Large, persistent rhyolitic magma reservoirs above Columbia River Basalt storage sites: The Dinner Creek Tuff Eruptive Center, eastern Oregon

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ABSTRACT

Our understanding of the Yellowstone hotspot and its connection to flood basalts of the Columbia River Basalt province (western and northwestern USA) has grown tremendously over the past decades since the model was first proposed in 1972. Despite strong support for a plume origin of the entire Yellowstone–Columbia River Basalt magmatic province, new non-plume models have emerged to explain early flood basalt volcanism. Unresolved issues of the early flood basalt stage include the location of crustal magma reservoirs feeding these voluminous eruptions and to what extent these were associated with contemporaneous silicic reservoirs.

This study focuses on the newly defined ca. 16–15 Ma Dinner Creek Tuff Eruptive Center that overlaps in time and space with flood basalt volcanism of the Columbia River Basalt Group. New work on distribution, lithologic variations, geochemical compositions, and eruption ages indicate that the extensive Dinner Creek Welded Tuff (herein Dinner Creek Tuff) and associated mapped and unmapped ignimbrites include a minimum of 4 discrete cooling units that spread over an area of ~25,000 km². Widespread fallout deposits in northeast Oregon and the neighboring states of Nevada, Idaho, and Washington have now been compositionally correlated with the redefined Dinner Creek Tuff. Compositional coherence of the ignimbrite sheets and fallout deposits indicate a common source, herein referred to as the Dinner Creek Tuff eruptive center (DITEC).

Cognate mafic components (glass shards, pumice shards, and mafic globules) that range from dacite (~68 wt% SiO₂) to Fe-rich basaltic andesite (~56 wt% SiO₂) in composition are found in two of the cooling units. Major and trace element compositions of the more mafic components match the compositions of nearby Grande Ronde Basalt flows and dikes. Compositional similarities between cognate mafic components and Grande Ronde Basalt flows are direct evidence for coeval mafic and silicic magmatism linking DITEC and Grande Ronde Basalt eruptions. Furthermore, finding Grande Ronde Basalt magmas as coeruptive component in Dinner Creek Tuff suggests that Grande Ronde Basalt magmas were stored beneath Dinner Creek Tuff rhyolites, thereby providing the first direct evidence for the location of a storage site of Columbia River Basalt magmas. Shallow crustal rhyolitic reservoirs active during ca. 16–15 Ma that yielded tuffs of the DITEC and other surrounding contemporaneous and widespread rhyolites of the area likely imposed control on timing and place of eruption of Columbia River Basalt Group lava flows.

INTRODUCTION

Our understanding of the Columbia River Basalt province (western USA) and its likely connection to the Yellowstone hotspot has grown tremendously since the Yellowstone volcanic field was first proposed as the present location of a continental hotspot (e.g., Morgan, 1972). There is now strong support for a plume origin for the entire Yellowstone hotspot track and flood basalts of the Columbia River Basalt Group (CRBG) (Pierce and Morgan, 2009). However, the decades-long controversy as to whether this large igneous province (LIP) is due to the arrival of a deep mantle plume continues, and new non-plume models for the origin of the CRBG have been proposed (e.g., Liu and Stegman, 2012). Age-progressive rhyolites of the Snake River Plain starting at the oldest centers in southeastern Oregon–northern Nevada have been a centerpiece in the model to connect flood basalts to the present location of the Yellowstone hotspot (e.g., Pierce and Morgan, 1992, 2009). However, rhyolites have not been associated much with the flood basalt stage until recently (Coble and Mahood, 2012; Streck and Ferns, 2012).

We report our first results on one of the main silicic systems, the Dinner Creek Tuff eruptive center (DITEC), which was active near the center of flood basalt eruptive sites, where new age dates suggest that activity overlaps with mainstage CRBG activity, and where petrological data suggest tapping and interaction of CRBG magmas during explosive silicic eruptions. The Dinner Creek Welded Tuff was originally defined as a single ignimbrite that erupted from the Castle Rock caldera (Wood, 1976; Rytuba and Vander Meulen, 1991) and was found to extend over an area of ~2000 km² centered along the Malheur River (Haddock, 1967). Our work shows that the original Dinner Creek Welded Tuff and other correlative ignimbrites mapped elsewhere in the same stratigraphic position consist of a minimum of four discrete ignimbrite sheets that we herein name the Dinner Creek Tuff, extending over an area >25,000 km². We further propose that several well-known fallout tuff deposits of Oregon, Nevada, Idaho, and Washington erupted from the same center, active from ca. 16 to ca. 15 Ma. Fallout tuffs either correlate with ignimbrites (cf. Nash and Perkins, 2012) or fall between ignimbrite eruptions. Minor amounts of mafic magmas found in the Dinner Creek Tuff match CRBG magmas and thus provide direct evidence for CRBG flood basalt reservoirs beneath this large and long-lived rhyolitic eruptive center.

