the overlying upper Littlefield Rhyolite is underlain by a thin, moderately welded dacitic tuff. The upper Littlefield Rhyolite is in turn overlain by the Wildcat Creek Welded Ash-Flow Tuff of Kittleman et al. (1965, 1967), a 15.5 Ma rhyolite-dacite tuff (Sales et al., 2017). The icelandite of Alder Creek occupies the same stratigraphic position as the Hunter Creek Basalt (Kittleman et al., 1965, 1967; Evans and Binger, 1999c) and seemingly provides evidence of mixing of upper Littlefield Rhyolite and Hunter Creek Basalt magmas (see below and cf. Figs. 4, 7).

Based on petrology and geochemistry data, the dacite tuff that underlies the upper Littlefield Rhyolite at Alder Creek correlates with the dacite tuff beneath the upper Littlefield Rhyolite at Namorf (Webb, 2017). In contrast to Namorf exposure, the dacite tuff at Alder Creek has not been disturbed by emplacement of the upper Littlefield Rhyolite and occurs as a thin layer through Alder Creek canyon at the base of the rhyolite. The contact between the dacite tuff and overlying upper Littlefield Rhyolite lava at Alder Creek is sharp and horizontal (Fig. 11). No basal breccia of the upper Littlefield Rhyolite occurs anywhere in Alder Creek canyon. Instead, throughout the area, the glassy base of the upper Littlefield Rhyolite directly overlies the dacite tuff unit.

DISCUSSION

Connection between the Lower Littlefield Rhyolite and the Rhyolite of Cottonwood Mountain

Data and observations presented herein show that the older lower Littlefield Rhyolite exposed at Namorf is correlative with the widespread rhyolite lava to the northeast that has been mapped as the rhyolite of Cottonwood Mountain (Evans, 1994, unpublished mapping, Hope Butte and Swede Flat 75′ quadrangles) and the rhyolite of Bully Creek canyon (Brooks and O’Brien, 1992a, 1992b) (Fig. 2). It is unclear, however, whether the lower Littlefield Rhyolite erupted from a singular vent or from a series of widely dispersed vents tapping a homogenous, contiguous magma reservoir.

Soechemistry and petrography strongly argue that these geographically separated rhyolite exposures are sampling the same magma batch and are thus the same eruptive unit. Major and trace element data of widely separated samples of these older rhyolites are indistinguishable and notably homogenous (Figs. 4, 5, 6; Table 2). Phenocryst abundances are similar, and compositions of plagioclase and pyroxene overlap (Fig. 6). Furthermore, 87Sr/86Sr ratios are the same, if rounded to the fourth decimal (0.7066 for plagioclase and 0.7067 for groundmass) (Hess, 2014). And finally, the ages of rhyolite from Cottonwood Mountain samples of this study are 16.10 Ma and 16.17 Ma, similar to ages of 16.09 Ma and 16.13 Ma for lower Littlefield Rhyolite samples from the Malheur Gorge (Table 1; Fig. 3).

The roughly north-trending dike of lower Littlefield Rhyolite exposed just west of the Namorf transect (Fig. 2) marks one known conduit for the lower Littlefield Rhyolite. A second conduit is marked by a rhyolite dike at Bully Creek, south of Cottonwood Mountain (Fig. 2) (Ferns and McClaughey, 2013; Ferns et al., 2017). The two dikes follow narrow north-south–trending features that are ~30 km apart from one another, which suggests that the lower Littlefield Rhyolite unit was homogeneous magma that erupted from multiple, widely dispersed vents to form a rhyolite flow field.

Flow Unit Area, Volume, and Vents of Snake River–Type Littlefield “Flood” Rhyolites

The Littlefield Rhyolite consists of two distinct, widespread, silicic lavas. Both rhyolite lavas have features that are atypical with respect to flow dimensions of the majority of rhyolite lavas worldwide but are strikingly similar to a limited number of Miocene rhyolite lavas found within the Snake River Plain of central Idaho (Bonnichsen and Kaufman, 1987; Branney et al., 2008).

