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Picture Gorge Basalt: Internal stratigraphy, eruptive patterns, and its importance for understanding Columbia River Basalt Group magmatism

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ABSTRACT

The Picture Gorge Basalt (PGB) of the Columbia River Basalt Group (CRBG) has been previously thought to be limited in its eruptive volume (<3000 km^3) and thought to not extend far from its type locality. At present, PGB represents only 1.1 vol% of the CRBG with a relatively limited spatial distribution of ~10,000 km^2. New age data illustrate that the PGB is the earliest and longest eruptive unit compared to other main-phase CRBG formations and that some dated basaltic flows reach far (~100 km) beyond the previously mapped extent. This study focuses on extensive outcrops of basaltic lavas and dikes south of the type locality at Picture Gorge, in order to reassess the spatial distribution and eruptive volume of the PGB. Field observations coupled with geochemical data indicate that PGB lava flows and mafic dikes covered a significantly greater area than shown on the published geologic maps. We find that additional mafic dikes located farther south of the original mapped distribution have geochemical compositions and northwest-trending orientations comparable to the dikes of the Monument dike swarm. We also identify new lava flows that can be correlated where stratigraphic control is well defined toward the original mapped PGB distribution. Our analyses and correlations are facilitated by comparison of 20 major- and trace-element abundances via a principal component analysis. This statistical comparison provides a new detailed distribution of PGB with stratigraphic significance that more than doubles the total distribution of PGB lavas and dikes and brings the eruptive volume to a new minimum of at least ~4200 km^3. Geochemically correlated basaltic lavas and dikes in the extended distribution of PGB represent the earlier and later sections of the internal PGB stratigraphy. This is an intriguing observation as new geochronological data suggest an eruptive hiatus of ~400 k.y. during PGB volcanic activity, which occurred from 17.23 Ma to 15.76 Ma.

The geochemical identifiers used to differentiate PGB from other main-phase CRBG formations include lower TiO_2 (<2 wt%) concentrations, lower incompatible trace-element (i.e., La, Th, and Y) abundances, and a more pronounced enrichment in large-ion-lithophile elements (LILEs) on a primitive mantle–normalized trace-element diagram (Sun and McDonough, 1989). Geochemical characteristics of PGB are interpreted to represent a magmatic source component distinct from the other main-phase CRBG units, possibly a localized backarc-sourced mantle melt. However, this source cannot be spatially restricted as there are observed PGB lava flows and dikes extending as far east as Lake Owyhee and as far south as Hart Mountain, covering at least 15,000 km^2. In context with the existing stratigraphy and the new extent of PGB lavas and dikes, these ages and coupled geochemical signatures demonstrate this mantle component was not spatially localized but rather tapped across a wide region.

INTRODUCTION

Continental flood basalts are a type of large igneous province (LIP) composed of lava flows, pyroclastic rocks, dikes, and sills. The majority of erupted material is often observable as thick sections of laterally continuous basaltic lavas. Their stratigraphic sections preserve records of chemical variation associated with the dynamics of mantle upwellings and provide insights into differentiation processes in the continental crust and mantle geodynamic processes through time. Evaluating the geochemical signatures, phenocryst content, magnetic polarity, and radiometric ages within these dominantly basaltic lavas is required to categorize different magmatic components and establish a robust internal stratigraphy of flood basalt subunits, their eruptive patterns, and the overall importance and history of Columbia River Basalt Group (CRBG) magmatism.

The CRBG is the youngest and least volumetric flood basalt province on Earth, and its excellent preservation has provided geologists with an opportunity to better understand the eruptive evolution of a continental flood basalt province. Similar to other flood basalt provinces worldwide, volcanism of the CRBG was active for millions of years, with the majority of material erupted during the first million years, or "main-phase" of activity (Coffin and Eldholm, 1994). For the CRBG, this main-phase eruptive period lasted from ca. 17–16 Ma, and basaltic lavas of this interval can be subdivided into four units: Steens Basalt, Imnaha Basalt, Grande Ronde Basalt, and the Picture Gorge Basalt (PGB) (Reidel et al., 2013).

Models for CRBG magmatism range from those that do not necessitate the involvement of a deep mantle plume where magma generation is largely tectonically driven (Carlson and Hart, 1987; Hales et al., 2005; Liu and Stegman, 2012), to those that require

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the Yellowstone plume as the primary driver of volcanism across the province (Brandon and Goles, 1988; Geist and Richards, 1993; Hooper and Hawkesworth, 1993; Camp and Ross, 2004; Hooper et al., 2007; Camp and Hanan, 2008). In the latter class of models, the main-phase units of the CRBG are thought to represent mixtures of this deep-seated plume material with other components such as depleted mantle variably altered by subduction fluids, recycled basaltic crust within a plume, and accreted terranes and crustal material (Carlson et al., 1981; Carlson, 1984; Brandon et al., 1993; Hooper and Hawkesworth, 1993; Takahashi et al., 1998; Wolff et al., 2008).

Establishing stratigraphic packages and distribution patterns is imperative to understand emplacement and total eruptive volumes, and in conjunction with petrologic data, to provide the framework for models of magmatic progression. In the case of the CRBG, decades of work have improved our understanding of the timing, spatial extent, and geochemical evolution of these flood basalt lavas (Carlson, 1984; Wolff et al., 2008; Reidel et al., 2013; Kasbohm and Schoene, 2018; Cahoon et al., 2020). This study focuses on basaltic lavas and dikes of the PGB and their regional distribution, stratigraphy, and context to other main-phase CRBG units. We demonstrate that lavas and dikes of the PGB are dispersed across a significantly greater area than previously recognized (cf. Bailey, 1989a), leading to new stratigraphic relationships with other main-phase CRBG units and potentially new eruption center locations and a wider areal extent in eastern Oregon. The increased area and volume for the PGB have a greater significance when considered with its eruptive timing. Age data for the PGB suggest two temporal pulses of volcanism, with a decrease in eruption rate also observed in ages from all other CRBG main-phase formations.

GEOLOGIC SETTING

Main-Phase Lavas of the Columbia River Basalt Group

The Columbia River Basalt Group (CRBG) is preserved in the geologic record as thick stacks of mafic lavas throughout Oregon and Washington (Fig. 1). Volcanism associated with the CRBG occurred between 17.2–5.5 Ma, but the majority of the extruded volume erupted during the initial ~1.2 m.y. of activity (Camp et al., 2017; Cahoon et al., 2020). The first eruptive interval lasting ~1 m.y. (ca. 17.2–16 Ma) has been known as the main phase of CRBG activity, and basaltic lavas erupted during this time include the Steens, Imnaha, Grande Ronde, and Picture Gorge Basalt (PGB), distinguished by relative age, vent locations, and chemical composition and accounting for ~93% of the total CRBG eruptive volume (Reidel et al., 2013).

Initially inferred from field observations, lavas of the PGB and lavas of the Grande Ronde Basalt were thought to have erupted concurrently. Lava flows of Picture Gorge Basalt appear to interfinger with Grande Ronde lavas while seemingly erupting during the N1 and R2 magnetostratigraphic intervals (Reidel et al., 2013). Early K/Ar dating of multiple lava flows within the type section at Picture Gorge indicated a narrow eruptive range from 15.9 to 14.7 Ma (Watkins and Baksi, 1974), but eruptive timing of the PGB has been recently refined through high-precision $^{40}Ar/^{39}Ar$ incremental heating ages, with ages more widely distributed and as old as 17.23 Ma (Cahoon et al., 2020). Other recent dating studies have also reported older age data for magnetostratigraphic transitions observed within other main-phase CRBG units, including a zircon U-Pb age of 16.210 ± 0.043/0.047 Ma for the R2-N2 transition (Kasbohm and Schoene, 2018) that is consistent with the interpretation of Jarboe et al. (2010) that the N0-R1 transition is also older, at ca. 16.5 Ma.

PGB Stratigraphy and Geochemistry

Merriam (1901) correlated basaltic lava flows at Picture Gorge with the previously established "Columbia Lavas" throughout the Columbia River Gorge. The first reference to the name Picture Gorge Basalt (PGB) was by Waters (1961), who distinguished PGB and the Yakima Basalt as the chief subunits of the CRBG. Waters' (1961) original definition of PGB included the petrographically similar flows of northeastern Oregon, southwestern Washington, and western Idaho that were later reclassified as the Imnaha Basalt (Swanson et al., 1979). Following this correlation, the PGB has been mapped and described in detail between John Day and Kimberly in Oregon (Fig. 1) (Brown and Thayer, 1966; Wilcox and Fisher, 1966; Bentley and Cockerham, 1973; Nathan and Fruchter, 1974; Fruchter and Baldwin, 1975; Robinson, 1975; Bailey, 1989a, 1989b). Magmas in this region erupted through accreted terrane material of Paleozoic to Mesozoic age consisting of metamorphosed assemblages of volcanic and ophiolitic rocks, forearc basin sediments, and through Cenozoic volcanic and volcaniclastic rocks of the Eocene Clarno and Oligocene John Day Formations (Brown and Thayer, 1966; Robinson, 1975; Hooper and Swanson, 1990).

Stratigraphic work has divided the PGB into three informal subunits, which include the Twickenham, Monument Mountain, and Dayville Basalts (Fig. 2) (Bentley and Cockerham, 1973; Swanson et al., 1979). These three subunits are further subdivided into 17 chemical types in addition to several dikes that are distinguished as high-Mg dikes due to their distinct composition (Bailey, 1989a). Subunits were originally differentiated by plagioclase abundance, TiO_2 and MgO content (wt%), and magnetic orientation (Osawa and Goles 1970; Nathan and Fruchter, 1974; Watkins and Baksi, 1974; McDougall 1976; Swanson et al. 1979; Goles 1986; Bailey 1989a) (Figs. 2 and 3). These PGB lavas have a maximum thickness of 800 m and were interpreted to form a shield-like morphology across their exposure area (Swanson et al. 1979; Bailey, 1988; Brandon et al., 1993).

Throughout the literature, the terminology used to describe the stratigraphic subdivisions of the PGB is confusing. This is mostly due to disagreements among workers resulting in the application of stratigraphic nomenclature that does not abide by the Stratigraphic Code of North America (North American Commission on Stratigraphic Nomenclature, 2005). To summarize, Bailey (1989) recommended that the PGB be upgraded from a formation to a subgroup and referred to the Twickenham, Monument, and Dayville Basalts as Formations, which in turn are subdivided into members. Brandon et al. (1993) follows the recommendation of Bailey

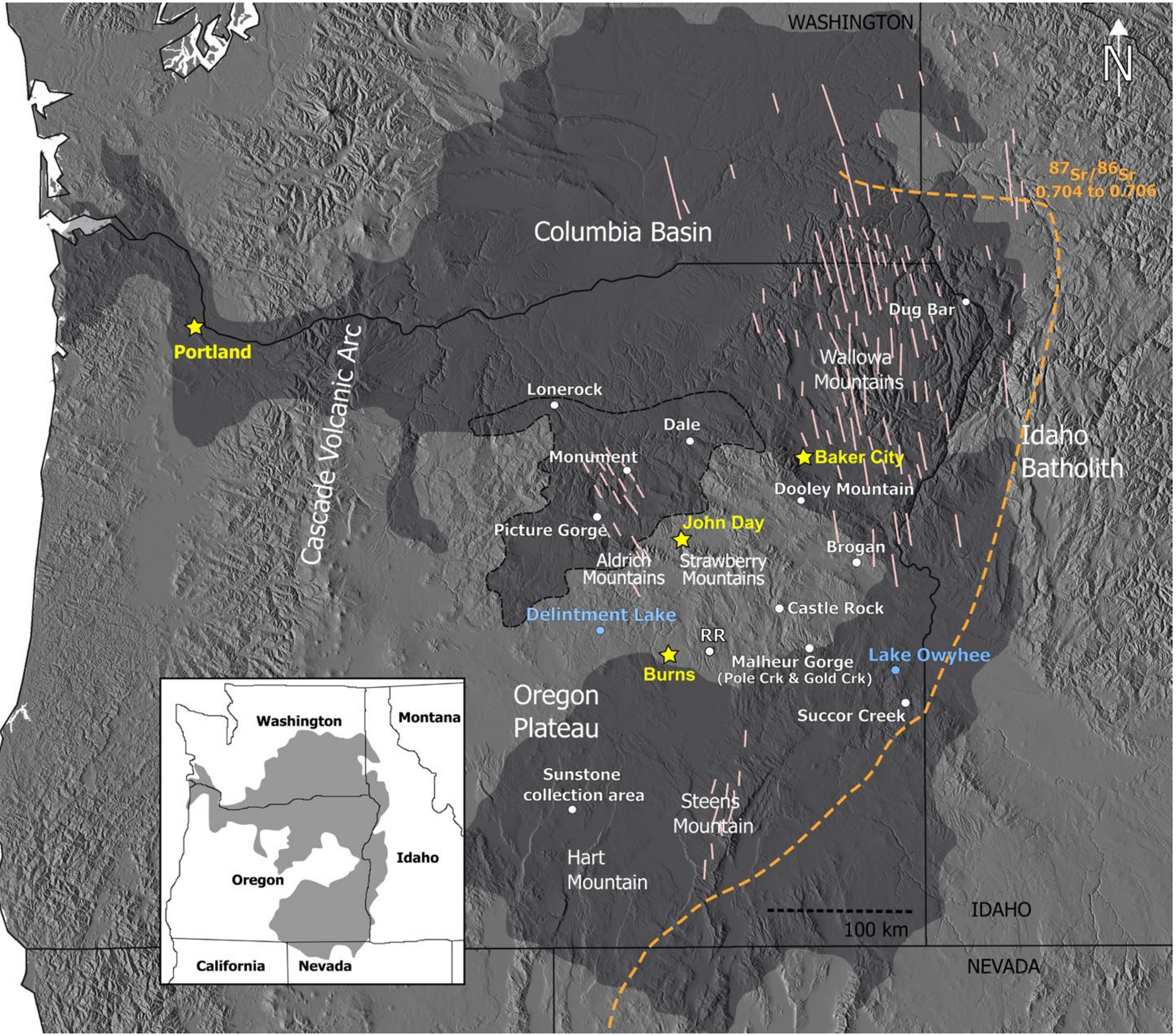

Figure 1. Regional map with current extent of the Columbia River Basalt Group (CRBG) with feeder dikes (light-pink lines) and Picture Gorge Basalt (PGB) (black dashed outline). Sample location "RR" represents Rattlesnake Road. Dashed 0.704/0.706 line represents the $^{87}Sr/^{86}Sr$ contact between accreted terranes and the western margin of the North American craton. Inset map showing distribution of Columbia River Basalt Group in northwestern United States with state lines for reference. Crk—Creek.