METHODS

Major and trace element compositions of bulk tuff and pumices were determined by X-ray fluorescence and by inductively coupled plasma-
Major element composition of glasses and feldspars were determined with the Oregon State University (OSU) Cameca SX100 electron microprobe, which was operated remotely from Portland State University. For analysis of the glass, we employed an accelerating voltage of 15 kV, a beam current of 8 nA, and a defocused beam (10 µm diameter). Peak and background counting was done as follows (in seconds): 10/5 for Na, Al, Si; 20/10 for Ca, Fe, Ti, Mn, P; and 30/15 for S, Cl, and Mg. First and short counting of Na and K was targeted to minimize loss under the electron beam. Natural mineral standards were used for calibration. We monitored our calibration during each session with natural rhyolitic and basaltic glass standards. Analysis conditions were similar for feldspar with the exception of a 15 nA beam current, a more focused beam, and analysis of a smaller range of elements.

Laser ablation ICP-MS analyses of trace element concentrations in glasses were done in the W.M. Keck Collaboratory for Plasma Mass Spectrometry at OSU using a Thermo XSeries II ICP-MS instrument coupled with a Photon Machines G2 ArF Excimer laser ablation system. Analyses using a spot size of mostly 40 µm and pulse rate of 10 Hz were conducted in an He atmosphere and an He flow rate of ~0.8 l/min was used to transfer ablated material to the plasma. Analyses and data reduction followed the general procedures outlined in Loewen and Kent (2012). Calibration of unknown glasses was performed via analysis of basaltic glass GSE-1G, using concentrations from the GeoRem compilation (georem.mpch-mainz.gwdg.de) and 28Si as an internal standard. Reported precision for individual analyses includes the reproducibility of standard measurements, and the uncertainty in the accepted composition of the calibration standard and in the concentration of the internal standard element for each unknown. Accuracy was monitored via analysis of BCR-2G glass and for most elements measured concentrations were within ~5%–10% of the reported concentrations in this glass. Exceptions were Cr, P, and Zn, which were within ~20%–25% of accepted values.

The Ar-Ar incremental heating experiments were performed at OSU. Crystalization ages on acid-rinsed fresh feldspars were determined by the 40Ar/39Ar incremental heating method at the Noble Gas Mass Spectrometry Laboratory at OSU. All samples were loaded into quartz vials containing small quantities of mineral monitor FCT-3 biotite and irradiated at the OSU TRIGA research reactor. Samples were heated in a double-vacuum, thermocouple-controlled resistance furnace. After each heating step, followed by gas cleanup, the isotopic composition of Ar was analyzed using a MAP 215-50 mass spectrometer. ArArCALC software (Koppers, 2002) was used to reduce the isotopic data and make age calculations. Further details of analytical procedures were described in Duncan and Keller (2004; see also the OSU laboratory website, http://www.coas.oregonstate.edu/research/mgg/chronology.html).

Single-crystal analyses were performed at the New Mexico Geochronology Research Laboratory at New Mexico Tech (Socorro), HF-cleaned alkali feldspar separates and interspersed Fish Canyon Tuff (FCT) sanidine monitors in machine Al discs were enclosed in evacuated quartz tubes and irradiated at the Denver U.S. Geological Survey TRIGA reactor. Individual grains were fused by CO2 laser and analyzed using a Thermo Argus VI mass spectrometer. Pychrn software (Ross, 2014) was used to control analysis and reduce data.

For all age calculations, we used a FCT age of 28.201 Ma (Kuiper et al., 2008).

**DINNER CREEK TUFF—ORIGINAL WORK AND LIKELY SOURCE AREA**

The recognized type section of the Dinner Creek Ash Flow Tuff, which we refer to as the Dinner Creek Tuff, is along the Malheur River gorge between the small towns of Juntura and Harper in eastern Oregon (Fig. 1). Here the Dinner Creek Tuff forms an important and easily recognizable stratigraphic marker near the top of a thick section of mafic lava flows (Kittleman et al., 1965, 1967). All mafic lava flows below the tuff are referred to as the basalt of Malheur Gorge and lava flows above the tuff as Hunter Creek Basalt. The basalt of Malheur gorge at the type section grades upward from a basaltic series of mafic flows that are correlative to the Steens Basalt, through an intermediate sequence of mafic flows correlative to the Immaha Basalt, into an upper series of iron-rich basaltic andesite and andesite lava flows known as the Birch Creek basalt that are correlative to the Grand Ronde Basalt, as are iron-rich andesite lava flows of the overlying Hunter Creek Basalt (Hooper et al., 2002; Camp et al., 2003; Barry et al., 2013; Ferns and McLaughry, 2013; Reidel and Tolan, 2013).

Pardee (1941) was the first to map a rhyolite tuff that separated older mafic from younger mafic lava flows in eastern Oregon. Others, such as Gilully (1937) and Brooks et al. (1976), mapped discontinuous exposures of ash-flow tuff as far east as Richland, Oregon. The earliest systematic work in the Dinner Creek type section was done by Haddock (1967), who determined that the ash-flow tuff extended over an area of ~2000 km². Haddock (1967) and Wood (1976) proposed that the Dinner Creek Tuff erupted from a vent in the vicinity of Castle Rock (Fig. 1A) in the area proposed to be part of the Castle Rock caldera (Ryutba and Vander Meulen, 1991). Thick sequences (~70 m) of rhyolitic tuff crop out north of Ironside Mountain and at Castle Rock, along what we consider to be the northern and southern margins of the DITEC. The DITEC has not been studied in any detail, in part due to concealment by a thick sequence of younger mafic lava flows, which are probably related to the Strawberry Volcanics (cf. Steiner and Streck, 2013).

