Reshuffling the Columbia River Basalt chronology — Picture Gorge Basalt, the Earliest- and Longest-erupting Formation

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Reshuffling the Columbia River Basalt chronology—Picture Gorge Basalt, the earliest- and longest-erupting formation

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ABSTRACT

The Columbia River Basalt Group (CRBG) is the world's youngest continental flood basalt province, presumably sourced from the deep-seated plume that currently resides underneath Yellowstone National Park in the northwestern United States. The earliest-erupted basalts from this province aid in understanding and modeling plume impingement and the subsequent evolution of basaltic volcanism. We explore the Picture Gorge Basalt (PGB) formation of the CRBG, and discuss the location and geochemical significance in a temporal context of early CRBG magmatism. We report new ARGUS-VI multicollector $^{40}Ar/^{39}Ar$ incremental heating ages from known PGB localities and additional outcrops that we can geochemically classify as PGB. These $^{40}Ar/^{39}Ar$ ages range between 17.23 ± 0.04 Ma and 16.06 ± 0.14 Ma, indicating that PGB erupted earlier and for longer than other CRBG main-phase units. These ages illustrate that volcanism initiated over a broad area in the center of the province, and the geochemistry of these early lavas reflects a mantle source that is distinct both spatially and temporally. Combining ages with the strongest arc-like (but depleted) geochemical signal of PGB among CRBG units indicates that the shallowest metasomatized backarc-like mantle was tapped first and concurrently, with later units (Steens and Imnaha Basalts) showing increased influence of a plume-like source.

INTRODUCTION

The Columbia River Basalt Group (CRBG) of the Pacific Northwest of the United States is the world's youngest flood basalt and has played an important role in understanding the dynamics of large igneous provinces (LIPs). Flood basalts are a type of LIP representing the most voluminous periods of volcanic activity on Earth, commonly coinciding with times of environmental crisis. While flood basalt provinces can be active for millions of years, the majority of lava erupts during the first million years, or "main phase" of activity (Coffin and Eldholm, 1994). This main-phase period is thought to represent impingement of the mantle plume head on the lithosphere (Ernst et al., 2005).

Continental flood basalt provinces are composed of pyroclastic rocks, lava flows, dikes, and sills, and cover extensive areas >100,000 km^2 (Coffin and Eldholm, 1994; Ernst et al., 2005). The location of the mantle plume and its temporal development are evaluated based on age and distribution patterns of lavas and dike swarms thought to represent the feeder systems to the surficial eruption sites. However, large volumes of these basaltic magmas can travel hundreds of kilometers subaerially and within dike and sill complexes, illustrating that even the location of dike swarms is not a conclusive indication of where magmatism originated (Ernst and Buchan, 1997; Ernst et al., 2019).

As basaltic magmas traverse the crust, they are prone to differentiation and contamination processes which may modify the geochemical signals of the mantle source in the eruptive products. As flood basalt activity waxes and wanes, these geochemical signals provide evidence for temporal changes in mantle source and/or evidence for interaction with the crust (Peate et al., 2008). Age distribution patterns of basaltic flows and dikes, along with changing chemical signatures, provide key fingerprints of underlying mantle dynamics of flood basalt provinces and the involvement of a deep mantle component.

Main-phase volcanism of the CRBG occurred between ca. 16.8 and 15.9 Ma, and represents an eruptive volume of >210,000 km^3 (Reidel et al., 2013). The erupted basalts are divided into formations based on geographic location of vents, geochemistry, and timing of eruptions (Camp and Ross, 2004) and include Steens, Imnaha, Grande Ronde, and Picture Gorge Basalts (e.g., Reidel et al., 2013). While several models have been proposed for CRBG magmatism, many researchers support that the flood basalts are sourced from the Yellowstone mantle plume (e.g., Geist and Richards, 1993; Camp, 1995). Our study investigates plume impingement both spatially and temporally through the lens of Picture Gorge Basalt (PGB) (Fig. 1).

PICTURE GORGE BASALT: PREVIOUS WORK AND CONTEXT TO OTHER CRBG UNITS

Geochronological studies on the CRBG and resulting ages have a complicated past due to accuracy and precision issues (e.g., Baksi, 2013; Barry et al., 2013). CRBG main-phase eruptions were originally hypothesized to have occurred over ~1–2 m.y., but this interval was later revised to ~1.3 m.y., between ca. 16.9 and 15.6 Ma (Barry et al., 2013). Recent studies have reduced the interval (Jarboe et al., 2010; Mahood and Benson, 2017) to ~0.56 m.y. (Kasbohm and Schoene, 2018) and placed the end of main-phase volcanism (i.e., end of Grande Ronde Basalt) at ca. 16 Ma rather than at 15.6 Ma (cf. Wolff and Ramos, 2013, and references therein).