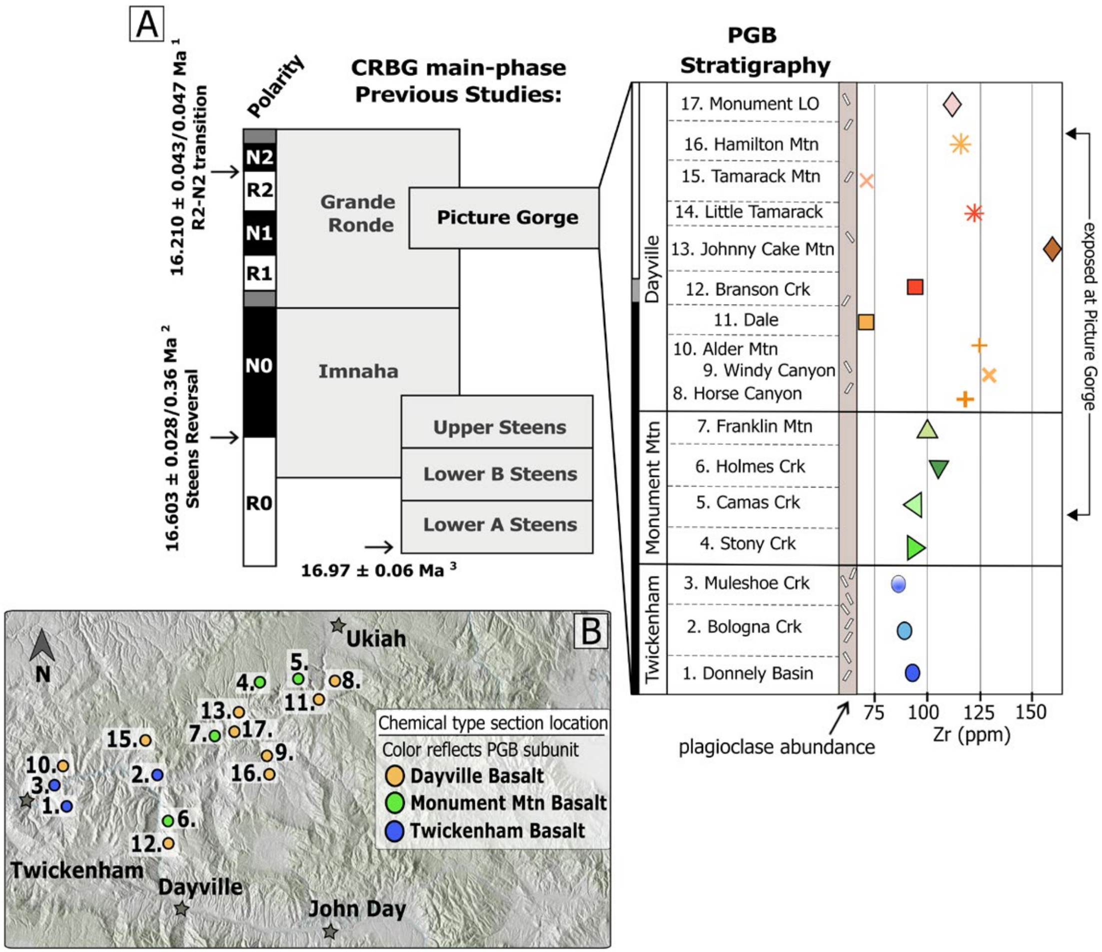

Figure 2. (A) Stratigraphy of main-phase Columbia River Basalt Group (CRBG) and the Picture Gorge Basalt (PGB) highlighting relative abundance of plagioclase phenocrysts, Zr concentration, and magnetic orientation of each subunit and respective chemical types of the PGB. Sources of CRBG ages are: [1]Kasbohm and Schoene (2018); [2]Mahood and Benson (2017); [3]Moore et al. (2018). All $^{40}Ar/^{39}Ar$ ages were calculated using Fish Canyon Tuff sanidine age of 28.201 ± 0.023 Ma after Kuiper et al. (2008), and U-Pb errors for Kasbohm and Schoene (2018) are reported as 95% confidence intervals given for internal uncertainty/decay constant uncertainty. (B) Generalized map illustrating type sections of each PGB chemical type (numbers 1–17) and color coded by corresponding PGB subunit. Map modified from Bailey (1989a).

(1989a) and uses the same terminology to describe the internal stratigraphy of the PGB. However, there was never a consensus, and the usage is in direct conflict with the formational status of the PGB used by others and in more recent literature (e.g., Swanson et al., 1979; Reidel et al., 2013). In this paper, we do not propose a formal adaptation or "upgrade" of any internal PGB grouping as recommended by Bailey (1989a), nor do we aim to add unnecessary confusion by switching which internal grouping and/or hierarchal classification is referred to as "member." Instead, our goals are simply to (1) acknowledge previous issues with the stratigraphic nomenclature, (2) maintain consistency as much as possible with the verbiage used in previous studies (i.e., Bailey, 1989a, 1989b; Brandon et al., 1993), and (3) conform with the Stratigraphic Code of North America (North American Commission on Stratigraphic Nomenclature, 2005) for the purpose of geochemical classification with newly identified flows of this study. To summarize, we use the term "subunit" to reference the Twickenham, Monument Mountain, and Dayville Basalts—and "chemical type" to reference the 17 groupings of lava flows (termed "members" by Bailey, 1989a).

The Twickenham Basalt is the earliest of the three PGB subunits and was originally divided into three chemical types (Bailey, 1989a). Lavas of the Twickenham Basalt are plagioclase-phyric, normally magnetized, and contain TiO_2 >1.5 wt% and MgO >6 wt% (Bailey, 1988) (Figs. 2 and 3). These basalts are interpreted to have erupted across areas of moderate relief forming intracanyon flows

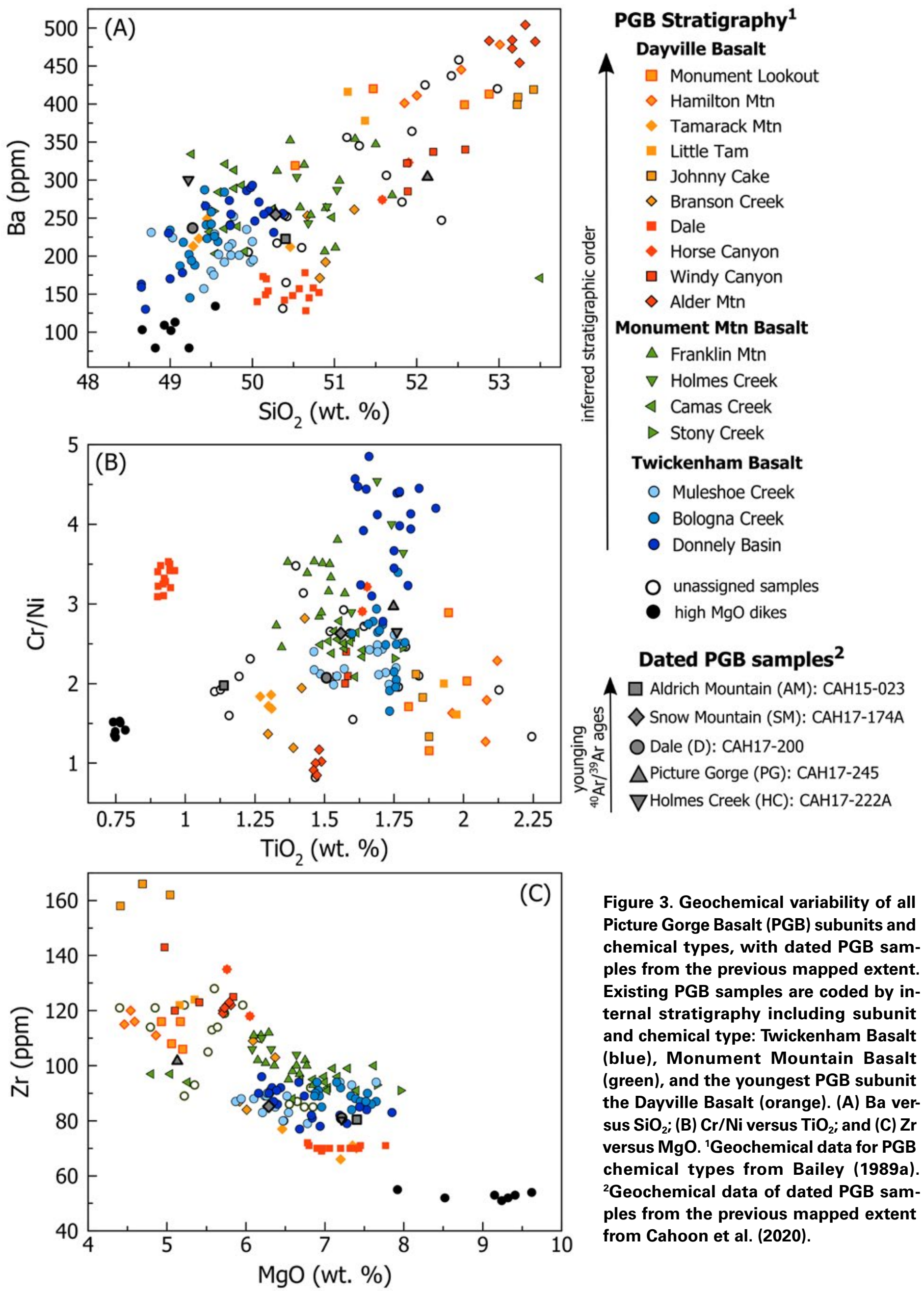

Figure 3. Geochemical variability of all Picture Gorge Basalt (PGB) subunits and chemical types, with dated PGB samples from the previous mapped extent. Existing PGB samples are coded by internal stratigraphy including subunit and chemical type: Twickenham Basalt (blue), Monument Mountain Basalt (green), and the youngest PGB subunit the Dayville Basalt (orange). (A) Ba versus SiO_2; (B) Cr/Ni versus TiO_2; and (C) Zr versus MgO. [1]Geochemical data for PGB chemical types from Bailey (1989a). [2]Geochemical data of dated PGB samples from the previous mapped extent from Cahoon et al. (2020).

exemplified by Kentucky Butte near Twickenham (Swanson et al., 1979). Lavas of the Twickenham Basalt are capped by predominantly aphyric basalts of the Monument Mountain subunit and further subdivided into four chemical types (Fig. 2). This subunit is normally magnetized, forms colonnades and entablatures, and contains TiO_2 between 1.4 and 1.7 wt% and MgO between 5 and 8.0 wt% (Bailey, 1989a). The Monument Mountain Basalt is overlain by variably plagioclase-phyric basaltic flows of the Dayville Basalt subunit. Exposures of Dayville Basalt are small in area and restricted to the highest elevations and peaks, which has led to the interpretation that there has likely been significant post-emplacement erosion (Bailey, 1989a). Currently the only documented magnetic reversal in PGB lavas occurs within the Dayville Basalt, and one chemical type exhibits transitional magnetic polarity—the Branson Creek chemical type (Watkins and Baksi, 1974) (Fig. 2). The Dayville Basalt subunit includes the most evolved lavas with <6 wt% MgO, elevated concentrations of incompatible elements (e.g., La >10 ppm) and exhibits the most geochemical variability. In fact, the geochemical variability observed in Dayville Basalt flows encompasses the entire compositional range of all three PGB subunits (Fig. 3). As a result of this compositional diversity, Bailey (1989a) divided the Dayville Basalt into ten chemical types (Fig. 3), and some chemical types consist only of two flows (i.e., Horse Canyon, Little Tamarack, and Stony Creek). Crustal assimilation in combination with fractional crystallization have been proposed to be the two main processes to account for the generation of the most evolved flows in the Dayville Basalt (Bailey, 1989b; Brandon et al., 1993). Due to the geochemical heterogeneity within the Dayville Basalt, each chemical type within the subunit is considered separately.

At the type locality of Picture Gorge, the middle (Monument Mountain) and upper (Dayville) subunits of the PGB are exposed. Here, both Mg and Cr sharply decrease stratigraphically upward, while K, La, Th, Fe, Rb, and the rare-earth elements increase (Bentley and Cockerham, 1973; Nathan and Fruchter, 1974; Swanson et al., 1979). However, basalt flows exhibiting similar textural features (i.e., predominantly aphyric or containing large plagioclase phenocrysts) define different geochemical groups, independent of their subunit classification (Bailey, 1989a).

Basalt of Malheur Gorge

More than 100 km southeast of Picture Gorge, a several hundred-meter-thick sequence of basaltic lavas is exposed along Malheur Gorge—often referred to as the basalt of Malheur Gorge (Figs. 1 and 4) (cf. Kittleman et al., 1965, 1967; Evans, 1990; Webb et al., 2018). This area is critical for stratigraphic inferences for main-phase CRBG formations. The basalt of Malheur Gorge has been subdivided by stratigraphic position and textural characteristics into Pole Creek lavas at the base and Birch Creek lavas. Overlying basalt of Malheur Gorge is the Hunter Creek Basalt, part of the informal Hog Creek sequence (Lees, 1994; Hooper et al., 2002). These basaltic lavas have been correlated to main-phase units of the CRBG, and Malheur Gorge is the only known location where three main-phase CRBG units are exposed together (Hooper et al., 2002; Camp et al., 2003).

The interpretation that many of the lower basaltic lavas at Malheur Gorge are correlative to Steens Basalt arises from geochemical data, spatial proximity to Steens Mountain, and the identification of sparse outcrops of Steens Basalt in between (Camp et al., 2003) (Fig. 1). However, new data also reveal that multiple basalt lavas in Malheur Gorge have geochemical characteristics more akin to the PGB than Steens Basalt (Cahoon et al., 2020). This observation raises questions on the geochemical nature of the basalts previously classified as Pole Creek lavas and the other CRBG subunits present within Malheur Gorge.

METHODS

New geochemical data on previously mapped but unnamed basaltic lavas, some located >100 km from the nearest PGB location, indicate the PGB extends beyond its current distribution. Samples from known PGB localities as well as new locations that are stratigraphically and geochemically correlated with PGB (Fig. 5) were selected for $^{40}Ar/^{39}Ar$ dating. We report three new $^{40}Ar/^{39}Ar$ ages for the PGB and discuss these with the 11 high-precision $^{40}Ar/^{39}Ar$ ages reported in Cahoon et al. (2020).