**DINNER CREEK TUFF—THIS STUDY**

Our data on lithology, chemistry, and petrography combined with new age dates allow us to update the distribution of the Dinner Creek Tuff, to determine chronostratigraphic eruptive units, to correlate the tuff with regional fallout tuffs, and to establish petrogenetic connections to mafic magmas of the CRBG.

**Distribution**

We can correlate widely distributed tuff outcrops (with local names or unnamed) with Dinner Creek Tuff and distinguish Dinner Creek Tuff units from other widespread middle to late Miocene ignimbrites in eastern Oregon based on major and trace element geochemistry, lithological characteristics, and stratigraphic position (Fig. 2A). Previously, workers did not attempt to correlate the ash-flow tuff outcrops.

Our data show numerous outcrops of generic Miocene welded tuff that had been mapped across northeast Oregon (e.g., Pardee, 1941; Prostka, 1962, 1967; Brooks et al., 1976) to be correlative with one or more outflow units of the Dinner Creek Tuff. The Mascall ignimbrite of Davenport (1971) is also determined to be Dinner Creek Tuff. This correlation shows that Dinner Creek Tuff extends into central Oregon and includes extensive unmapped areas of ash-flow tuff near and south of John Day (Fig. 1). Outcrops near John Day were included in the southern facies of the Columbia River Basalt by Brown and Thayer (1966) (Fig. 1). The Dinner Creek Tuff was originally considered to be a single ignimbrite, confined to the Malheur gorge region. Our work indicates that the Dinner Creek Tuff includes four separate cooling units at stratigraphic positions similar to the type section in the Malheur gorge. Evidence for these cooling units is given in the following.

Outcrops are discontinuous and severely broken up by Neogene faults, some of which have
>1000 m of cumulative vertical displacement (Ferns et al., 2010). Much of the outcrop area is obscured by younger volcanic and sedimentary cover. The best preserved sections occur in canyons or along fault ridges where they were capped by younger lava flows. Even within the canyons, outcrops are often obscured by landslide and talus deposits.

Outcrop thickness is typically 3–8 m; thicker exposures (~20 m) are found in areas more proximal to the presumed source, where the tuff can be ~70 m (Haddock, 1967; this study). Thicker tuff can also occur more distally and suggests that topography-controlled thickening and thinning occurs locally. Current Dinner Creek Tuff outcrops enclose an area of ~25,000 km². Ash-flows probably traveled farther than indicated by preserved outcrops. It is difficult to estimate how much landscape of the area was covered by tuff. The wide distribution and comparatively thin deposits suggest that Dinner Creek Tuff units are low-aspect-ratio ignimbrites emplaced at high energy, representing landscape-mantling deposits (Freundt et al., 1999). This suggests that most of the area was covered by Dinner Creek Tuff. Using our current distribution area with conservative thickness yields a volume of the erupted magma of ~300 km³ shallow equivalent (DRE) of the combined cooling units. The known extent of associated fallout tuffs preserved probably represents a magmatic volume of an additional 300 km³ DRE, and therefore doubles the volume erupted from the DITEC.

Lithology, Mineralogy, and Composition

Units of the Dinner Creek Tuff range from welded, marked by a basal vitrophyre typically overlain by primarily devitrified zones, to only incipiently welded tuff sections throughout. All cooling units are crystal poor with phenocryst contents of <1%–5%.

Outcrops of Dinner Creek Tuff range from pumice poor (~5%) to pumice rich (~30%); pumice is typically ~2–4 cm in the longest dimension, and rarely exceeds 15 cm. Colors range from white to tan to dark gray, but in single outcrops only one or two pumice colors are evident.

The mineralogy of single cooling units is dominated by a single feldspar type (anortho-
Components observed in the tuff have a wider range, note 1]. Glass shards and other glassy components include dacitic, and composition varies with cooling unit (Fig. 2; Supplemental Table 1 [see footnote 1]). Numbers are SiO₂ wt% values and lines approximately contour variations within Dinner Creek Tuff samples (all units); green arrow means that DCT compositions extend beyond shown range. Sample MS-11-27 is a sample from a distal location that yielded the highest Nb and Zr concentrations. (B) Zr versus SiO₂ for bulk analyses of Dinner Creek Tuff of all units (open black circles); color indicates samples currently identified as one of the four ignimbrite units based on a combination of bulk and glass composition, age, feldspar composition, and lithology (see Supplemental Table 1 [see footnote 1]).