The areal distribution of the lower Littlefield Rhyolite, based on existing outcrops, encompasses ~800 km², while the larger upper Littlefield Rhyolite has an areal extent of ~1000 km² (Fig. 2C). Observed maximal thicknesses from exposures near Namorf are 130 m for the lower Littlefield and 250 m for the upper Littlefield Rhyolite. Thicknesses >150 m are commonly observed for the upper Littlefield Rhyolite in Malheur Gorge. Near the southern extent in Alder Creek canyon, it reaches thicknesses of >80 m (Fig. 11). Eruption volumes for the lower and upper Littlefield Rhyolite are estimated at ~100 km³ and ~150 km³ respectively.

Aspect ratios (ratio of thickness to areal extent) of both Littlefield Rhyolite lavas are on the order of 10⁻²; which are similar to the aspect ratios of Snake River–type rhyolite lavas (Bonnichsen and Kaufman, 1987; Branney et al., 2008) (Fig. 12). The widespread areal extents and low aspect ratios would also be consistent with both Littlefield Rhyolite units being rheomorphic ignimbrites, and this has prompted the search for features indicative of a pyroclastic origin, but such features have yet to be found. The basal contact of the lower Littlefield Rhyolite at the Namorf site forms a basal vitrophyre overlying the Dinner Creek Tuff.
Figure 11. Outcrops at Alder Creek (Oregon). (A) Upper Littlefield Rhyolite overlying the icelandite of Alder Creek (concealed). Photograph is facing south (432986 mE, 4827111 mN: datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). Note the single-lane dirt track along Alder Creek for scale; ~100 m of relief is shown rising above it. (B) Base of the upper Littlefield Rhyolite overlying the orange, indurated, dacite tuff. Photograph is facing northeast (433132 mE, 4826053 mN: datum and projection North American Datum of 1983 [NAD83], Universal Transverse Mercator [UTM] zone 11N). Note hammer for scale. (C) Close-up of B showing sharp contact between upper Littlefield Rhyolite and dacite tuff. Note hammer for scale.
A thin section of a porous sample from the very base of this rhyolite shows a microbrecciated texture consistent with being a rhyolitic lava. None of our thin sections show any bubble-wall shard textures (Fig. 12D). In addition, no vitriclastic textures were observed in any of the other thin sections of samples collected from the lower or upper Littlefield Rhyolite. On the other hand, the physical appearance of the Littlefield Rhyolite units closely resembles that of nearby Snake River–type rhyolite lavas with recognizable flow lobes, sharp contacts with undisturbed substrata, basal vitrophyre and carapace breccias as well as flow folds, and in the case of the upper Littlefield Rhyolite, columnar jointing (Figs. 9–12).

The widespread areal dispersion and low aspect ratios of both Littlefield Rhyolite flow units are rarely observed in rhyolite lavas but are common features of the high-temperature Snake River–type silicic lavas that define the Yellowstone hot-spot track through Idaho. Littlefield Rhyolite lavas likely also erupted at high temperatures with relatively low effective viscosities that allowed them to be widely dispersed over distances of tens of kilometers. Distribution of linear feeder dikes separated by >30 km point to nearly simultaneous eruptions of a common magma from multiple vents. This is significant because vents for similarly widespread Snake River–type rhyolites are typically concealed, and to assume that Snake River–type rhyolites were fed by a single vent, analogous to typical smaller-scale eruptions of rhyolite domes and coulees, may be unwarranted. Multiple vents reduce the rheological difficulties of transporting rhyolite lava over large distances, and this scenario may be a contributing factor to the widespread extents of these types of rhyolite lavas. Duffield and Dalrymple (1990) proposed a multiple vent source and tapping of a contiguous reservoir for the Taylor Creek Rhyolite (southwestern New Mexico), forming a series of compositionally similar, but otherwise typical, non-extensive rhyolite domes. Such a scenario, though at a much larger scale, as is suggested for the lower Littlefield Rhyolite, may significantly contribute to the widespread dispersion of these types of rhyolite lavas, in combination with their higher eruption temperatures. Using abundance of zirconium in both units combined with a lack of zircon suggests eruption temperatures in excess of 900 °C.