All 14 dated samples are groundmass separates and reflect an eruptive age. Nine of the 14 PGB

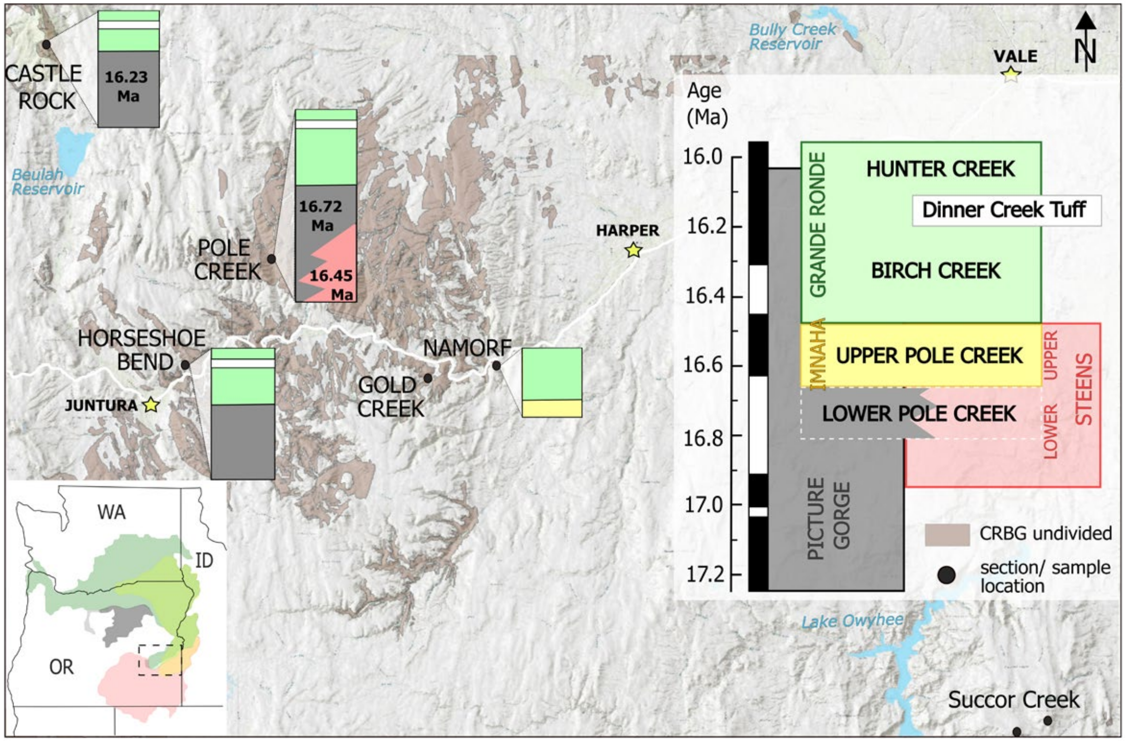

Figure 4. Regional map of Malheur Gorge highlighting locations of stratigraphic sections and interpretation of local basalt correlation to main-phase Columbia River Basalt Group (CRBG) units. Stratigraphic relationships are based on field relationships, age, and geochemical data (Hooper et al., 2002; Camp et al., 2003). Ages for the Picture Gorge Basalt (PGB) from Cahoon et al. (2020) and Steens Basalt from Jarboe et al. (2010).

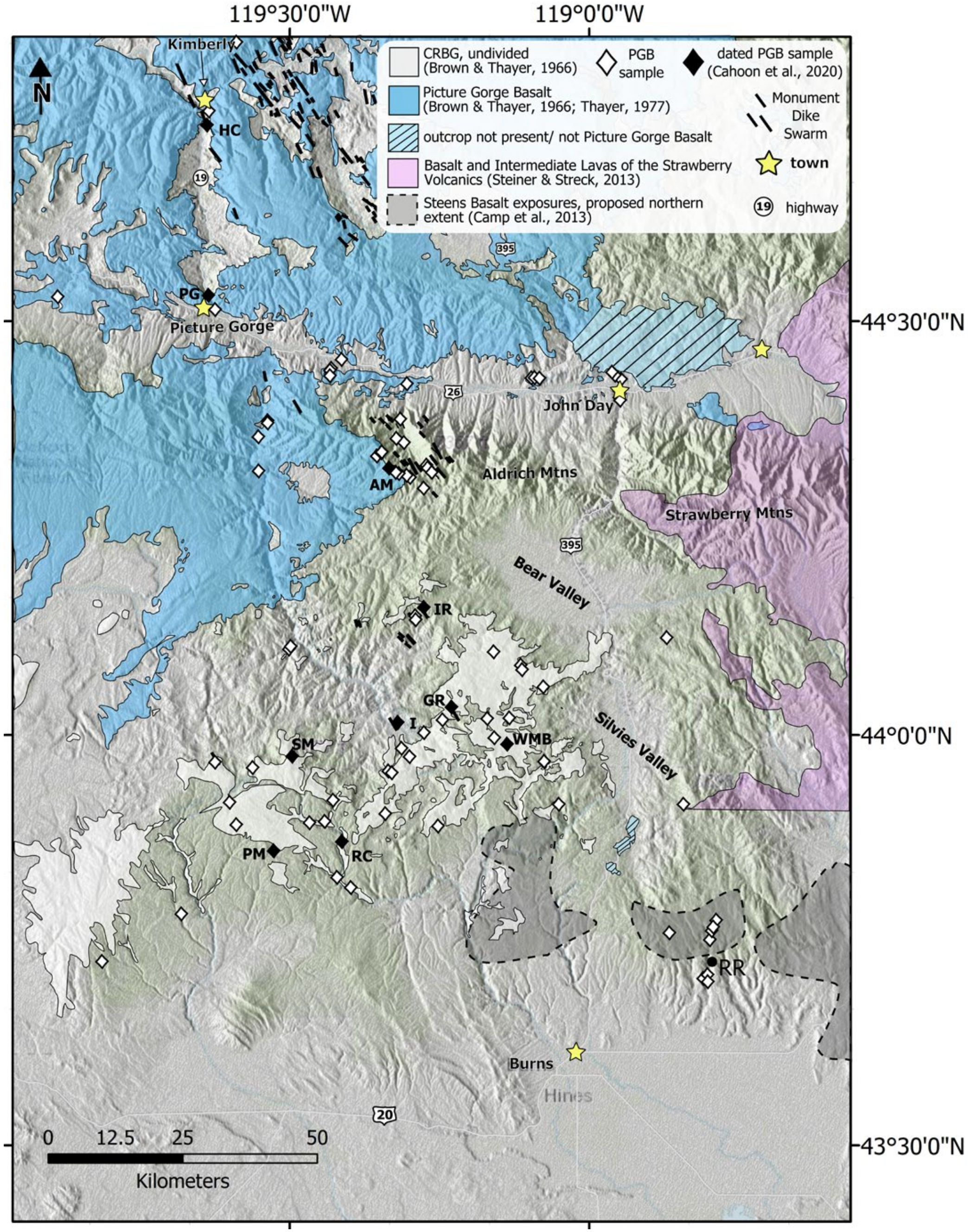

Figure 5. Distribution of basaltic lavas south of the type locality of Picture Gorge and the John Day Valley. Many of these undivided mid-Miocene basaltic lavas are geochemically identifiable as Picture Gorge Basalt (PGB) (see text for details). Shown for reference: Rattlesnake Road (RR) and locations of dated samples from this study and Cahoon et al. (2020). Abbreviations of sample locations are the same as listed in Table 1.

ages pass Baksi's (2013) statistical test for reliability, although the details of acceptable criteria to pass the statistical test are highly specific. Geochronological data and age spectra for all samples are located in the Supplemental Material[1].

Field Sampling

Our fieldwork and sample collection were focused across the Malheur and Ochoco National Forest in a broad corridor between John Day and Burns, Oregon. In this region, age is stratigraphically constrained by slightly younger ignimbrite units. Field sampling also included locations in the Picture Gorge type locality and in regions where the other three main-phase units of the CRBG are present.

Major- and Trace-Element Compositions

Major- and trace-element data were acquired at the Peter Hooper GeoAnalytical Lab at Washington State University (WSU) using a Thermo-ARL Advant XP automated X-ray fluorescence (XRF) spectrometer and an Agilent 7700 inductively coupled plasma mass spectrometer (ICP MS). These data provided whole-rock major- and trace-element data to support our interpretation that these samples are geochemically similar to PGB. This determination was further established using a statistical method—principal component analysis (PCA)—where each sample was compared to previously identified CRBG main-phase lavas from the data set of Wolff et al. (2008).

Statistical Comparison

Previous work of Bailey (1988) differentiated PGB lavas in the John Day Basin into three subunits composed of 17 different chemical types. In addition to the 17 chemical types, Bailey (1988) also distinguished high-Mg dikes within the Monument dike swarm that were originally identified by Fruchter and Baldwin (1975). These high-Mg dikes are distinguished from the high-MgO (>6%) flows and low-MgO (<6%) flows of PGB identified by Wright et al. (1973). These groups correspond to the compositional break of Osawa and Goles (1970). While Bailey (1988) does not provide a cutoff value for Mg content in the high-Mg dikes, these samples contain MgO wt% >7.92 and Mg# >64. For the purposes of this study, these high-Mg dikes are considered to be chemically equivalent to a chemical type, thus yielding 18 total geochemical groupings within the PGB.

To determine how PGB samples collected as part of this study compared with the established stratigraphy, we utilized a PCA and a multinomial logistic regression (MLR) on major-element and trace-element geochemical data in RStudio (File C; see footnote 1). Statistical methods such as MLR have been used in machine-learning–based approaches to geochemical classification (e.g., Ueki et al., 2018). Three separate PGB geochemical data sets were utilized during this analysis: Bailey (1988), Wolff et al. (2008), and this study. The geochemical data set reported by Wolff et al. (2008) contained a reanalysis of 23 PGB samples originally analyzed by Bailey (1988), including a sample from each of the 17 PGB chemical types in addition to some high-Mg basaltic dikes. When comparing geochemical data for the same samples (XRF and ICP-MS data of Wolff et al. [2008] to the original XRF data of Bailey [1988]), concentrations of most elements are similar, with the exception of Rb and Nb (File B). Due to the poor correlation of the elements Rb and Nb between XRF data (Bailey, 1988) and ICP-MS data (Wolff et al., 2008) from the same samples, the elements Rb and Nb were excluded and not incorporated in our analyses. To evaluate the accuracy and robustness of this statistical tool, geochemical data for 23 reanalyzed PGB samples (Wolff et al., 2008) were initially compared to 155 samples from the original PGB geochemical data set (Bailey, 1988). To do this, each sample in the original data set was labeled as the PGB subunit or chemical type it was classified as by Bailey (1988). Within the original data set, each sample was labeled as the Twickenham or Monument Mountain subunit, or more specifically as a chemical type within the youngest PGB subunit, the Dayville Basalt. This distinction was most useful due to a limited number of samples within some PGB chemical types of the Twickenham and Monument Mountain subunits (e.g., Stony Creek chemical type, n = 2) and the significant geochemical variability of all the chemical types within the Dayville Basalt.

The approach outlined above is condensed into the following procedural steps:

(1) Sample 1:1 elemental comparison: XRF data (Bailey, 1988) to ICP-MS data (Wolff et al., 2008)
(2) Exclude elements that are poorly correlated for geochemical analysis of the same sample (R^2 value <0.9)
(3) Using geochemical data from 23 reanalyzed PGB samples with known subunit and chemical type classification, compare samples from Wolff et al. (2008) to Bailey (1988) using a PCA and MLR to gauge accuracy of predictions.
(4) Once the model has been refined to yield the highest accuracy, compare geochemical data of our PGB samples to the original data set of Bailey (1988) using the same model to predict PGB subunit (Twickenham and Monument Mountain) or specific chemical type (Dayville Basalt).

Each sample included in this study has been classified as a PGB subunit using both methods. The key finding is when the data are organized in a similar manner, the resulting stratigraphic predictions of MLR and PCA are comparable. The utilized data sets, detailed methods, and the results are included in File C (see footnote 1). This approach provides a robust statistical tool for comparing geochemical data from our PGB samples to the original data set and stratigraphic interpretations of Bailey (1988).

Area and Volume Calculations

Samples in our PGB data set were correlated with a PGB subunit, and their locations were mapped using ArcGIS. To determine the added area

[1]Supplemental Material. File A: Sample location and geochemical table (XRF and ICP-MS data). File B. Geochemical correlation of PGB samples. File C: Principal component analysis code. File D: Age spectra: Age plateaus and inverse isochrons. File E: ArArCALC age summary table. Please visit https://doi.org/10.1130/GEOS.S.21620850 to access the supplemental material, and contact editing@geosociety.org with any questions.

from our PGB samples, we drew polygons around samples located in the extended distribution; these polygons were classified as the same subunit (i.e., Twickenham, Monument Mountain, or Dayville). To determine the added volume of each PGB subunit, we used the average thickness of chemical types in the respective subunit and multiplied it by the newly determined area. This provides a low estimate for newly added PGB volume, and an upper limit was calculated by multiplying the newly determined area by 0.22 km, the average PGB thickness calculated by Tolan et al. (1987). These values represent best estimates for total volume, as many of the newly identified PGB lavas are found as laterally discontinuous exposures and likely vary in thickness from the PGB original distribution area.

$^{40}Ar/^{39}Ar$ Geochronological Methods

Three new high-precision $^{40}Ar/^{39}Ar$ ages (Table 1; File E; see footnote 1) were obtained by incremental heating methods using the ARGUS-VI mass spectrometer. Groundmass samples were irradiated for 6 h (Irradiation 15-OSU-07) in the TRIGA CLICIT nuclear reactor at Oregon State University, along with the Fish Canyon Tuff (FCT) sanidine (28.201 ± 0.023 Ma, 1σ) flux monitor (Koppers, 2002; Kuiper et al., 2008). Detailed geochronological methods are included in File E.

RESULTS

PGB Original Extent

The PGB subunit of the CRBG has been limited in its spatial distribution and thought to not extend far from its type locality at Picture Gorge based on field studies completed throughout the 1970s–1980s (Fig. 1 and Table 2). North-northwest–trending feeder dikes are compositionally and spatially associated with the PGB and have collectively been called the Monument dike swarm after Monument Mountain (Baldwin, 1973; Fruchter and Baldwin, 1975). PGB lavas and dikes have been mapped as far north as Lonerock and as far south as the Aldrich Mountains (Fig. 1) (Brown and Thayer, 1966; Bentley and Cockerham, 1973; Nathan and Fruchter, 1974; Fruchter and Baldwin, 1975; Robinson, 1975). The detailed stratigraphic work of Bailey (1989a, 1989b) was based on field data, including paleomagnetic and lithological data and geochemical evidence, and was confined spatially to north of the John Day Valley.

Correlating Samples with PGB Stratigraphy Using Principal Component Analyses

In the stratigraphic framework by Bailey (1989a), the Dayville Basalt is the interpreted youngest PGB subunit. Lava flows of the Dayville Basalt are limited in geographic extent and highly variable in geochemistry. Conversely, the older subunits of the Twickenham Basalt and Monument Mountain Basalt appear more homogeneous, consisting of lavas with intermediate (~6 wt% MgO) to high (7.5 wt%) MgO content (Fig. 3). In this original stratigraphic framework, however, there are multiple PGB lavas that exhibit overlapping compositions between the three subunits as well as chemical types within a subunit. Due to the degree of compositional overlap, correlation of distinct PGB chemical types based on a single element or elemental ratio is tenuous. To overcome this problem and help facilitate correlation, we utilize a PCA on major- and trace-element data of PGB. This approach enables us to take PGB samples of our extended distribution and place them within the established stratigraphy of PGB in the John Day Valley (Bailey, 1989a).