Bulk tuff samples of the Dinner Creek Tuff range from high-silica to low-silica rhyolite to dacitic, and composition varies with cooling unit (Fig. 2; Supplemental Table 1 [see footnote 1]). Glass shards and other glassy components observed in the tuff have a wider range, from high-silica rhyolite to andesite (Figs. 4 and 5; Supplemental Table 2). Lithic fragments in the tuffs are mostly reworked tuff fragments with compositions matching the host tuff. Bulk tuffs with high-silica rhyolitic composition have exclusively high-silica rhyolite glass shards and are generally pumice poor and welded. High-silica rhyolite units are the oldest (see following). Bulk compositions of low-silica rhyolite or those straddling the low-silica–high-silica rhyolite boundary typically contain pumice of low-silica rhyolite, a subordinate amount of pumice with dacitic composition, and mostly contain glass with ≥75wt% SiO₂. Outcrops of these are seldom welded, but are typically pumiceous and in the middle of the age spectrum. Tuff samples with dacitic bulk compositions are complex, consisting of high-silica rhyolite to dacitic glass shards, pumice shards of dacitic composition, and andesitic glassy globules (microscoria) (Fig. 5). Outcrops of dacitic bulk composition are distinctly darker than either low- or high-silica rhyolite outcrops. Tuff belonging to this eruptive unit yielded the youngest age. The rhyolitic component of each individual cooling unit seems compositionally unzoned to little zoned. There are only small compositional variations between low-silica rhyolite and high-silica rhyolite, and some incompatible trace element variations are near analytical uncertainties (Fig. 2; Supplemental Table 1 [see footnote 1]).

The most mafic components (≤56wt% SiO₂) are typically recorded as variously vesicular glassy globules (Fig. 5) (cf. Sumner and Wolff, 2003). Petrographic features (glassy, vesicular, friable textures), compositional continuity with more silicic compositions, and direct contact of andesitic with more silicic glasses all argue for the globules recording a liquid component of the Dinner Creek Tuff magmatic systems. Dacitic glass shards and dacitic pumices are in linear compositional continuum between the andesitic component and the rhyolites on element–element variation diagrams (Fig. 5).

Age Data of Ignimbrite Cooling Units and Correlation with Regional Fallout Tuffs

Our current age information on the lithostratigraphic and glassy composition of Dinner Creek Tuff ignimbrite units 1–4. If you are viewing the PDF of this paper or reading it offline, please visit http://dx.doi.org/10.1130/GES01086.S1 or the full-text article on www.gsapubs.org to view Supplemental Table 1.

Figure 2. (A) Nb versus Zr of all four Dinner Creek Tuff cooling units relative to 15–7 Ma regional rhyolitic ash-flow tuffs. Data of 43 Dinner Creek Tuff (DIT) bulk analyses are plotted. Data sources for other tuffs: Wildcat Creek Welded Tuff (WCT)—Hooper et al. (2002); Rattlesnake Tuff (RST)—Streck and Gruber (1997); Devine Canyon Ash-Flow Tuff (DCT)—Wacaster and Streck (1997); Spring Creek Tuff (SCT), Leslie Gulch Tuff Member (LGT)—our data. Numbers are SiO₂ wt% values and lines approximately contour variations between low-silica rhyolite and high-silica rhyolite units are the oldest (see following). Each unit is constructed to show range. Sample MS-11-27 is a sample from a distal location that yielded the highest Nb and Zr concentrations.

Figure 3. Dinner Creek Tuff feldspar compositions: n—number of samples; N—number of crystals analyzed; Or—orthoclase; An—anorthite; Ab—albite. Three analyses were obtained on each crystal (with a few exceptions). Unit number refers to Dinner Creek Tuff units (see text).
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Figure 4. Rhyolite (>74.5 wt% SiO₂) glass compositions of Dinner Creek ash-flow tuff units and regional fallout tuffs. All data for fallout tuff glass and glass of Dinner Creek Tuff unit 3 are from Nash and Perkins (2012); abbreviations of fallout localities are as in Figure 1. Each data point of this study is the average of several analyses per shard (typically 3 analyses) (Supplemental Table 2 [see footnote 2]). Dinner Creek Tuff samples with glass data are following: Unit 1—MS-MC02–09, MS-11–27, MS-11–54. Unit 2—MS-PCIT1, MS-11–30, (recalculated to 16.0 Ma). It is now clear that one Dinner Creek Tuff cooling unit has an age of ca. 16 Ma and it is the high-silica rhyolitic ash-flow tuff that we designate as Dinner Creek Tuff unit 2. Samples of Dinner Creek Tuff unit 2 produced ages from 15.53 to 15.45 Ma, are low-silica rhyolite in bulk composition, and contain An₀₂ plagioclase (Fig. 3). Dinner Creek Tuff unit 3 produced an age of 15.46 Ma and is low-silica rhyolite, albeit with some geochemical variations. Unit 3 can be distinguished from unit 2 as it contains anorthoclase and different glass composition (Figs. 3 and 4). Dinner Creek Tuff unit 3 includes the tuff of Bully Creek (dated here at 15.46 ± 0.02 Ma; Table 1) that is near the middle of the Bully Creek Formation, a tuffaceous, diatomite-bearing sedimentary unit with several intercalated thin fallout ash beds distributed east to northeast of Vale (Brooks and O’Brien, 1992; Ferns et al., 1993; Nash and Perkins, 2012). Rhyolite with a glass and feldspar composition close to that of Dinner Creek Tuff unit 3 erupted again ca. 15 Ma (14.88 ± 0.15 Ma; Table 1), along with substantial amounts of dacitic and more mafic magmas to generate Dinner Creek Tuff unit 4 (Figs. 3 and 4).