Correlation of Mafic Lavas of the Malheur Gorge with the Columbia River Basalt Group

Columbia River Basalt Group (CRBG) formations of the Columbia Basin north of the Malheur Gorge have been subdivided on the basis of magnetic polarity, geochemistry, and stratigraphic position into formally and informally named members (e.g., Reidel and Tolan, 2013). On the other hand, the Picture
Gorge Basalt and Steens Basalt have only been divided into informally named members representing eruptive packages (Bailey, 1989; Camp et al., 2013). Intercalated stratigraphy of tholeiitic lavas within the Malheur Gorge remain stratigraphically isolated from CRBG stratigraphy of the Columbia Basin as well as from Steens Mountain in the south.

Geochemical data acquired by prior investigators in the Malheur Gorge have been largely limited to XRF data, which have supported the division of the basalt of Malheur Gorge into three distinct formations and the correlation of these with main-phase CRBG units (Ferns et al., 1993a; Lees, 1994; Binger, 1997; Cummings et al., 2000; Hooper et al., 2002; Camp et al., 2003). Our data (including ICP-MS data) further support the work of prior investigators. Data on Birch Creek and Hunter Creek Basalt lavas collected mostly from the Namorf area plot on the more-enriched end of data from the Grande Ronde Basalt (Fig. 13A). This corroborates that both units represent Grande Ronde Basalt volcanism. Data from our sample of upper Pole Creek lavas from the west side of Namorf correlate well with those of the Imnaha Basalt (Fig. 13B). Farther west in the Malheur Gorge along Pole Creek (Fig. 2), Jarboe et al. (2010) acquired a $^{40}$Ar/$^{39}$Ar age date of 16.49 ± 0.09 Ma from a sample near the base of the section that they identify as being a sample of lower Pole Creek formation (Steens Basalt). The bulk geochemical composition of this unit (E. Cahoon, 2017, personal commun., their sample CAH16-061A) indeed corresponds well with it being Steens Basalt.

Besides the overall correlation of main-phase CRBG units with mafic units of the Malheur Gorge, another question concerns which Grande Ronde Basalt units are represented by Hunter Creek Basalt and Birch Creek formation lavas. Reidel and Tolan (2013) correlated Hunter Creek lavas with the Wapshilla Ridge Member of the Grande Ronde Basalt (R2 magnetostratigraphic unit), based on the similarity in geochemistry between these units (Fig. 14). Birch Creek lavas are considered to be a distinct (informal) Grande Ronde member between the Buckhorn Springs and Teepee Butte members (R1 magnetostratigraphic unit) (Reidel and Tolan, 2013). Based on our new ages on the lower and upper Littlefield Rhyolite, the age of the Hunter Creek Basalt is constrained to a narrow age window of 16.02 Ma to 16.11 Ma (Fig. 15). This in turn demands that the Hunter Creek Basalt is age equivalent to units of the N2 magnetostratigraphic unit of the Grande Ronde Basalt and not units of the R2 magnetostratigraphic unit. Compositonally however, no available data from any N2 unit match up as well with the composition of the Hunter Creek Basalt sample as the data from the Wapshilla Ridge Member (Fig. 14).

Geochemical data presented herein indicate that lavas in the upper part of the Birch Creek formation closely resemble the Hunter Creek Basalt in the Malheur Gorge. Birch Creek formation lavas exposed immediately beneath the Dinner Creek Tuff (unit 1) at Namorf would be somewhat older than 16.16 Ma. Given the close stratigraphic connection and compositional similarities of Hunter Creek Basalt and Birch Creek lavas, it is likely that both units are part of the same magmatic sequence. Consequently, the upper Birch Creek formation may also be time equivalent to the N2 magnetostratigraphic unit of the Grande Ronde Basalt. (During the final editing process, we used a flux gate magnetometer and measured three blocks of a Birch Creek lava at Namorf. Two of three blocks yielded a normal magnetic orientation while the third block was inconclusive.)

Another important aspect is the consideration of eruption sites of mafic lavas. There is now good evidence for local eruption sites of Hunter Creek Basalt and Birch Creek lavas, as demonstrated in this study and by Ferns and McClaughry (2013). An observation in favor of the argument that some Birch Creek lavas may be laterally continuous with recognized Grande Ronde stratigraphy in the Weiser embayment (west-central Idaho) is that the number of units on passing north-northeast away from the Malheur Gorge increases, which suggests that Birch Creek lavas erupted in the north and flowed south.