At Picture Gorge, the Monument Mountain and Dayville Basalt subunits are exposed as 15 distinct flows that dip south at 18° (Brown and Thayer, 1966). We sampled the lowermost and uppermost lavas at Picture Gorge and found that they are geochemically correlative with the Camas Creek and Hamilton chemical type, respectively (Figs. 2 and 6). This interpretation is also consistent with the interpretation of Bailey (1989a). Our interpretation was initially made with a review of Zr, TiO_2, and Cr/Ni values and substantiated using PCA on major- and trace-element geochemical data (Fig. 3).

The Twickenham Basalt, the oldest PGB subunit, is not exposed at the type locality of Picture Gorge but is found along the western portion of the previously mapped extent. We sampled a section of multiple lava flows at Kentucky Butte, the type locality of the Twickenham Basalt, and confirmed the geochemical similarity to this subunit (Bailey, 1989a) (Fig. 6). Similarly, the uppermost flows at Monument Mountain and Tamarack Mountain conform with the stratigraphy established at each location by Bailey (1989a) (Fig. 6). At Monument Mountain, we observe the Monument Lookout chemical type at the top, and at Tamarack Mountain, we observe the Hamilton chemical type capping the section, with both chemical types being part of the Monument Mountain subunit (Figs. 6 and 7). These interpretations are made on the basis of TiO_2, Cr/Ni, and trace-element concentrations such as La and Zr (ppm), and further corroborated through our PCA on the PGB geochemical data.

Stratigraphy in Context of New Ar/Ar Ages

Combining the stratigraphy with 11 recently reported $^{40}Ar/^{39}Ar$ ages (Cahoon et al., 2020) and three new $^{40}Ar/^{39}Ar$ ages (Table 1) allows us to shed light on emplacement time of the basal PGB units at different locations while taking the whole-rock composition of undated PGB flows (Figs. 7 and 8) into account. We also note the apparent stratigraphic interfingering of all three PGB subunits in the extended area over the duration of PGB eruptions (Fig. 8). Given the high precision of collected geochemical and geochronological data, this is likely a result of overlapping geochemical signatures in PGB subunits causing PCA misidentification of some samples.

At Picture Gorge, the lowermost basalt yields a 17.14 ± 0.04 Ma weighted mean age, within error of the inverse isochron age (PG; sample CAH17-245; Table 1) (Cahoon et al., 2020). This age and compositional correlation with the Camas chemical type of the Monument Mountain Basalt subunit of the PGB imply that the lower Twickenham Basalt subunit would need to be even older. Another basal PGB lava located at Holmes Creek (HC; sample CAH17-222A), 20 km north of the type locality, has a mini-plateau age of 17.23 ± 0.04 Ma (Cahoon et al., 2020). While a mini-plateau age is calculated using less than 50% of the total radiogenic argon released, this age is consistent with the observed stratigraphy as the sample is geochemically similar to the Twickenham Basalt (Cahoon et al., 2020) (Fig. 8). A third basal PGB lava near the town of Dale (D; sample CAH17-200) is located 80 km northeast of Picture Gorge. This lava is exposed directly above the 33 Ma tuff of Dale from the Tower Mountain volcanic field (Brown, 2017) and yields a plateau age of 17.02 ± 0.03 Ma. This 17.02 Ma age however is not perfectly consistent with other PGB ages and established stratigraphy, as this basaltic lava is most similar to the Twickenham Basalt. Nevertheless, all newly dated basal PGB lavas represent chemical types of the lower third of the internal PGB stratigraphy, and thus place onset of PGB eruptions just prior to 17 Ma (Fig. 8).

At the southernmost extent of the PGB and Monument dike swarm (Fruchter and Baldwin, 1975), an aphyric dike in the Aldrich Mountains (AM; sample CAH15-023) yields an age plateau of 16.88 ± 0.06 Ma (Cahoon et al., 2020). This recently reported age is robust as it is within error of the inverse isochron age and has a concordant isochron with $^{40}Ar/^{36}Ar$ initial ratio of 296.22 ± 0.28. This age, coupled with first-order observations of its geochemical characteristics, indicate this dike is chemically correlative with Twickenham Basalt, the oldest of the three PGB subunits (Fig. 3). However, the principal component analysis suggests this dike is best geochemically correlated to a different chemical type, the Dale chemical type of the Dayville Basalt, the youngest of the three PGB subunits. While the accuracy of the PCA on the geochemical similarities of PGB subunits was gauged against known samples (and correct at >85%), this specific prediction is questionable. All previous samples of the Dale chemical type cluster tightly in geochemical space, and our sample (CAH15-023) does not reflect this consistency (Fig. 3). Furthermore, basalts of the Dale chemical type exhibit elevated Cr/Ni ratios (>3.1) and depleted incompatible element concentrations, while this sample has a Cr/Ni ratio <2 (Fig. 3B). If indeed correlative with the Dale

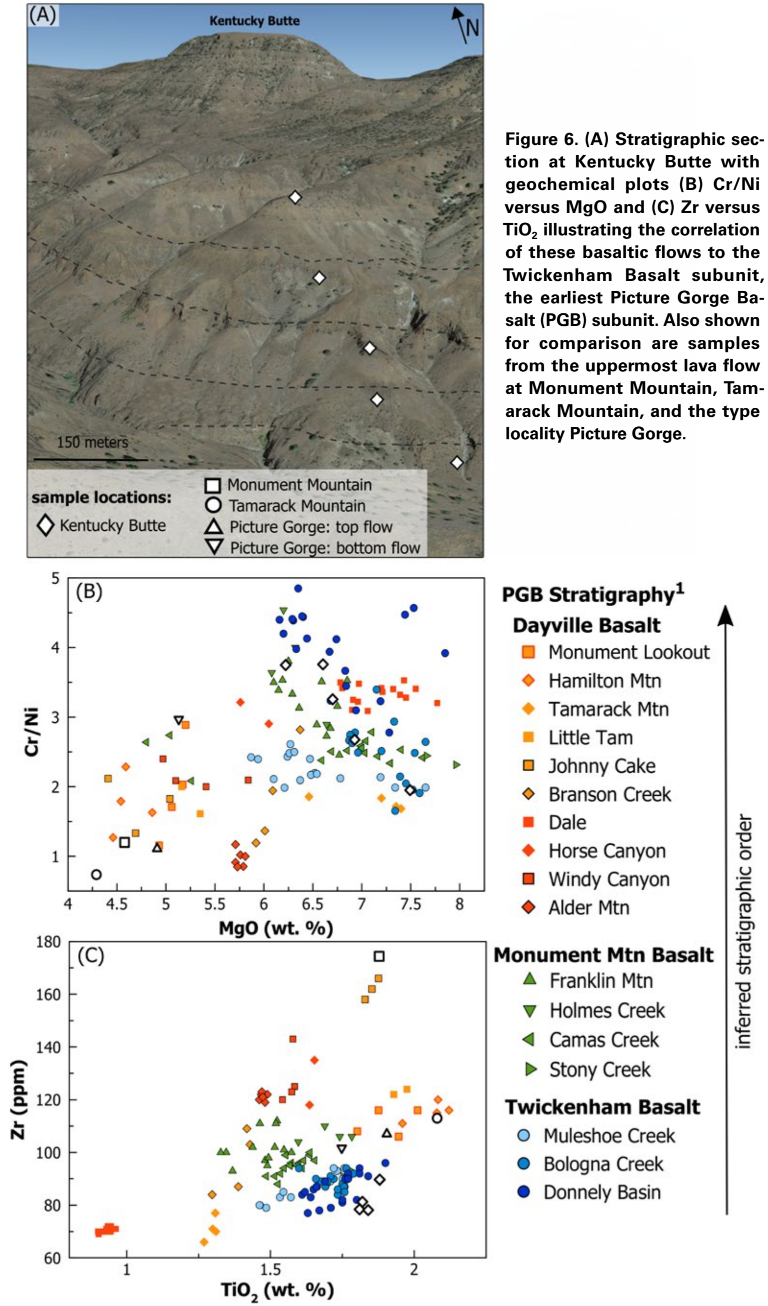

Figure 6. (A) Stratigraphic section at Kentucky Butte with geochemical plots (B) Cr/Ni versus MgO and (C) Zr versus TiO_2 illustrating the correlation of these basaltic flows to the Twickenham Basalt subunit, the earliest Picture Gorge Basalt (PGB) subunit. Also shown for comparison are samples from the uppermost lava flow at Monument Mountain, Tamarack Mountain, and the type locality Picture Gorge.

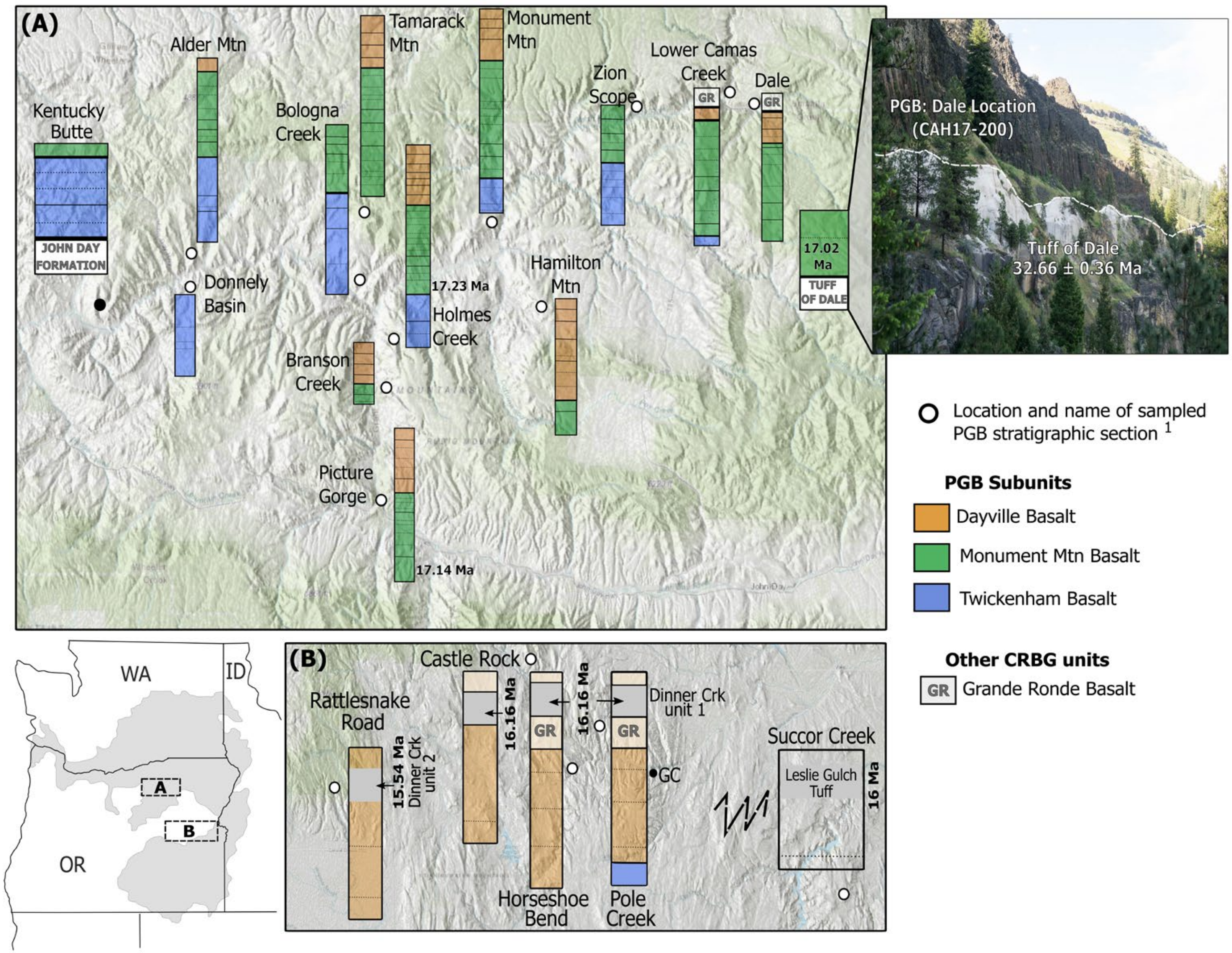

Figure 7. Fence diagram illustrating the relative thickness of each Picture Gorge Basalt (PGB) subunit across (A) the original mapped distribution area with our added ages and (B) our added distribution throughout the Malheur Gorge with colors corresponding to PGB subunit prediction from a principal component analysis (PCA). With the exception of the lowermost flow at Pole Creek, all analyzed PGB samples from these four transects were assigned via PCA to the Dayville subunit. GC—Gold Creek. [1]Stratigraphic sampling and identification of PGB subunits by Bailey (1988).

TABLE 1. SUMMARY OF GROUNDMASS $^{40}Ar/^{39}Ar$ AGES FOR PICTURE GORGE BASALT

Sample location	Sample name	Age (Ma)	Error (±2σ)	MSWD
Dooley Mountain (DM)[1,*]	DM255B	15.76	0.11	0.58
Rainbow Campground (RC)*	CAH16-179B	16.02	0.08	1.83
Gilbert Ridge (GR)	MS-11-6	16.06	0.14	1.09
Ponderosa Mine (PM)*	CAH16-163	16.18	0.05	4.34
West Myrtle Butte (WMB)	CAH15-007	16.22	0.06	0.96
Castle Rock (CR)[2]	MC-76-16	16.23	0.09	0.9
Izee (I)	CAH16-148	16.62	0.07	1.82
Inshallah Ranch (IR)	CAH16-138	16.70	0.09	0.8
Pole Creek/Malheur Gorge (PC)	CAH16-065	16.72	0.03	1.84
Aldrich Mountains (AM)	CAH15-023	16.88	0.06	1.1
Snow Mountain (SM)	CAH16-174A	16.96	0.07	0.85
Dale (D)	CAH17-200	17.02	0.03	0.86
Picture Gorge (PG)	CAH17-245	17.14	0.04	2.95
Holmes Creek (HC)	CAH17-222A	17.23	0.04	2.25

[1]Sample from Large (2016).
[2]Sample from Cruz (2017).
*Age data from this study.
Note: Other ages from Cahoon et al. (2020). MSWD—mean square of weighted deviates.

chemical type, the 16.88 Ma age of this dike would indicate the majority of the PGB erupted over a period of ~300 k.y. or suggests this chemical type was not properly placed within the PGB stratigraphy. Overall, the oldest PGB samples with ages near 17 Ma contain geochemical characteristics that are most similar to the inferred lower stratigraphic chemical types of Bailey (1989a, 1989b) (Fig. 8B).

Extended Distribution

Adjacent to the original distribution area of the PGB, widespread unstudied, mid-Miocene basaltic lavas and dikes are exposed between the southern extent of the PGB and the presumed northern extent of Steens Basalt in a wide corridor of Malheur National Forest, eastern Oregon (Fig. 5). These basalts are depicted on earlier geologic maps (Wallace and Calkins, 1956; Brown and Thayer, 1966; Greene et al., 1972) and distributed southeast of the Picture Gorge type locality. These lavas are geochemically similar to PGB (Fig. 9) and can be placed in the same stratigraphic interval as PGB flows of the original distribution, occurring below the 16.16 Ma Dinner Creek Tuff unit 1 (Streck et al., 2015) in the area between the towns of John Day and Burns along the western corridor to highway 395 (Fig. 5). Similar stratigraphic constraints have been revealed for other unassigned basalt lavas considerable distances west and southeast of the original distribution at Dooley Mountain (Large, 2016), at Castle Rock (Cruz, 2017; Cruz and Streck, 2022), and north of Fort Harney along Rattlesnake Creek (Isom and Streck, 2016; Houston et al., 2017) (Fig. 1).