Dinner Creek Tuff unit 1 can be correlated with fallout tuffs in central Nevada (ash buf94–623 of Buffalo Canyon; Nash et al., 2006), the Carlin Basin in northern Nevada, and the Paulina Basin in eastern Oregon (Figs. 1 and 4; Table 2) (Nash and Perkins, 2012).

Cooling unit 2 of the Dinner Creek Tuff has no known coeruptive fallout ash deposits. However, a regionally widespread fallout unit with glass compositions overlapping those of Dinner Creek ignimbrite unit 2 closely precedes eruption of cooling unit 2 at 15.97 ± 0.04 Ma (previously 15.77 ± 0.04; Swisher, 1992) (Table 2; Fig. 4). This 15.97 Ma fallout is the prominent Mascall ash of the John Day Fossil Beds near the Picture Gorge locality in eastern Oregon and several other correlative fallout exposures, one in Oregon (Bully Creek Formation) below the tuff of Bully Creek, three in Nevada (Buffalo Canyon, Carlin, Virgin Valley), one in Idaho (White Bird), and one in Washington (Asotin) (Fig. 1; Table 2) (Nash and Perkins, 2012). Glass compositions of these fallout deposits match that of Dinner Creek Tuff unit 2 (Fig. 4). Based on this, we can say that the Mascall ash is older than the ca. 15.5 Ma ash-flow tuff, but the fallout unit and Dinner Creek Tuff unit 2 have overlapping glass compositions (Fig. 4; Table 2; Supplemental Table 2 [see footnote 2]).

Cooling unit 3 may be correlated with the 15.66 ± 0.07 Ma (recalculated from the original 15.46 ± 0.07 Ma; Downing and Swisher, 1993) basal fallout tuff (Lough ash) at Succor Creek near the Oregon-Idaho state border (Fig. 1). The Lough ash was previously correlated with the tuff of Bully Creek based on glass compositions (Nash and Perkins, 2012). Our obtained age of 15.46 ± 0.02 Ma for the previously undated tuff of Bully Creek based on single-crystal Ar-Ar dating questions this correlation, if the age for the Lough ash is correct (Table 1).

The 15.02 ± 0.08 Ma (originally 14.93 Ma) Obliterator fallout tuff, that occurs in Succor Creek, in western and northwestern Idaho, and possibly in Nevada (Nash and Perkins, 2012), has the correct age to be correlated with the 14.88 Ma ignimbrite unit 4. However, an εNd isotopic ratio of –9.1 is much too low to be derived from an eruptive site that gave rise to the Dinner Creek Tuff (cf. Nash et al., 2006).
In summary, ages, geochemical data, and mineral compositions indicate that at least 4 discrete ignimbrites were emplaced between ca. 16 and ca. 15 Ma (Table 3). The earliest and possibly largest eruptions generated Dinner Creek Tuff unit 1 and extensive fallout deposits. Dinner Creek Tuff units 2 and 3 were emplaced nearly simultaneously at 15.5 Ma. Units 2 and 3 were preceded by compositionally similar fallout tuffs ca. 15.9 and ca. 15.7 Ma, based on existing age information (Table 2). Dinner Creek Tuff unit 2 is almost as voluminous as unit 1. Dinner Creek Tuff unit 4 was erupted near 15 Ma and appears to be the least voluminous of the four units.

**CRBG Units Coeruptive with Dinner Creek Tuff**

Radiometric ages of ignimbrites and fallout tuffs originating from the DITEC range from 16.1 to 15 Ma. Main phase CRBG magmas, consisting of the Steens, Immaha, and Grand Ronde Basalts and accounting for 92% of all CRBG volume (Camp and Ross, 2004), erupted in c1–1.5 m.y. starting ca. 16.9 Ma (Jarboe et al., 2010; Barry et al., 2013). Based on the Barry et al. (2013) chronology, the Grande Ronde Basalt eruptions took place from ca. 16 to 15.6 Ma, while the Jarboe et al. (2010) chronology indicates a beginning at 16.54 Ma and an end at geomagnetic chron C5Cn.1n, which corresponds to an age of 15.95 Ma (Fig. 6). Therefore, most Dinner Creek Tuff eruptions (the first 3 ignimbrites, units 1–3, and several fallout units, e.g., Mascall ash and Lough ash) are in the same eruptive time window as the most voluminous of all CRBG units, the Grande Ronde Basalt (Fig. 6) (Barry et al., 2013). Alternatively, only Dinner Creek Tuff unit 1 and associated fallout tuffs would coincide with Grande Ronde Basalt activity (Jarboe et al., 2010). Our geological evidence unequivocally indicates that equivalents to Grande Ronde Basalt lavas are 16 Ma or younger (see following). The last silicic eruptions leading to Dinner Creek Tuff unit 4 in either chronology
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Eruption sites of mafic units correlative with Grande Ronde Basalt are located peripherally to the inferred sources of Dinner Creek Tuff magmas (Cummings et al., 2000; Hooper et al., 2002; Ferns and McClaughry, 2013). Field evidence includes mafic lavas underlying and overlying Dinner Creek Tuff in the Malheur gorge and the occurrence of dikes and other vent proximal deposits. Underlying and overlying mafic lavas are fractionated and incompatible trace element–rich basaltic andesites of the Birch Creek basalt and Hunter Creek Basalt, respectively (Cummins, 2000; Hooper et al., 2002; Camp et al., 2003). The overlying Hunter Creek Basalt has two distinct compositions, one basaltic andesitic and the other icelanditic, reaching 60 wt% SiO\textsubscript{2} (Ferns and McClaughry, 2013). The Birch Creek basalt and Hunter Creek Basalt