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Figure 13. Primitive mantle normalization plots of Grande Ronde Basalt ($n = 40$) and Imnaha Basalt ($n = 52$) (data of Wolff et al., 2008) and samples of Hunter Creek Basalt, Birch Creek formation lavas, and an upper Pole Creek formation lava.
ward into the greater Malheur Gorge area (Lees, 1994). Irrespectively, it is clear that Hunter Creek Basalt and Birch Creek lavas are geochemically similar to late-stage eruptions of Grande Ronde Basalt, as samples plot near the most-enriched Grande Ronde Basalt compositions (Fig. 13A).

**Petrogenetic Link between Grande Ronde Basalt and Littlefield Rhyolite Magmas: Icelandite of Alder Creek**

As presented above, a local variant of what is mapped as Hunter Creek Basalt (i.e., late-stage Grande Ronde Basalt) is Icelandite, occurring at Alder Creek canyon. Similar Icelandites occur near Neal Hot Springs on the eastern side of Bully Creek canyon (Edwards, 2013; Ferns and McCloughry, 2013; Ferns et al., 2017). Close relationships between the silicic and mafic magmas are indicated by the close spatial and temporal association between the Littlefield Rhyolite and Hunter Creek Basalt. A possible petrogenetic scenario explored below, in the context of the Icelandite of Alder Creek, is that mixing between Littlefield Rhyolite and tholeiitic Hunter Creek Basalt magmas yielded the Icelandite magma.

Rhyolite-mafic magma mixing ratio was determined by performing a linear regression of the ratios of trace element concentrations between the upper Littlefield Rhyolite, Icelandite of Alder Creek, and the more commonly observed tholeiitic Hunter Creek Basalt (inset of Fig. 16). The derived mixing ratio was then used to calculate the trace and major element composition of the mixture (Fig. 16; Table 2). The calculated trace and major element composition resulting from magma mixing closely matches the composition of samples of the Icelandite of Alder Creek (Fig. 16; Table 2). Results of the mixing model are shown only for using the upper Littlefield Rhyolite as the silicic end member (Fig. 16; Table 2) because the model using the lower Littlefield Rhyolite did not produce a satisfactory match to the Icelandite of Alder Creek. In contrast, modeling results for the upper Littlefield Rhyolite are remarkable. Twenty-one incompatible and all major element concentrations of the calculated mixture provide an excellent match to the actual concentrations observed in natural lava samples. This suggests that the Icelandite of Alder Creek magma resulted from mixing of the upper Littlefield Rhyolite and Hunter Creek Basalt magmas. This is not to suggest that this indicates that all Icelandites of the Columbia River province were generated by mixing; others may follow a fractional crystallization liquid line of descent. The implication of this petrogenetic relationship between the upper Littlefield Rhyolite and Grande Ronde Basalt magmas, as recorded by the Hunter Creek Basalt, are explored in the next section.
Grande Ronde Basalt Reservoirs of the Greater Malheur River Gorge Area

In order for the magma mixing to have occurred to make the icelandite of Alder Creek, late-stage Grande Ronde and upper Littlefield Rhyolite magmas needed to have been in close contact, which ties a Grande Ronde magma storage site to within the greater Malheur Gorge area. Similarly, Streck et al. (2015) identified a basaltic-andesitic component in a late Dinner Creek Tuff unit that is comagmatic with Dinner Creek Tuff rhyolites. This basaltic-andesite component also has a Grande Ronde Basalt composition, which infers that rhyolite reservoirs of the Dinner Creek Tuff were underlain by Grande Ronde Basalt-type magmas as well (Streck et al., 2015). The existence of Grande Ronde Basalt reservoirs underlying the greater Malheur Gorge area is supported by the fact that venting sites for such magmas occur near Namorf, as determined in this study (Fig. 10), and around the town of Westfall to the north (Fig. 2) (Ferns and McClauthry, 2013). Furthermore, icelandites erupted after rhyolites in the presumed source area of the Dinner Creek Tuff (Cruz, 2017). Our findings support that Grande Ronde Basalt crustal reservoirs existed in the greater Malheur Gorge area, as was initially postulated by Wolff et al. (2008).