In addition, lavas previously assigned at Pole Creek in Malheur Gorge to Steens Basalt reveal that they are compositionally more akin to PGB and hence should instead be reassigned (Fig. 10) (Cahoon et al., 2020). Careful evaluation of basaltic lavas exposed throughout this region thus provides an opportunity to expand the PGB distribution area and explore the petrogenetic and temporal transition between PGB and other CRBG units. Below, we first review compositional variations of PGB lavas in context of other main-phase CRBG units. We then identify compositional parameters that best distinguish PGB from other CRBG units, and finally, we present results of geochemical correlation to local flows with PGB.

PGB: Compositional Variability and Contrast to Other Main-Phase CRBG Units

Main-phase CRBG units cover an extensive compositional spectrum often overlapping in terms of major-, trace-element, and isotopic compositions (Fig. 9). In general, samples of PGB have most compositional commonalities with Steens Basalt (e.g., Carlson, 1984; Wolff and Ramos, 2013); yet there are distinguishing features, the most notable of which are that PGB has the lowest $^{87}Sr/^{86}Sr$, highest $^{143}Nd/^{144}Nd$ ratios, the lowest concentrations of some incompatible elements, and elevated ratios of large ion lithophile elements (LILEs) to high field strength elements (HFSEs).

The PGB can be distinguished from other main-phase units using a variety of geochemical parameters. In comparison to the Grande Ronde Basalt, the PGB exhibits lower concentrations of SiO_2 (mostly <53 wt%) and in general lower incompatible trace-element contents, for example, La, Y, and Hf (Fig. 9).

When compared to Imnaha Basalt and Steens Basalt, the PGB exhibits a comparable SiO_2 range, ~48.5–53 wt% (Fig. 9). Imnaha Basalt contains <51% SiO_2 for Rock Creek and >51% for American Bar chemical types (cf. Hooper, 1974), and the Rock Creek subtype is not found along the Oregon plateau (V. Camp, 2019, personal commun.). At a given silica content, the PGB contains lower concentrations of various incompatible elements such as Th, Hf, La, and typically most HFSEs, and LREEs (Fig. 9). Finally, the vast majority of PGB samples contain concentrations of Nb under 8.5 ppm (Fig. 10C), which is useful to distinguish PGB from Imnaha lavas except for the stratigraphically lowest flows at Dug Bar and surroundings.

When evaluated against the Steens Basalt, the PGB contains lower Hf, Th, and La and is clearly separated from samples of Steens Basalt on a Sc versus TiO_2 plot (Fig. 9). Other geochemical parameters provide also a clear distinction such

TABLE 2. AREA AND VOLUME OF PICTURE GORGE BASALT SUBUNITS AND CHEMICAL TYPES

PGB subunit	PGB chemical type	John Day Basin*					Added distribution**		
		Average thickness (m)	Chemical type area (km^2)	Chemical type min. volume (km^3)	Subunit thickness (m)	Subunit volume (km^3)	Area (km^2)	Volume† (km^3)	Volume§ (km^3)
Dayville	Monument Lookout	20			160 (max.)	160	12,500	350	2750
	Hamilton	45	600						
	Tamarack Mountain	20							
	Little Tamarack	20							
	Johnny Cake	30							
	Branson Creek	30							
	Dale	30							
	Horse Canyon	25							
	Windy Canyon	45							
	Alder Mountain	20							
Monument Mountain	Franklin Mountain	160	1600	255	240–350	480	3050	210	670
	Holmes Creek	30	1200						
	Camas Creek	65	1300	85					
	Stony Creek	30							
Twickenham	Muleshoe Creek	105			400 (max.)	150	10,100	610	2220
	Bologna Creek	27							
	Donnely Basin	60							
PGB total:					910 (max.)	790		1170	5640

Note: Picture Gorge Basalt (PGB) chemical types in relative stratigraphic order with the oldest at the bottom.
*Mapped across 1600 km^2 in the John Day Basin (Bailey, 1988).
**Added PGB distribution (this study).
†Volume calculated using the average single chemical type thickness within a respective PGB subunit: 0.06 km Twickenham Basalt, 0.07 km Monument Mountain Basalt, and 0.028 km Dayville Basalt.
§Volume calculated using the calculated thickness of PGB (Tolan et al., 1987).

as Zr/Y values. Samples of PGB have Zr/Y <4 at low SiO_2 and <4.5 at high SiO_2 while samples of Steens Basalt indicate ratios >4 and >4.5, respectively (Fig. 10D).

Locations with Lavas of PGB Composition

Corridor from John Day to Burns. Exposed south of the town of John Day, the main Monument dike swarm, and the Strawberry and Aldrich Mountains (Fig. 5), lava flows of mid-Miocene basalt are abundant but lack the lateral continuity of exposures farther north near the type locality (Brown and Thayer, 1966; Greene et al., 1972). This is likely the result of the paleo-topography, subsequent erosion, or coverage by the 16.16 Ma Dinner Creek Tuff (unit 1) or younger widespread ignimbrites (e.g., Streck et al., 2015). Despite the fact that the area is overlapping with the southern portion of the Monument dike swarm, these basalts have not been adopted into recent compilations of PGB distributions (Reidel et al., 2013, and references mentioned therein).

Just south of the original distribution area, there are NNW-trending plagioclase-phyric dikes with PGB composition. At Inshallah Ranch (Fig. 5), one of these dikes (IR; sample CAH16-138) yields a plateau age of 16.70 ± 0.09 Ma. This age matches the inverse isochron age and has an $^{40}Ar/^{36}Ar$ initial ratio of 295.37 ± 1.06. Less than 20 km farther south, near the town of Izee, a plagioclase-phyric lava (I; sample CAH16-148) yields a plateau age of 16.62 ± 0.07 Ma, within error of the inverse isochron age. These two samples are similar in their texture and age and have a PGB geochemistry.

To the east, an olivine-phyric lava at West Myrtle Butte (WMB; sample CAH15-007) yields an age plateau of 16.22 ± 0.06 Ma (Table 1). This age is within error of the inverse isochron age and has a $^{40}Ar/^{36}Ar$ initial ratio of 298.52 ± 0.91. Proximal to this flow, a plagioclase-phyric dike at Gilbert Ridge (GR; sample MS-11-6) yields a plateau age of 16.06 ± 0.14 Ma, which places it during the younger eruptive period of the PGB (Fig. 8B). This dike was not previously included as part of the Monument dike swarm and does not protrude from the surrounding country rock. This lack of topographic relief is different from the bulk of the PGB dikes to the north

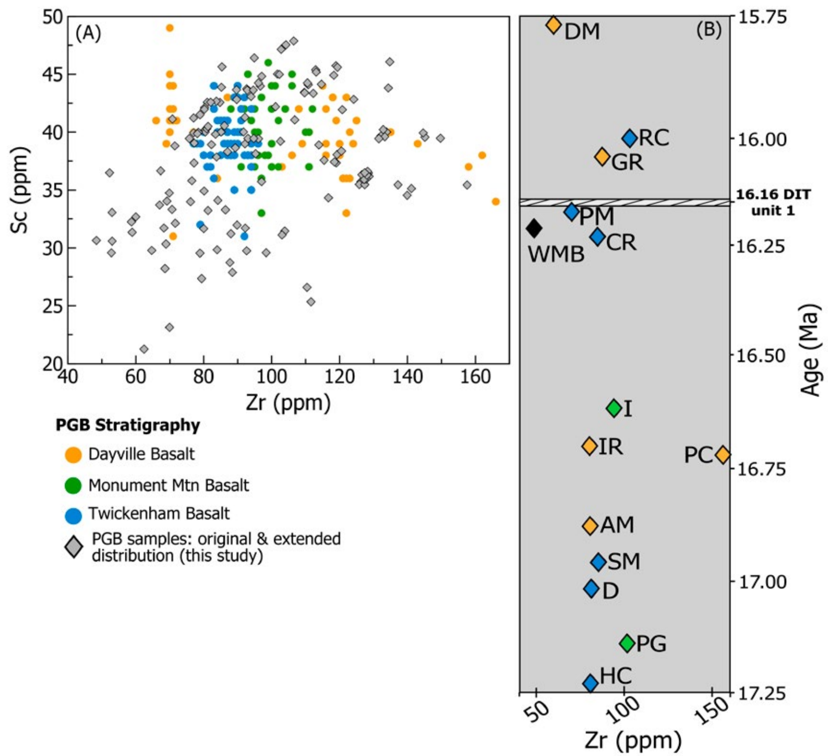

Figure 8. (A) Sc versus Zr scatterplot of Picture Gorge Basalt (PGB) samples from our added distribution compared to the three PGB subunits. (B) Stratigraphic column of dated PGB samples highlighting the PGB subunit represented by each dated sample and the Zr concentration with respect to age. Abbreviations of sample locations are the same as listed in Table 1.

in the Monument dike swarm extent; these dikes do create topographic protrusions. Finally, near the southern end of this corridor, a PGB lava is exposed at the top of Snow Mountain, a topographic high on the north side of the High Lava Plains with an elevation >2200 m. This sample (SM; sample CAH16-174A) reflects an age at the older end of the PGB age spectrum, yielding a plateau age of 16.96 ± 0.07 Ma (Table 1). This age is robust as it is within error of the inverse isochron age and has a $^{40}Ar/^{36}Ar$ initial ratio of 296.88 ± 0.34 (Files D and E; see footnote 1) (Cahoon et al., 2020).

Rattlesnake Road. East of the town of Burns, there are multiple lavas of PGB composition exposed along Rattlesnake Road (Fig. 1). Temporally, these basaltic lavas are stratigraphically constrained as they overlie and underlie Unit 2 of the Dinner Creek Tuff, dated at ca. 15.6–15.5 Ma (Streck et al., 2015; Hanna, 2018). This field relationship indicates some basaltic lavas exposed here are younger than the dated PGB lavas or dikes to the northwest surrounding the type locality.

Malheur Gorge and Castle Rock area. Malheur Gorge is the only locality where lavas of Steens Basalt, exposed to the south, interfinger with lavas from Imnaha and the Grande Ronde Basalt, both typically exposed farther to the north. The presumed prior stratigraphy in Malheur Gorge is lower Steens Basalt overlain by upper Steens Basalt and/or Imnaha Basalt and in turn overlain by Grande Ronde Basalt (Fig. 4). Stratigraphic control in Malheur Gorge is aided by conspicuous outcrops of unit 1 of the Dinner Creek Tuff (16.16 Ma), which, by definition, is overlain by lavas of the Hunter Creek Basalt and underlain by Birch Creek lavas—with both units belonging to the Grande Ronde Basalt. In addition, intercalated rhyolite units of the Littlefield Rhyolite yield additional temporal constraints on the final flood basalt activity in Malheur Gorge (cf. Webb et al., 2018). Samples for this study were taken from lava flows stratigraphically below unit 1 of the Dinner Creek Tuff, exposed along three vertical sections within Malheur Gorge (Pole Creek, Horseshoe Bend, and Gold Creek) (Fig. 10).

Within the Pole Creek section, the lower basaltic lavas have been previously described as the lower Steens Basalt (Jarboe et al., 2008), but other identified basaltic flows exhibit geochemical signatures most similar to the PGB (Cahoon et al., 2020). At the Pole Creek section, PGB flows are overlain by the Birch Creek lavas and Dinner Creek Tuff unit 1 and are capped by Hunter Creek Basalt (Fig. 10).

At Horseshoe Bend, ~10 km southwest of Pole Creek, the stratigraphy is comparable to the one at Pole Creek. This stratigraphic section of basalt is also capped by the 16.16 Ma Dinner Creek Tuff. Below the Dinner Creek Tuff, there are first lavas belonging to the Birch Creek unit and these overlie lavas that have geochemical traits most similar to the PGB (Fig. 10). Less than 10 km to the southeast at Gold Creek, additional basaltic lavas with PGB geochemical affinities are present, but their stratigraphic placement is unclear (Fig. 7).

Adding PGB to the lava packages occurring in Pole Creek, Horseshoe Bend, and Gold Creek indicates that Malheur Gorge is the area where all main-phase CRBG units are in stratigraphic contact (Fig. 10). The lava flow immediately below Grande Ronde Basalt in Pole Creek yields an age plateau of 16.72 ± 0.03 Ma (PC; sample CAH16-065). This is within error of the inverse isochron age (16.73 ± 0.05 Ma) and has a concordant isochron with $^{40}Ar/^{36}Ar$ initial ratio of 302.88 ± 1.14. This age fits within the age relationships defined by Camp et al. (2003) but is not within 2σ uncertainty with