| Sample identification | Material dated | Age\(^*\) (Ma) | Steps plateau MSWD | Weighted Plateau\(^*\) MSWD | Isochron Age\(^*\) (Ma) | Isochron MSWD |
|-----------------------|---------------|-----------------|--------------------|-----------------------------|-------------------------|---------------|
| CR-U31c               | plagioclase    | 15.95 ± 0.09    | 9                  | 92.38 ± 0.58               | 15.88 ± 0.17            | 0.61          |
| CR-U10b               | plagioclase    | 15.53 ± 0.15    | 11                 | 99.4 ± 0.31                | 15.52 ± 0.23            | 0.31          |
| MS-PO7T1              | plagioclase    | 15.48 ± 0.13    | 12                 | 100 ± 0.49                 | 15.48 ± 0.15            | 0.46          |
| CR-U2a                | plagioclase    | 15.45 ± 0.15    | 10                 | 96.3 ± 1.61                | 15.38 ± 0.45            | 1.64          |
| MS-11-20              | anorthoclase   | 14.88 ± 0.15    | 5                  | 96.95 ± 1.05               | 14.91 ± 0.17            | 1.20          |

**Note:** All ages calculated relative to Fish Canyon Tuff sanidine age at 28.201 Ma (cf. Kuiper et al., 2008). MSWD—mean square of weighted deviate. Additional information in Supplemental Figures 1–3 (see text footnotes 3, 4, and 5, respectively).

**Table 1. Incremental heating age determinations (Oregon State University) and single crystal ages (New Mexico Tech), Dinner Creek Tuff**

| Sample identification | Material dated | Age\(^*\) (Ma) | Steps plateau MSWD | Weighted Plateau\(^*\) MSWD | Isochron Age\(^*\) (Ma) | Isochron MSWD |
|-----------------------|---------------|-----------------|--------------------|-----------------------------|-------------------------|---------------|
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**Table 2. Regional fallout tuffs originating from Dinner Creek Tuff eruptive center**

| Name of dated fallout tuff and locality | Reported age (Ma) | Source of age | Recalculated age (Ma) | Correlated fallout tuff localities (after Nash and Perkins, 2012) |
|---------------------------------------|-------------------|---------------|-----------------------|-----------------------------------------------------------------|
| Lough Ash–Succor Creek, southeast OR  | 15.46 ± 0.07      | FCT, 27.84*   | 15.66 ± 0.07          | Bully Creek Formation, OR; Virgin Valley, NV; White Bird, ID; Asotin, WA |
| Mascall ash–Mascall Formation at Picture Gorge, OR | 15.77 ± 0.07 | FCT, 27.84*   | 15.97 ± 0.07          | Paulina Basin, OR; Carlin Basin, NV |
| Buffalo Canyon, NV                    | 15.9 ± 0.06       | FCT, 28.02*   | 16.0                  | Paulina Basin, OR; Buffalo Canyon, NV |
| Carlin Basin, NV                      | 16.3 ± 0.25       | FCT, 28.02*   | 16.4 ± 0.25           | Paulina Basin, OR |

**Table 3. Dinner Creek Tuff eruptive center**

| Ma       | Unit  | Dinner Creek Tuff | Fallout tuff Localities | Glass      |
|----------|-------|-------------------|-------------------------|------------|
| 16.15–16.0 | 1     | hi-Si             | loCa-loFe               | An\(_{10}\) |
| 15.54–15.47 | 2     | lo-hi-Si          | hiCa-miFe               | An\(_{20}\) |
| 15.46     | 3     | lo-Si             | loCa-hiFe               | Anorth     |
| 14.99     | 4     | dacite            | loCa-mi-hiFe            | Anorth     |

Oregon: BU (Bully Creek F.) M (Mascal), PB (Paulina Basin), SC (Succor Creek); UM (Umatilla; Ferns, unpubl.)
Nevada: BC (Buffalo Canyon), C (Carlin), VV (Virgin Valley)
Idaho: WB (White Bird)
Washington: A (Asotin)
An\(_{10}\), An\(_{20}\): An content of plagioclase
Anorth: Anorthoclase
hi-Si: high-silica rhyolite (>75% SiO\textsubscript{2})
lo-Si: low-silica rhyolite (< 75% SiO\textsubscript{2})
dacite (<69% SiO\textsubscript{2})
loCa: low CaO (~0.5 wt.%)
hiCa: high CaO (~0.9 to >1 wt.%)
loFe: low FeO* (~2.0 wt.%)
hiFe: high FeO* (~2.8 wt.%)