The only PGB geochronological study was within the type section at Picture Gorge, Oregon (Fig. 1). The K-Ar ages from that study range from 15.9 to 14.7 Ma with uncertainties of as much as 0.8 m.y. (2σ) (Watkins and Baksi, 1974), although presumed PGB eruptive activity spans from 16.4 Ma to 15.2 ± 0.4 Ma (Barry et al., 2013). Using these ages and the magnetic reversal observed in flows at Picture Gorge, it has been inferred that PGB erupted concurrently with the N1 and R2 flows of Grande Ronde Basalt (Nathan and Fruchter, 1974; Reidel et al., 2013) (Fig. 1C).

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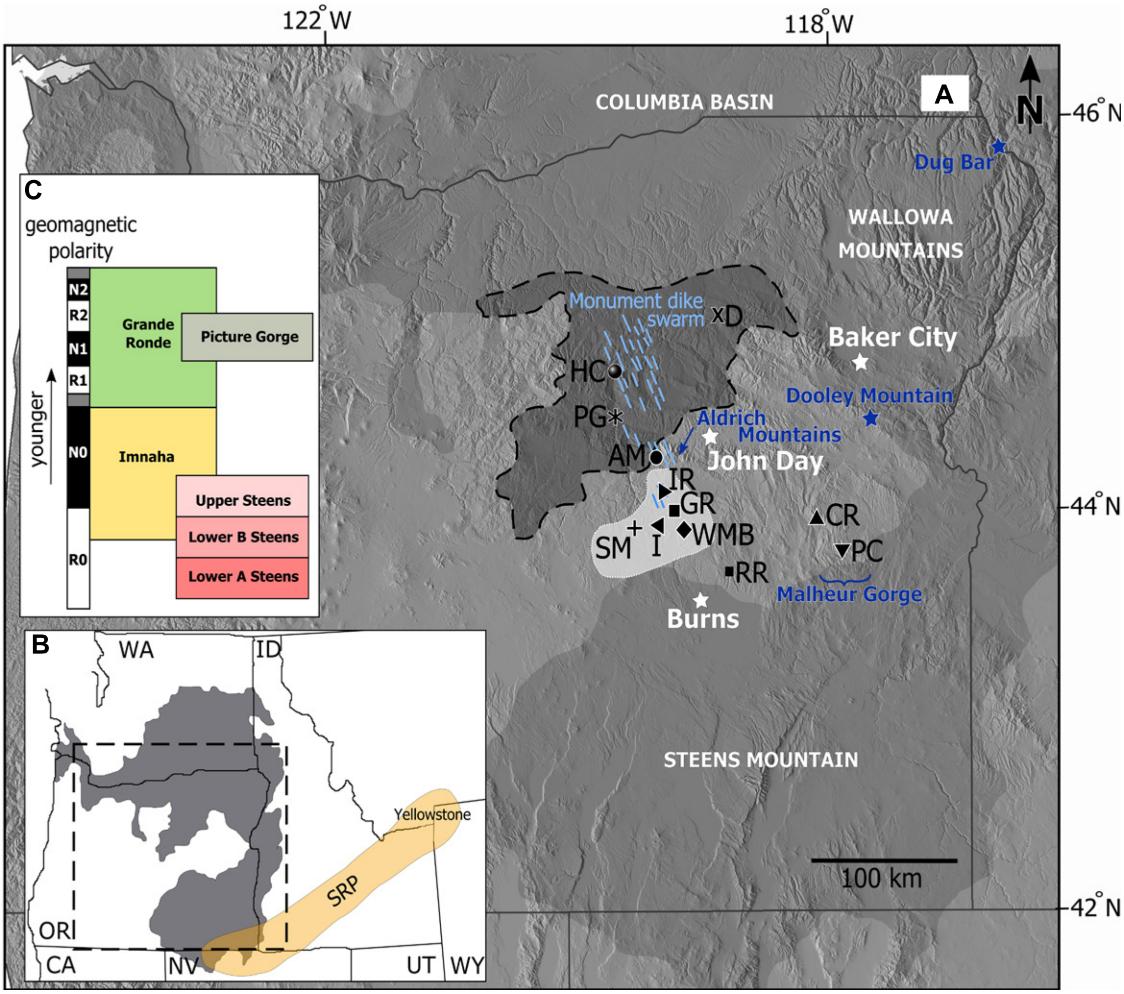