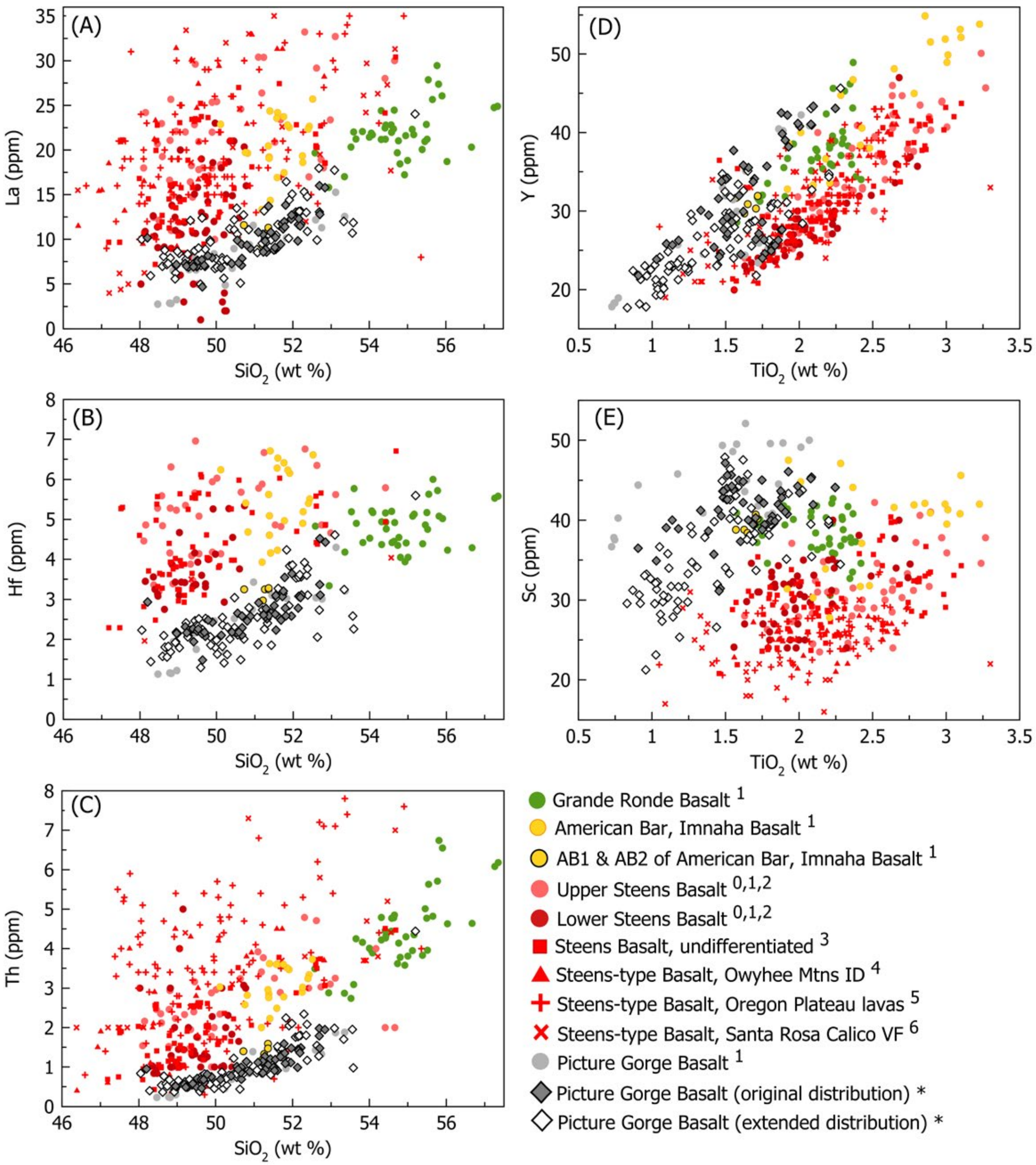

Figure 9. Geochemistry of Picture Gorge Basalt (PGB) samples from this study compared to the other main-phase Columbia River Basalt Group (CRBG) units. (A) La versus SiO_2; (B) Hf versus SiO_2; (C) Th versus SiO_2; (D) Y versus TiO_2; and (E) Sc versus TiO_2. The PGB samples from this study (*) are subdivided based on their location either in the previous mapped extent of the PGB or our proposed added distribution. Of the Imnaha Basalt chemical types defined by Hooper et al. (1984), only the American Bar types are found in the study area. The American Bar chemical type lavas are plotted here as undifferentiated American Bar, AB1, and AB2 at Dug Bar. AB1 and AB2 lavas are highlighted for their geochemical similarity to PGB. Geochemical data compiled from the following studies: [0]Johnson et al. (1998); [1]Wolff et al. (2008); [2]Binger (1997); [3]Moore et al. (2018); [4]Hasten (2012); [5]Brueseke et al. (2007); and [6]Brueseke and Hart (2008). The geochemical data sourced from studies 0, 2, 4, 5, and 6 contain only X-ray fluorescence (XRF) data, and the geochemical data compiled from studies 1 and 3 contain both XRF and inductively coupled plasma-mass spectrometer data.

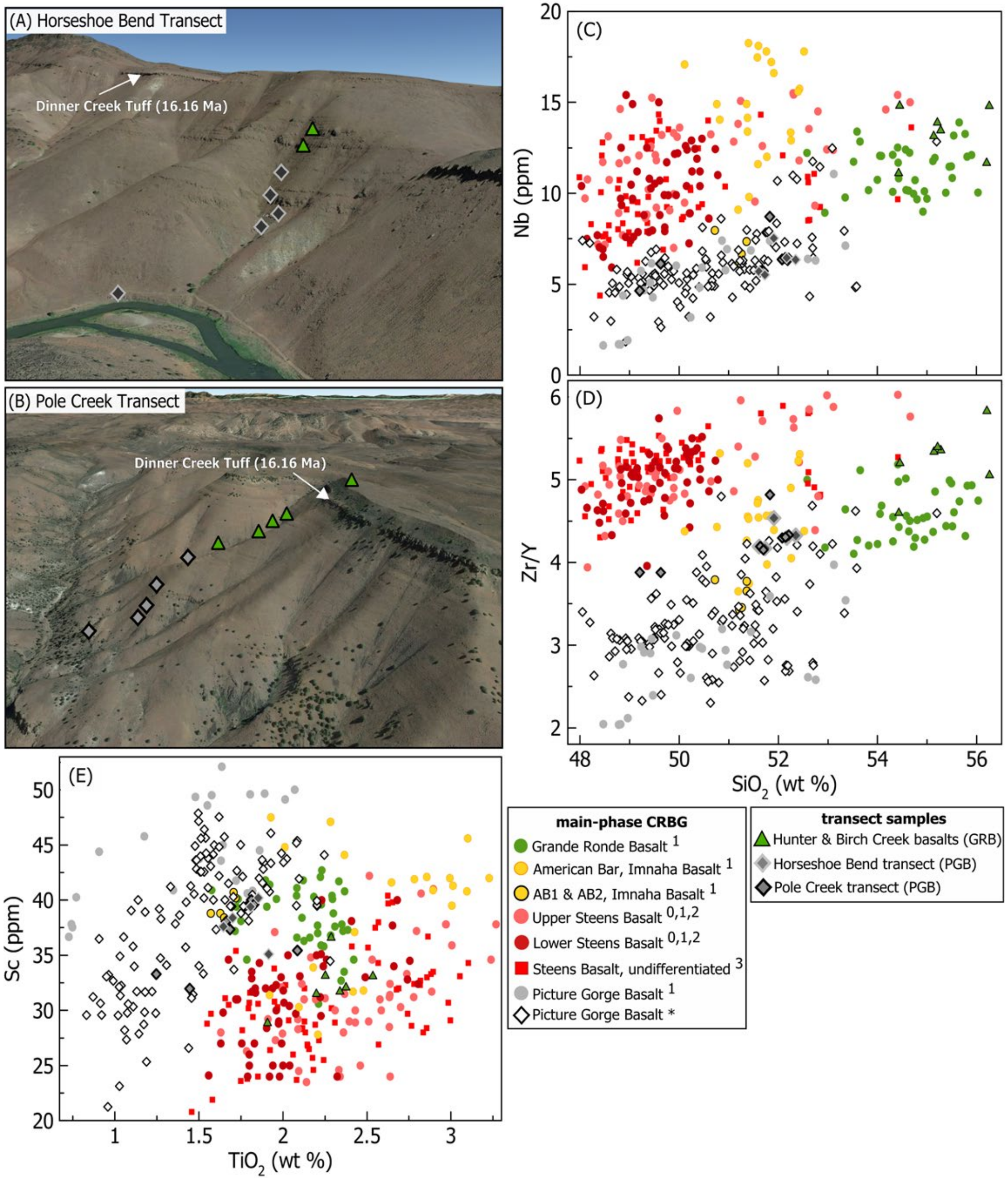

Figure 10. Section photographs of basaltic lava flows in the Malheur Gorge at (A) Horseshoe Bend and (B) Pole Creek highlighting our sample locations and relative stratigraphic position of the Dinner Creek Tuff (unit 1). Geochemical data of basaltic samples along transects at Horseshoe Bend and Pole Creek compared to Columbia River Basalt Group (CRBG) main-phase CRBG units, and our samples of Hunter and Birch Creek basalt include (C) Nb versus SiO_2; (D) Zr/Y versus SiO_2; and (E) Sc versus TiO_2. Geochemical data compiled from the following studies: [0]Johnson et al. (1998); [1]Wolff et al. (2008); [2]Binger (1997); [3]Moore et al. (2018); and *this study. The geochemical data sourced from studies 0 and 2 contain only X-ray fluorescence data, and the geochemical data compiled from studies 1, 3, and this study contain both XRF and inductively coupled plasma-mass spectrometer data.

an apparently younger plagioclase age (16.45 ± 0.11 Ma, 1σ) of Steens Basalt in Pole Creek (Jarboe et al., 2010). This dated Steens Basalt lava is thought to represent the base of the Pole Creek section, although the section with Steens Basalt is not in direct stratigraphic continuity but is offset by an inferred normal fault from the section with our dated sample and with PGB at the lowest stratigraphic exposures. The presence of a fault is supported by field evidence and the relative stratigraphic height of the Dinner Creek Tuff, which serves as a conspicuous marker bed throughout the western extent of the Malheur Gorge. Finally, the interpretation that all lower Pole Creek lavas are correlative to Steens Basalt is based on major- and trace-element data (XRF only) primarily sourced from Binger (1997) and inferred field relationships.

Along the northwestern edge of the Malheur Gorge, a prominent topographic high, Castle Rock, is interpreted as a source area for unit 1 of the Dinner Creek Tuff. Here, lavas with PGB compositions underlie Grande Ronde–type basalts, which, in turn, are capped by the 16.16 Ma Dinner Creek Tuff unit 1 (Cruz, 2017; Cruz and Streck, 2022). These stratigraphic relationships at Castle Rock are similar to the sections at Pole Creek and Horseshoe Bend. The age of our PGB sample at Castle Rock (CR; sample MC-76-16) is consistent with observed stratigraphy and yields a slightly older age plateau of 16.23 ± 0.09 Ma (Cahoon et al., 2020). This plateau age is within error of the inverse isochron age and has a concordant isochron with $^{40}Ar/^{36}Ar$ initial ratio of 294.85 ± 0.27.

PGB extent in northeast Oregon. Farther northeast, lavas with PGB composition are exposed at Dooley Mountain, 150 km away from the type locality at Picture Gorge (Figs. 1 and 11) (Large, 2016). Dooley Mountain is the northernmost rhyolite complex of the mid-Miocene rhyolite associated with initiation of Yellowstone hotspot. Various lavas with PGB geochemical affinities and Dinner Creek Tuff units both cap and underlie the Dooley Mountain rhyolite complex (Fig. 11) (Large, 2016). The oldest unit of the Dinner Creek Tuff (unit 1) is exposed beneath the 15.59 ± 0.04 Ma base of the Dooley Mountain complex (Hess, 2014). Here, we dated a PGB sample (DM; sample DM255B) that appears to underlie the Dinner Creek Tuff (unit 1), dated at 16.16 Ma (Streck et al., 2015). Our sample, however, yields an age plateau of 15.76 ± 0.11 Ma, arguing against the observed stratigraphy. This plateau age is within error of the inverse isochron age (15.76 ± 0.25 Ma) and exhibits a concordant isochron with $^{40}Ar/^{36}Ar$ initial ratio of 295.75 ± 1.28. We argue that this lava may not underlie unit 1 of Dinner Creek Tuff but may represent an intra-canyon flow. Near Brogan, Oregon, there are sections of multiple basaltic lavas that match PGB composition and directly overlie pre-Cenozoic accreted terrane rocks (Figs. 1 and 11) (Fox, 2022). These basaltic lavas are similar to the middle and upper subunits of the PGB, and a lateral continuity is likely between Dooley Mountain and the PGB of the original extent (Fig. 13).

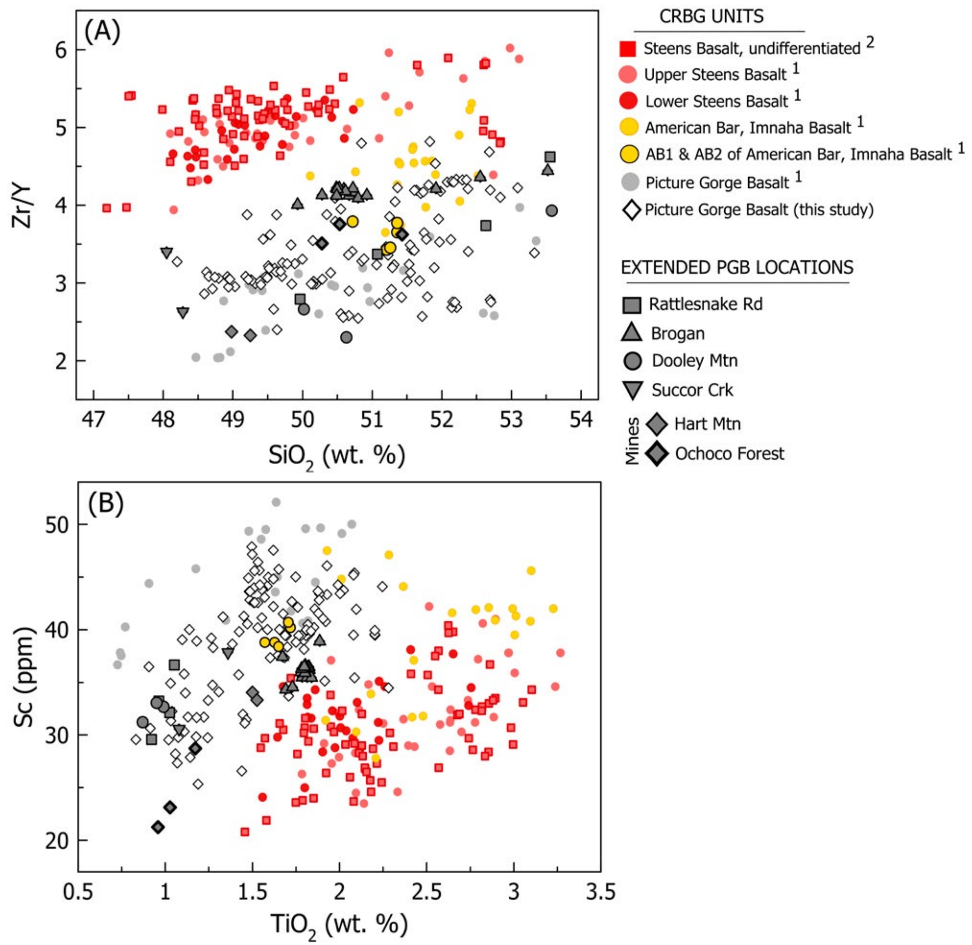

Figure 11. Main-phase Columbia River Basalt Group (CRBG) geochemistry and multiple Picture Gorge Basalt (PGB) samples highlighted from specific locations in the extended distribution. Both mine locations are denoted by "Mines." (A) Zr/Y versus SiO_2 and (B) Sc versus TiO_2. Data compiled from [1]Wolff et al. (2008) and [2]Moore et al. (2018).

Farther to the northeast, early workers identified basaltic lavas with PGB chemistry below Imnaha lavas at Dug Bar, east of the Wallowa Mountains (Waters, 1961; Bond, 1963; Baksi and Watkins, 1973; Wright et al., 1973; Watkins and Baksi, 1974; Kleck, 1977) (Fig. 9). These lavas were originally described as "PGB-type" but never correlated with PGB because of their distance from the type locality (Swanson et al., 1979; Fiebelkorn et al., 1983). Based on the older ages and identification of PGB lavas >100 km from the type locality at Picture Gorge, these Dug Bar lavas likely share a mantle source component with other lavas of PGB composition.