Wolff et al. (2008) proposed a centralized reservoir area of main-stage CRBG magmas located in the general area of the Malheur Gorge that straddles the accreted terrane–North American craton boundary as demarcated by the 0.704 $^{87}\text{Sr}/^{86}\text{Sr}$ line into Idaho (cf. Pierce and Morgan, 2009) (Fig. 1). They showed that more-radiogenic Grande Ronde Basalt magmas can be generated by contamination of more-primitive Imnaha Basalt magmas by radiogenic crust such as that which exists east of the 0.704 line. Recent isotope data by Hess (2014), but also by Lees (1994), have shown that the lower and upper Littlefield Rhyolite have relatively high $^{87}\text{Sr}/^{86}\text{Sr}$ ratios ($^{87}\text{Sr}/^{86}\text{Sr} > 0.706$). The $^{87}\text{Sr}/^{86}\text{Sr}$ ratios for the Littlefield Rhyolite units are notable given their locations west of the currently recognized cratonic margin. This opens the possibility that more-radiogenic isotopic signatures in Grande Ronde magmas are due, in part, to involvement of radiogenic crust located west of the 0.704 line, from which Littlefield Rhyolite magmas themselves are possibly derived.

**Littlefield Rhyolite in Context of Other Co–Flood Basalt Rhyolite Volcanism of the Columbia River Basalt Province and Implications for the Storage and Transport of Flood Basalt Magmas**

Most continental flood basalt provinces are associated with silicic volcanism (Bryan et al., 2002). However, strong uplift, erosion, and tectonic dismembering in older provinces make it difficult to evaluate precisely the significance of rhyolite centers for information on arrival, storage, and dispersal of flood basalt magma in the crust (Bryan et al., 2002). Our study is contributing to further the understanding of interactions between mafic flood basalt magmas supplied from the mantle and rhyolites generated in the crust of the Columbia River Basalt province—the youngest and best-preserved flood basalt province that exists—and their consequences for time-space-composition patterns of volcanism of the province.

In addition to recent data on the Dinner Creek Tuff (Streck et al., 2015), we provide critical data showing that voluminous rhyolite volcanism contemporaneous with main-stage flood basalt volcanism of the CRBG (i.e., ≥16 Ma) occurred not only along the Oregon-Nevada state boundary on transitional or cratonic crust (e.g., Brueseke et al., 2008; Coble and Mahood, 2012, 2016; Henry et al., 2017), but also ~200 km farther north where the crust is made up of accreted terranes (cf. Figs. 1, 17) (cf. Leeman et al., 1992; Pierce and Morgan, 2009). Lava flows of Littlefield Rhyolite are essentially coeval with several other explosive and effusive rhyolite centers around the Malheur Gorge, with ages equal to or slightly older than 16 Ma (Hess, 2014; Streck et al., 2015) (Fig. 17). Our broader work to provide new and improved ages, distributions, and volumes of these eruptive centers is ongoing, but it is clear that the Dinner Creek Tuff (unit 1) and the lavas of the Littlefield Rhyolite are the most voluminous units. The combined volume of both Littlefield Rhyolite lavas and the Dinner Creek Tuff (unit 1) is ~420 km$^3$, erupting over a period of ~100 k.y. In comparison, this amounts to ~60% of the total volume of rhyolite magma that erupted over a period of ~1 m.y. from the High Rock caldera (northwestern Nevada) (Coble and Mahood, 2016), which is considered to be a prolific rhyolitic center. This suggests that although cumulative rhyolite volumes in areas made up of accreted terrane crust are generally lower than in areas composed...
of more fertile transitional or cratonic crust (cf. Sinigoi et al., 2011; Coble and Mahood, 2012), there can be pulses of rhyolite volcanism associated with relatively more mafic terrane crust that are intense and voluminous.