Note: OR—Oregon; NV—Nevada; ID—Idaho; WA—Washington. Sources: 1—Downing and Swisher (1993); 2—Swisher (1992); 3—Nash and Perkins (2012; reflects stratigraphically interpolated age); 4—Wallace et al. (2008).
*Age of Fish Canyon Tuff (FCT) used to calculate reported ages.
†Correlation age, Wallace et al. (2008).
Figure 6. Age relationships of ignimbrites (Table 1) and fallout tuffs (Table 2) originating from the Dinner Creek Tuff eruptive center (DITEC) in relation to eruption period of Grande Ronde Basalt lavas based on the Barry et al. (2013) and Jarboe et al. (2010) chronology.

are correlative with R1 and R2 lavas of the upper Grande Ronde Basalt, respectively (Reidel and Tolan, 2013; Barry et al., 2013). These occur on the southern side of the DITEC. In this regard, if Hunter Creek Basalt is correlative to Wapshilla Ridge member of the Grande Ronde Basalt (Reidel and Tolan, 2013), this would require that this R2 unit is ca. 16 Ma or younger, because it overlies Dinner Creek Tuff unit 1 in Malheur Gorge, which in turn would conflict with an age of 16.3 based on the magnetostratigraphy of R2 (CSCn.1r chron) (cf. Jarboe et al., 2010).

On the northern side, Fiddlers Hell icelandic lavas (15.51 ± 0.1 Ma; Ferns and McClaughry, 2013), with compositions close to icelandites of the Hunter Creek Basalt, erupted at several localities (near the towns of Baker City and La Grande, Oregon) and constitute the top of the Grande Ronde Basalt (Ferns and McClaughry, 2013). We have also found icelandic lavas with comparable compositions immediately north and south of Ironside Mountain (Fig. 1), which is the likely northern terminus of the DITEC. Dikes of basaltic andesitic compositions like Hunter Creek Basalt were mapped 20 km northeast of the proposed venting site for the Dinner Creek Tuff (Brooks, 2006).

DISCUSSION

Mafic Dinner Creek Tuff: Records of Grande Ronde Basalt Magmas

Close relationships in terms of time and space of lavas of Hunter Creek Basalt (i.e., upper Grand Ronde Basalt) with the Dinner Creek Tuff have been found ~20 km southeast of the proposed source area from where Evans (1990) and Evans and Binger (1998) reported a mafic vitrophyric lense with Hunter Creek Basalt composition in Dinner Creek Tuff, they suggested that these two magmas may have erupted contemporaneously. We investigate this further and use our compositional glass data obtained on shards, pumice shards, mafic globules, and pumices that we found in one of the two 15.5 Ma cooling units (unit 2) and in the 14.9 Ma ignimbrite (unit 4). Comparing these intermediate to mafic components of the Dinner Creek Tuff to regionally occurring lavas reveals the following. The more mafic the components of the Dinner Creek Tuff are, the more strongly they resemble regional CRBG magmas (Fig. 5). The basaltic andesitic mafic globules of the Dinner Creek Tuff have major and trace element glass compositions within the range of basaltic andesitic composition of the Hunter Creek and Birch Creek lavas, mafic dikes of Mormon Basin, basaltic andesites of Fiddlers Hell, icelandites immediately north and south of Ironside Mountain, and members of the Grande Ronde Basalt (Fig. 5). The icelanditic (~60–63 wt% SiO₂) components of the Dinner Creek Tuff are also similar to the regionally exposed, more evolved Hunter Creek and Fiddler Hell lavas, although there are some differences; for example, FeO* of ~9 wt% in Dinner Creek Tuff glass compositions is lower than the ~11 wt% of regional lava flows (Fig. 5). In general, observed differences are consistent with Dinner Creek Tuff icelanditic compositions having evolved from basaltic andesitic Hunter Creek magmas slightly differently than icelanditic Hunter Creek magmas. The difference of evolutionary paths is likely due to mixing of Dinner Creek Tuff rhyolites with Hunter Creek magmas in addition to fractional crystallization, similar to what is observed in the 7.1 Ma Rattlesnake Tuff (Streck and Grunder, 1999). Evidence for that is seen in icelanditic and dacitic Dinner Creek Tuff compositions plotting on mixing lines between rhyolites and basaltic andesitic compositions of Dinner Creek Tuff mafic globules as well as Hunter Creek Basalt magmas (Fig. 5; Supplemental Table 4').

Based on the compositional overlap combined with concurrent ages of Hunter Creek and other equivalents of Grande Ronde Basalt with Dinner Creek Tuff unit 1, we make the inference that basaltic andesitic to icelanditic components of the Dinner Creek Tuff are in fact components of upper Grande Ronde Basalt magmas, even though they postdate the main eruption phase of Grande Ronde Basalt.