Southcentral and southeastern Oregon. To the south near Hart Mountain, there are multiple open-pit sunstone mines (Fig. 1). Sunstones are copper-enriched plagioclase phenocrysts (up to ~10 cm, An_{65} to An_{72}) hosted in scattered, highly porphyritic basaltic lavas in two primary localities in eastern Oregon. These two localities are ~150 km apart—near Delintment Lake, Ochoco National Forest, and near Plush, located west of Hart Mountain (Fig. 1) (Stewart et al., 1966; Hofmeister and Rossman, 1985). These sunstone-bearing lavas near Delintment Lake yield whole-rock geochemical data that are equivalent to PGB (Fig. 11), and a dated sample collected from the sunstone mine yields a plateau age of 16.18 ± 0.05 Ma (Table 1; PM, sample CAH16-163).

To the south near Hart Mountain, the basaltic lavas containing sunstones yield whole-rock geochemical signatures similar to the PGB (Welch et al., 2019). Although this geochemical observation suggests that these basaltic lavas are associated with sunstone-bearing lavas near Delintment Lake, the sunstone-bearing lavas near Hart Mountain are significantly younger (e.g., ca. 9 Ma; Badur, 2022). We do not propose that eruptions of PGB lavas continued until 9 Ma, although this age discrepancy between sunstone-bearing lavas could have implications for the extent and geometries of crustal reservoirs and storage conditions. Given their geological rarity, sunstones are unlikely the result of localized post-emplacement surficial processes. It is also extremely unlikely that the locations reflect a single laterally continuous lava flow, as sunstone-bearing lavas are located ~150 km apart and contain ~25%–40% crystals; and the physical volcanology indicates proximity to an eruptive vent. The specific magmatic processes associated with eruptions of coarse plagioclase crystals in CRB provinces are unclear but may include growth of plagioclase phenocrysts in deep crustal sills that are later transported to the surface (Sheth, 2016).

Moving east toward the Oregon-Idaho border, there are multiple mid-Miocene rhyolitic calderas that appear to be coeval with the CRBG. Some of these calderas include the Mahogany Mountain, Three Fingers, and Rooster Comb caldera (Vander Meulen et al., 1989; Mahood and Benson, 2017). On the northeastern margin of these silicic centers near Succor Creek, there are some scattered basaltic dikes and associated lava flows (Black, 2022). The dikes are northwest trending and have whole-rock compositions that suggest they share a mantle component with PGB lavas exposed in the type locality of Picture Gorge (Fig. 11). We do not aim to correlate the basaltic lavas and dikes to established stratigraphic subunits and/or chemical types within PGB, but we communicate the existence of these basaltic compositions to improve our understanding of the storage and plumbing of CRBG magmas.

DISCUSSION

Placing Basalts of Extended Distribution into the PGB Stratigraphy

The PGB internal stratigraphy documented by Bailey (1989a) is based on three subunits that are in turn subdivided into 17 chemical types, which represent observed stratigraphy within the type locality and the original distribution area north of the John Day Valley (Brown and Thayer, 1966). However, without stratigraphic context, many chemical types of the PGB are indistinguishable and difficult to differentiate even with geochemical data. Additionally, Bailey (1989a, 1989b) identified 18 geochemically unique basalt lava flows that were left unassigned and not included in the original PGB and CRBG stratigraphy.

The compositional ambiguity, along with the lack of multiple laterally continuous basalt exposures over the extended PGB distribution area, provides challenges when assigning newly identified lavas as a specific subunit or chemical type in the PGB stratigraphy. By extending the distribution of PGB lavas beyond the original distribution—as we are doing in this study—the geochemical variability of PGB lavas and dikes also somewhat increases (Fig. 9). Despite these uncertainties, we show that the newly identified PGB samples can be compared to geochemical data of the original PGB stratigraphy using a PCA on geochemical data for 20 total major and trace elements. The results indicate that newly identified PGB samples best conform to the lower and upper subunits of the PGB, the Twickenham and Dayville Basalts, respectively, and only a limited number of our PGB samples have similarities to chemical types in the middle subunit within the PGB stratigraphy (Monument Mountain) (Fig. 8). This observation is also supported by the $^{40}Ar/^{39}Ar$ ages collected on 14 of the PGB basalts (Cahoon et al., 2020; and data presented here). Though it should be noted that some newly identified PGB flows in this study may represent unassigned flows that were not represented in the stratigraphic section of Bailey (1988).

Basalt of Malheur Gorge

More than 100 km southeast of Picture Gorge, the Malheur Gorge has been highlighted as a key area for demonstrating stratigraphic relationships among Steens, Imnaha, and Grande Ronde Basalt chemical types of the CRBG (Hooper et al., 2002; Camp et al., 2003). In light of the discovery that PGB lavas also reach into the Malheur Gorge area, it is worthwhile to review data that allowed for correlation of lavas of the basalt of Malheur Gorge, divided into lower, upper Pole Creek lavas, Birch Creek lavas, and Hunter Creek Basalt, with specific main phase CRBG units. The interpretation that all lower Pole Creek lavas (part of the basalt of Malheur Gorge) are correlative with Steens Basalt is based on geochemical data from Binger (1997) and Hooper et al. (2002).

Comparing the current geochemical data on Steens Basalt and PGB to the geochemical data on the lower and upper Pole Creek basalts of Binger (1997) raises questions about the robustness of the original correlations (Fig. 12). In fact, major- and

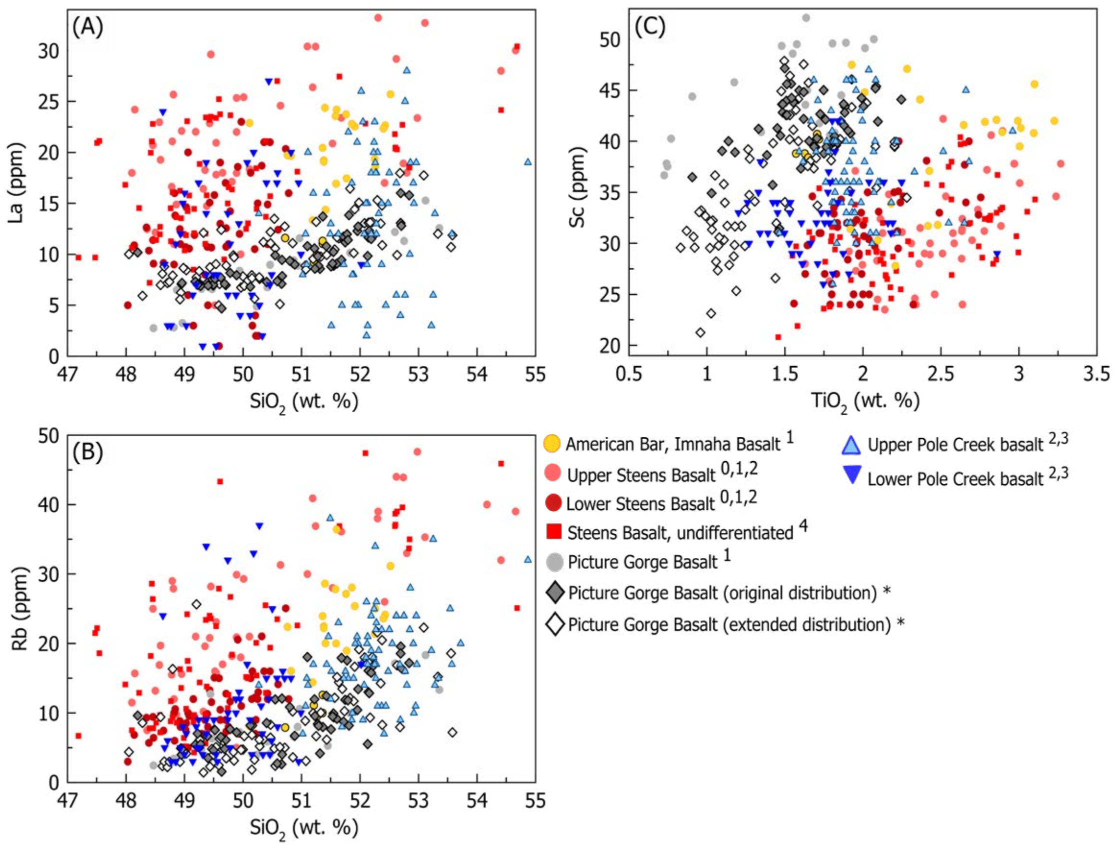

Figure 12. Variation diagrams comparing upper and lower Pole Creek lavas to select main-phase Columbia River Basalt Group (CRBG) units. (A) La versus SiO_2; (B) Rb versus SiO_2; and (C) Sc versus TiO_2. Geochemical data compiled from the following studies: [0]Johnson et al. (1998); [1]Wolff et al. (2008); [2]Binger (1997); [3]Hooper et al. (2002); and [4]Moore et al. (2018). The geochemical data sourced from studies 0 and 2 contain only X-ray fluorescence (XRF) data, and the geochemical data compiled from studies 1 and 3 contain both XRF and inductively coupled plasma-mass spectrometer data. PGB samples from this study (*) are subdivided based on their location either in the previous mapped extent of the PGB or our proposed added distribution.

trace-element geochemical plots highlight the overlap of lower and upper Pole Creek basalts with PGB and Steens Basalt, where the degree of overlap with either CRBG unit varies depending on plot (Fig. 12). In fact, lower Pole Creek lavas exist between PGB and Steens Basalt on many plots—including Sc (ppm) versus TiO_2 (wt%), which otherwise clearly distinguishes PGB and Steens Basalt. Additionally, upper Pole Creek lavas are chemically distinct from upper Steens Basalt (e.g., Zr/Y and Rb) and share more geochemical space with PGB compared to Imnaha Basalt (Fig. 12).

These geochemical comparisons indicate that PGB lavas may be present throughout Malheur Gorge, not restricted to the western edge. Current data are insufficient to fully confirm this, but these data sets demonstrate that all lower Pole Creek lavas cannot be assigned as Steens Basalt.

Eruptive Locations

The original distribution of the PGB was limited to the type locality at Picture Gorge and surroundings, and no lavas were found to extend southward of the John Day Valley (Fig. 1). Our field and geochemical data indicate basaltic lavas and dikes of the PGB extend well beyond the current distribution and covered a larger areal extent with a greater volume of material erupted. Although outcrops are not laterally continuous, lavas of the PGB occur >100 km from the previously mapped extent. This observation indicates that either lavas of the PGB flowed a considerable distance subaerially (>150 km), or lavas erupted locally from multiple eruptive centers. Local eruptive centers are probable for lavas with PGB-like geochemistry that occur most distally to the Monument dike swarm (i.e., Succor Creek, Dug Bar, and Brogan), and especially for basaltic lavas that host sunstones near Hart Mountain, as their >25% phenocryst crystallinity suggests these were highly viscous lava flows. For PGB-like lavas of the Brogan area and of Succor Creek, there is field evidence that supports local eruptions (Fox, 2022; Black, 2022, respectively). This revised spatial extent is based on inferences of whether these PGB lavas are sourced from local eruptions or are the result of lavas that flowed a substantial distance. Based on these interpretations, we drew envelopes to connect lavas from far travelled flows back to the likely eruption site (Fig. 13).

Revised Areal Extent and Volume

In combination with geochronological and geochemical data, revised area and volume estimates for the PGB are calculated using locations of newly identified mid-Miocene lavas (Table 3). These newly identified flows reflect compositions of PGB lavas exposed within the Monument dike swarm. By geochemically correlating PGB lavas of extended distribution with PGB subunits, we revise the distribution of each subunit (Fig. 13). Based on ages and geochemical similarities, we find that the majority of PGB flows and dikes in the extended distribution represent the earliest and latest PGB subunits within the previously defined stratigraphy. In the extended spatial distribution, only a few sparse flows are geochemically comparable to the Monument Mountain Basalt (Fig. 8A).

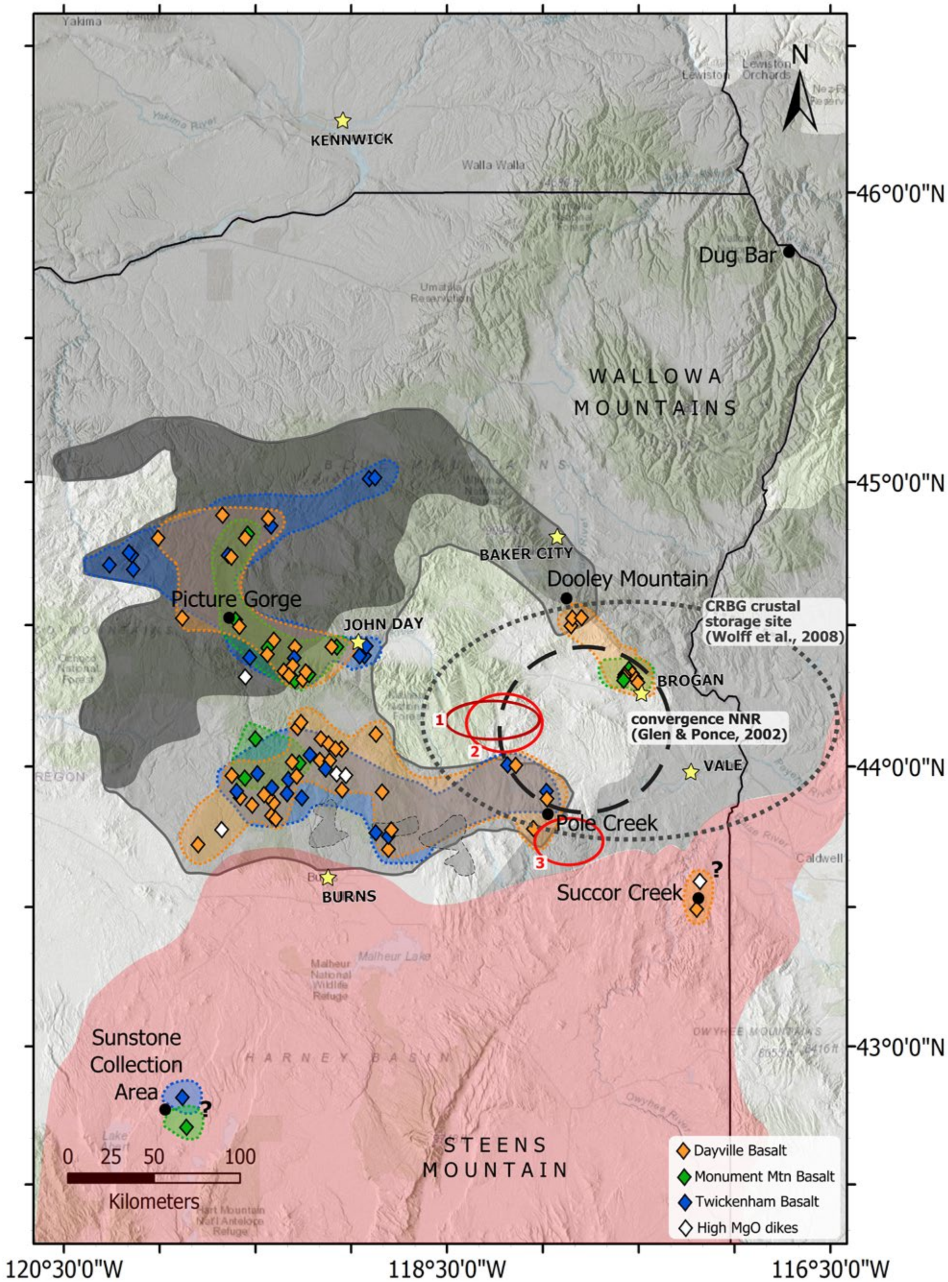

Figure 13. Extended distribution map of Picture Gorge Basalt (PGB) and geochemical correlation of our samples to PGB subunits. Newly proposed PGB area and volume were calculated using extended distribution of each PGB subunit (orange, green, and blue polygons) that did not overlap with the original mapped distribution (dark-gray polygon). The larger polygon that encompasses all newly proposed locations (light gray) is the more likely original extent to include all PGB lava flows and dikes. The ellipsoids (dashed outline) represent the inferred crustal storage site for Columbia River Basalt Group (CRBG) magmas (Wolff et al., 2008) and fault locations from structural convergence associated with the Northern Nevada Rift (NNR) zone (Glen and Ponce, 2002). The ellipsoids (solid outline) depict: (1) the likely source area of the Dinner Creek Tuff (Streck et al., 2015); and (2) and (3) inferred storage locations for Grande Ronde Basalt (Webb et al., 2018).