One important aspect of rhyolite volcanism within large flood basalt provinces is that rhyolite centers may provide better information than the basalts about the location of crustal basalt reservoirs that are implicated in the generation of these rhyolite magmas (Hildreth, 1981; Johnson, 1991). It is now recognized that flood basalt magmas can be transported and then erupt at significant distances from where they were stored in the crust or supplied from the mantle (Ernst et al., 1995; Ernst and Buchan, 1997; Hastie et al., 2014; Airoldi et al., 2016). In the case of the CRBG province, there must have been widespread crustal reservoirs during the most voluminous phase, the Grande Ronde Basalt, in which Grande Ronde magmas could have undergone evolution to their evolved basaltic andesitic composition (Wolff et al., 2008). The wide distribution of rhyolites with ages equal to or older than 16 Ma (e.g., Bonnichsen et al., 2008; Coble and Mahood, 2016; Streck et al., 2017) from near Baker City, Oregon, in the north to the Oregon-Idaho state border (Figs. 1, 17) suggests storage of flood basalt magmas at depth over a large portion of eastern Oregon and neighboring areas. However, currently the only direct petrological evidence for the locations of crustal storage sites of flood basalt magmas near rhyolites is documented for the Dinner Creek Tuff (Streck et al., 2015) and now for the Littlefield Rhyolite (e.g., Fig. 16), both of which are located within the greater Malheur Gorge area (Fig. 17). We suggest that relatively thinner and more mafic terrane crust facilitates this. On the other hand, the areas of the main dike swarms of the CRBG are void of local rhyolite centers. It appears that there, mafic magmas in dikes caused partial melting only to produce silicic melt along the margins of dikes (Petcovic and Dufek, 2005). We interpret this to indicate that magma transport and residence in these areas was too brief or too shallow to initiate generation and volcanism of silicic magmas (Annen and Sparks, 2002) and not that the crust was insufficiently fertile (Coble and Mahood, 2016). With regards to the Grande Ronde Basalt, this implies that evolved magmas were laterally transported to their main erupting sites, the Chief Joseph dike swarm, rather than being supplied from greater depths (Fig. 17).
CONCLUSIONS

The lower and upper Littlefield Rhyolite are petrologically distinct, widespread, Snake River–type (high temperature, low aspect ratio) rhyolite lava flow units emplaced at 16.11 Ma and 16.02 Ma, respectively, based on new single-crystal 40Ar/39Ar ages. Observed maximal thicknesses of the lower and upper Littlefield Rhyolite are 150 and 250 m, and distribution areas are ~800 and 1000 km², respectively. Two exposed lower Littlefield Rhyolite venting sites that are 30 km apart suggest that eruption from multiple vents facilitated widespread distribution, and this may be the case for other Snake River–type rhyolite lavas as well.

Detailed stratigraphic data at historical Namorf located at the eastern side of Malheur Gorge reveal a remarkable stratigraphy, with Hunter Creek Basalt and Birch Creek lavas—representing local Grande Ronde Basalt units—underlying and intercalated with rhyolites and recording local venting sites for these Grande Ronde Basalt magmas. The Littlefield Rhyolite units, along with the Dinner Creek Tuff, exemplify the recently recognized bimodal volcanism of the Columbia River flood basalt province along the centrally located Malheur Gorge corridor.

Ages of the upper and lower Littlefield Rhyolite flow units constrain the eruption of the Hunter Creek Basalt to an approximate age span of ~90 k.y., ca. 16.07 Ma. Given the close stratigraphic connection and compositional similarities of Hunter Creek Basalt and Birch Creek lavas, it is likely that flows of Hunter Creek Basalt and Birch Creek lavas directly underneath the Dinner Creek Tuff are part of the same magmatic sequence. Consequently, the Hunter Creek Basalt and upper Birch Creek formation are likely equivalent to the N2 magnetostратigraphic unit of the Grande Ronde Basalt.

A compositional variant of the Hunter Creek Basalt is icelandite that is lithologically similar to common basaltic andesites of the Hunter Creek Basalt. One such icelandite is found near the southern extent of the upper Littlefield Rhyolite. Geochemical modeling with this icelandite strongly suggests that it results from mixing of Hunter Creek Basalt and upper Littlefield Rhyolite magmas, thereby tying a Grande Ronde magma storage site to within the greater Malheur Gorge area and indicating contemporaneity of rhyolitic and Grande Ronde magma reservoirs.

Our study highlights the close spatial and age relationship of mafic magmas of the Grande Ronde Basalt with voluminous lavas of the Littlefield Rhyolite generated from accreted terrane crust at the youngest known continental flood basalt province. It highlights that understanding the timing and distribution of rhyolites provides important complementary data on the temporal evolution of arrival, dispersion, and storage of mafic magmas of continental flood basalt provinces.

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