Dinner Creek Tuff: Prolonged Silicic Reservoir above CRBG Magma Storage Sites

The inference that mafic components of the Dinner Creek Tuff are correlative with upper units of the Grande Ronde Basalt allows us to identify the DITEC as one location where mafic magmas of the CRBG resided in crustal reservoirs. The intimate relationships between the mafic components and rhyolites of the Dinner Creek Tuff indicate that upper Grande Ronde Basalt components were stored below a long-lived (1 m.y.) mid-Miocene rhyolite magmatic system.

The details on the existence of the silicic reservoir (or reservoirs), such as whether it waxed and waned, and whether it existed continuously or periodically, are not known. Whatever the status and distribution of these rhyolites, multiple eruptions led to crystal-poor rhyolites. Some of the erupted rhyolite batches have some subtle, yet unique, chemical and mineralogical fingerprints. Such differences between Dinner Creek Tuff units 2 and 3, the ages of which are irresolvable by our new age data, suggest either two compositionally silicic systems operating nearby ca. 15.7–15.5 Ma, or that both evolved in short succession at the same locus. Widespread fallout tuffs were either associated with ash-flow eruptions or preceded ignimbrites. All rhyolites are compositionally very similar, suggesting cognetic or cospatial relationships (Fig. 2; Supplemental Table 1 [see footnote 1]). Therefore, petrogenetic stages leading to each rhyolite must have been nearly identical, generating individual batches of chemically practically unzoned rhyolites.

In summary, persistent silicic reservoirs generating the erupted Dinner Creek Tuff rhyolites developed above a major storage site of Grande Ronde Basalt magmas that likely persisted for several hundred thousand years (Table 3). The storage site of Grande Ronde Basalt magma identified here (i.e., DITEC) is within the area of the previously hypothesized crustal magma reservoir area of the CRBG (Wolff et al., 2008; Wolff and Ramos, 2013).

Eruption versus Storage Sites of CRBG

Numerous rhyolitic centers with ages ranging from 16.5 to 15 Ma surround the DITEC in eastern Oregon (Figs. 1 and 7) (Cummings et al., 2000; Ferns and McClaughry, 2013; Steiner and Streck, 2013; our data). Independent of the model that leads to the production of rhyolites, mafic magma is ultimately involved in their production either as heat source to induce melting, as material source for fractional crystallization processes, or generally to maintain rhyolites at
known contemporaneous rhyolite centers are at radial fractures to form the well-known Columbas) were staged in a common area in the magmas (Steens, Imnaha, and Grande Ronde et al. (2008) suggested that the main CRBG to peripheral areas or erupt after rhyolites. Wolff et al., 2008). Numbers are ages (in Ma) and are near onset of activity of select centers based on our data.

**CONCLUSIONS**

Our study focuses on the newly defined DITEC, a long-lived silicic center in eastern Oregon that is part of other numerous silicic centers overlapping in time and space with flood basalt volcanism of the CRBG and thus demonstrating abundant rhyolite activity during flood basalts stage.

The Dinner Creek Tuff, formerly considered a single ignimbrite deposit, is determined to consist of a minimum of 4 cooling units erupting over a time span of 1 m.y from ca. 16 to 15 Ma and covering ~25,000 km². Well-known fallout tuff deposits in Oregon and elsewhere can be matched both chemically and chronologically with individual cooling units but also precede ignimbrite eruptions.

The first ash-flow tuff eruptions (unit 1, 16.1–16 Ma) were the most silicic, producing high-silica rhyolites. Later eruptions (units 2 and 3, 15.5 Ma) were high- to low-silica rhyolite, some with ubiquitous dark pumices of dacitic composition. Bulk compositions of tuff deposited during the last eruptions (unit 4, 14.9 Ma) are dacite, but the lower SiO₂ in this unit is due to substantial commingling of dacitic and andesitic components with high-silica rhyolite. Major and trace element compositions of rhyolite of all four cooling units are surprisingly similar and differ markedly from all other regional Miocene ash-flow tuffs in eastern Oregon. This evidence and current field data on thickness and distribution suggest a common source area for all ignimbrites and fallout tuffs. This common source we define as the DITEC.

Coeruptive basaltic andesitic magmatic components of the Dinner Creek Tuff are compositionally indistinguishable from regional mafic lava flows belonging to the upper Grande Ronde Basalt of the CRBG, and this implies that Grande Ronde Basalt magmas were ponded below Dinner Creek Tuff rhyolites. This effectively pins down one location where CRBG magmas were stored in the crust. Therefore, Dinner Creek Tuff rhyolites and other widespread 16–15 Ma rhyolites of the area possibly acted as rheological and density barriers, allowing CRBG magmas stored underneath to erupt after rhyolites or in peripheral areas after traveling in dikes for many kilometers, as proposed by Wolff et al. (2008).

Our study highlights the close spatial and age relationship of mafic magmas with rhyolites at the youngest continental flood basalt province we know. Understanding rhyolites may provide important complementary data on the existence and location of storage areas of mafic magmas.

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Large, persistent rhyolitic magma reservoirs above Columbia River Basalt storage sites: The Dinner Creek Tuff Eruptive Center, eastern Oregon

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