TABLE 3. ESTIMATED AREA AND VOLUME FOR PICTURE GORGE BASALT (PGB)

Region	Source	Area (km^2)	Volume (km^3)	Calculated thickness (km)
John Day Basin	Bailey (1988)	1600	790	0.49
John Day Basin and south of the Blue Mountains Uplift	Bailey (1988)	7500	3300	0.44
Mapped PGB extent	Tolan et al. (1987)	10,677	2391	0.22
Added PGB distribution	This study	14,000	1170 (low)	
			5640 (high)	
Total:		24,677	3561 (low)	
			8031 (high)	

Note: Low volume uses the thickness of an average chemical type within the respective PGB subunit. High volume uses the calculated thickness of PGB (Tolan et al., 1987).

This assessment focused on PGB exposures within the proposed extended distribution using previous estimates of PGB distribution to revise the total area and eruptive volume. These results suggest that an area of 14,000 km^2 be added to the previous PGB extent of 10,677 km^2, yielding a total PGB distribution area of 24,500 km^2. Our calculated volume for the extended distribution ranges between ~1200 and 5600 km^3, dependent on interpreted thickness and yielding a new total PGB volume between ~3500 and 8000 km^3 (Table 3). The thickness was calculated as 0.028–0.07 km and represents a low or conservative estimate (the average thickness of a single chemical type within each subunit), ranging up to 0.22 km at a higher end (the overall calculated PGB thickness in the previously mapped extent and reported by Tolan et al. [1987]).

Paleogeographic Implications

Most of the prominent exposures south of the type locality are geochemically similar to the chemical types associated with the youngest stratigraphic PGB subunit, the Dayville Basalt. Conflicting with Bailey's (1989a) finding that the Dayville Basalt are limited to the highest stratigraphic exposures across the original PGB extent, south of the type locality, these exposures are predominantly observed at lower elevations. These observations suggest the paleo-topography onto which the PGB lavas erupted just south of the original distribution was different from the paleotopography farther north and was characterized in the south by uplift concurrently to emplacement of lava flows. Consequently, regional uplift would result in the preferential removal of higher elevation lava flows which also would have been the earliest erupted (i.e., the early and middle PGB subunits). This of course would need to be relatively rapid uplift occurring over a timespan of <0.5 m.y.

Finally, the extended PGB distribution includes many locations where lava flows and dikes are exposed >1 km higher in elevation than the type locality at Picture Gorge. A likely explanation for this difference is post-emplacement uplift. These observations suggest that the inferred rapid uplift of the Wallowa Mountains immediately following the main-phase of CRBG eruptions (Hales et al., 2005) was more widespread including a corridor from the Wallowa Mountains to the area NW of Burns, and compositionally similar PGB lavas documented as far as Dug Bar and Succor Creek that argue for widespread dispersion of PGB-like lavas.

Spatial and Temporal Progression of CRBG Eruptions

It was previously inferred that the extruded volume of each younger CRBG subunit gradually increases, along with the ratio of younger-to-older dikes progressing northward from Steens Mountain to the northern termination of the Chief Joseph Dike swarm in southeastern Washington (Fig. 1) (Camp, 1995; Camp and Ross, 2004). These observations, coupled with stratigraphic and compositional data (Brandon and Goles, 1988; Geist and Richards, 1993; Camp, 1995; Hooper, 1997; Hooper et al., 2002), have led to the interpretation that CRBG eruptions underwent a progressive south to north migration. This notion has also been supported by the observation of Steens Basalt stratigraphically below Imnaha Basalt in Malheur Gorge (Hooper et al., 2002; Camp et al., 2003). This northward migration of CRBG magmatism became a centerpiece in models that try to explain the origin of CRBG magmatism, either due to a northward opening tear in the slab (Liu and Stegman, 2012), a progressive peeling-off of the Farallon plate (Hales et al., 2005), or the result of plume spreading deflected northward against the thicker cratonic margin of North America (Camp, 1995; Camp and Hanan, 2008). However, there has been limited geochronological data to support this migration pathway, and we provide evidence that the southern portion of this pathway is no longer viable. If a progressive migration exists, age data for the PGB suggest a slightly earlier eastern to southeastern migration that started at the Monument dike swarm (Cahoon et al., 2020; this study).

Ages for the PGB also suggest eruptive activity was pulsed, as these age data exhibit a temporal gap of ~0.4 m.y.—between 16.62 and

16.23 Ma—indicating a decrease in eruptive flux that is also observed within the entire CRBG (Fig. 14). While the published ages for PGB indicate an eruptive "hiatus" (Cahoon et al., 2020; this study), we do not imply there was zero volcanic activity during this 0.4 m.y. period; rather that it represents a substantial decrease in the eruption rate. Interestingly, Kasbohm and Schoene (2018) report no CRBG age data between 16.572 and 16.288 Ma, a duration of 0.28 m.y. This temporal interval also aligns with our proposed hiatus in PGB eruptive activity (between 16.62–16.23 Ma).

A lull in eruptive activity may also be evident from estimations of eruption rate and volumes during the CRBG magnetozones. According to Kasbohm and Schoene (2018), Grande Ronde Basalt lavas correlate with magnetozones R1 and N1, which erupted between 16.637 and 16.288 Ma. Constraining eruptive rates through time, Jarboe et al. (2008, 2010) found that magnetozone N1 has a longer duration but a small eruptive volume (i.e., a lower eruption rate compared to R1 or R2). Although this estimate is dependent on which chron is used, and a lower eruption rate is based on the chron boundaries of ATNTS2004 (Lourenes et al., 2004). It is worth noting that there are inconsistencies between published ages and correlations to magnetostratigraphic intervals. For example, at Picture Gorge, the magnetic reversal within PGB flows has been assumed to belong to magnetozones N1 and R2. This is based on K-Ar ages (Watkins and Baksi, 1974) and the observation of one PGB lava interbedded with a Grande Ronde lava at a single location (Butte Creek described in Nathan and Fruchter, 1974). This is suspicious as the timing of N1-R2 magnetozones spans from ca. 16.47–16.21 Ma, a period of time that exists within our observed PGB hiatus. Only one of the 14 PGB ages fits within this established time period for the N1-R2 magnetozones. This discrepancy highlights that some magnetozones may be mislabeled (i.e., N1 vs. N0).

At a minimum, the magmatic footprint of initial CRBG eruptions is widespread from the PGB to the Steens Basalt source areas. This is in turn supported by the distribution area of the earliest mid-Miocene rhyolites, which are cogenetic with CRBG magmatism with ages of rhyolites ca. 16.7–16.5 Ma that

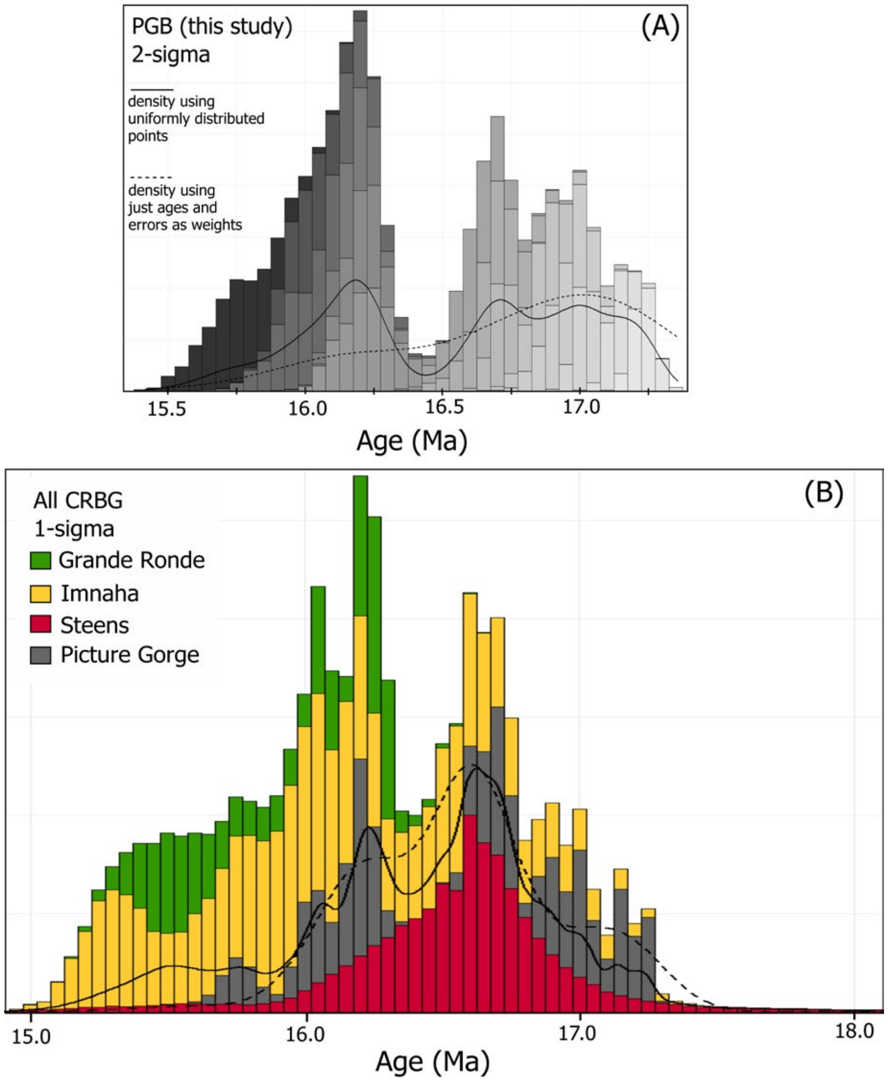

Figure 14. Histogram of published Columbia River Basalt Group (CRBG) ages illustrating a bimodal distribution of ages. (A) Picture Gorge Basalt (PGB) histogram of each age at 2-sigma using 1000 uniformly distributed points. (B) CRBG histogram of each age at 1-sigma using 4000 uniformly distributed points. Ages are binned as 0.05 Ma and only included ages calculated with a 40K decay constant of 5.463 × 10–10/a (Min et al., 2000) and Fish Canyon Tuff (FCT) age of 28.201 Ma (Kuiper et al., 2008). Ages are compiled from the following studies listed in chronological order: Baksi and Watkins (1973); Baksi (1974); Watkins and Baksi (1974); Long and Duncan (1983); Baksi (1989); Hooper et al. (2002); Brueske et al. (2007); Brueseke and Hart (2008); Barry et al. (2010); Jarboe et al. (2010); Baksi (2013); Barry et al. (2013); Camp et al. (2013); Wolff and Ramos (2013); Mahood and Benson (2017); Kasbohm and Schoene (2018); Moore (2018); Cahoon et al. (2020); and this study.

crop out from areas along the Oregon-Nevada state border in the south to near Baker City in the north (Brueske et al., 2007; Brueseke and Hart, 2008; Benson and Mahood, 2016; Coble and Mahood, 2016; Benson et al., 2017; Henry et al., 2017; Streck et al., 2017; Webb et al., 2018; Swenton et al., 2022). Ascent of the first CRBG magma and initial impingement of the mantle upwelling in the greater Vale area is also consistent with large-scale geological and geophysical features that converge there and are potentially induced by stress imposed on the base of crust due to inception of the Yellowstone plume (Glen and Ponce, 2002) (Fig. 13). In this context, the previous observations used in favor of a northward migration could also be the surficial expression of dynamic uplift following arrival of a plume creating a topography that leads to ponding of lavas progressively farther north.

CONCLUSIONS

This study identifies basaltic lavas with PGB composition among previously mapped but unnamed units and newly discovered basalt lavas and dikes across a wide swath of eastern Oregon. Sampled lava flows and dikes with PGB composition extend this CRBG unit beyond the current mapped extent, eliminating the exposure gap between lavas of PGB, Steens, and Imnaha Basalt, and increasing the total eruptive volume of this continental flood basalt. Combining stratigraphic correlation and geochemical similarities (via PCA) with $^{40}Ar/^{39}Ar$ geochronology, the spatial distribution of early and later PGB units is extended. This study more than doubles the previously published PGB distribution area from 10,677 km^2 to >24,000 km^2 (Table 3).

Compositional and textural variations between the three subunits of the previously established PGB stratigraphy are useful for classification when considered within the previous mapped distribution of the PGB and in a stratigraphic sequence. However, a detailed reassessment of PGB stratigraphy raises questions on the distinct characteristics of individual chemical types within each subunit as there is significant compositional overlap among chemical types. On the other hand, a loose correlation of PGB lavas from the extended distribution here to previously established PGB subunits can be done based on the variability among PGB chemical types, field observations, and associated geochronological data.

Combining stratigraphic correlation and geochemical similarities, PGB lavas erupted as two discrete pulses across a wide distribution in Oregon. The first pulse occurred as the initial pulse of CRBG eruptive activity (17.23 ± 0.04–16.62 ± 0.07 Ma), and the second erupted contemporaneously with the Grande Ronde Basalt (16.23 ± 0.09–15.76 ± 0.11 Ma) (Table 1). The younger ages corroborate previous field observations of PGB and Grande Ronde Basalt lavas being interstratified (Nathan and Fruchter, 1974). Therefore, it appears that, cumulatively, PGB lavas erupted for ~1.4 m.y. and throughout the entire activity span of the Grande Ronde Basalt. The wide distribution was likely achieved as PGB lavas traveling farther than previously recognized, although local tapping of a similar mantle to produce PGB-like lavas is also plausible. Combining ages, distribution, and geochemistry of lavas with PGB compositions suggests that a mantle geochemically representative of the PGB was tapped across Oregon. This PGB-like mantle fed the earliest CRBG eruptions and continued throughout main-phase activity, although volcanism was intermittent as evidenced by a 0.4 m.y. period of eruptive dormancy.

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