Figure 1. (A) Current distribution of the Columbia River Basalt Group (CRBG, northwestern United States) (gray), the original extent of the Picture Gorge Basalt (PGB) (dark gray, black dashed outline), and our added PGB extent (shaded white region). Locations of dated PGB samples: D—town of Dale; HC—Holmes Creek; PG—Picture Gorge; AM—Aldrich Mountains; IR—Inshallah Ranch; GR—Gilbert Ridge; SM—Snow Mountain; I—town of Izee; WMB—West Myrtle Butte; CR—Castle Rock, north of the Malheur Gorge; PC—Pole Creek, in Malheur Gorge; RR—Rattlesnake Road (undated). CRBG extent is after Reidel et al. (2013), and Monument dike swarm locations are after Brown and Thayer (1966). (B) Overview map with CRBG extent (gray), current location of the Yellowstone plume, and presumed hotspot track (orange) along the Snake River Plain (SRP). Box shows extent of panel A. WA—Washington; ID—Idaho; OR—Oregon; CA—California; NV—Nevada; UT—Utah; WY—Wyoming. Extent of main map is outlined with dashed line. (C) Stratigraphy and geomagnetic polarity of main-phase CRBG.

Recent data on mid-Miocene magnetic reversals highlight inconsistencies with PGB ages. Jarboe et al. (2010) proposed that the older N0-R1 magnetic reversal occurred at ca. 16.5 Ma. This is also supported by constraining the R0-N0 transition to ca. 16.6 Ma by sanidine geochronology on interbedded silicic tuffs (Mahood and Benson, 2017), and by high precision U-Pb dating work (Kasbohm and Schoene, 2018). Kasbohm and Schoene (2018) also constrained the later R2-N2 transition to slightly younger than 16.210 ± 0.043/0.048 Ma. Consequently, the N1-R2 transition falls between 16.5 and 16.2 Ma, signifying that PGB flows must be older than the published K-Ar ages.

PGB lavas erupted from NNW-trending feeder dikes of the Monument dike swarm in northeastern Oregon (Fruchter and Baldwin, 1975), and are thought to represent only 1.1% of the entire CRBG (Reidel et al., 2013; Barry et al., 2013) (Fig. 1A). Geochemical and isotopic data from the known PGB distribution area led previous researchers to acknowledge that, while comparable to Steens Basalt, PGB contains a dissimilar mantle source component (Carlson, 1984; Bailey, 1989; Wolff et al., 2008; Wolff and Ramos, 2013).

METHODS

Samples selected for $^{40}Ar/^{39}Ar$ dating are from known and newly correlated PGB localities (Figs. 1 and 2).

Preferred eruptive ages (groundmass separates) for all samples are summarized in Table 1. Detailed analytical procedures and age spectra are provided in the GSA Data Repository[1] (Fig. DR1, Table DR3, and supplemental text).

RESULTS

PGB Geochemical Characteristics

Samples selected for geochronology are a subset of all samples collected in this study. We sampled along stratigraphic sections of the known outcrop area of PGB, age-equivalent basalts that are adjacent to the known outcrop area (between the towns of John Day and Burns; Fig. 1), and sections that were previously correlated with other CRBG units such as Steens or Imnaha Basalts at Malheur Gorge (Hooper et al., 2002; Camp et al., 2003, 2013).

When compared to all main-phase CRBG units, PGB is geochemically and isotopically most similar to Steens Basalt (Carlson, 1984; Wolff and Ramos, 2013). PGB samples show a comparable SiO_2 range (48.5–53 wt%) as Steens and Imnaha Basalts (with <51% SiO_2 for Rock Creek and >51% for American Bar chemical types of Imnaha Basalt; cf. Hooper, 1984), but for a given SiO_2 weight percent, PGB contains lower values of Th, high field strength elements (HFSEs), light rare earth elements, and Zr/Y (Fig. 2; Fig. DR4). The only exceptions are a few lowermost Imnaha (American Bar subgroup) flows at Dug Bar, northeastern Oregon (Fig. 1) (Swanson et al., 1979) that are distinct from other more-typical early Imnaha flow types. Early on, it was noted that these basal flows exhibit

[1]GSA Data Repository item 2020093, Figure DR1 (age spectra: age plateaus and inverse isochrons), Table DR2 (sample locations and XRF and ICP-MS data), Table DR3 (summary table), and Figure DR4 (geochemical plots), is available online at http://www.geosociety.org/datarepository/2020/, or on request from editing@geosociety.org.

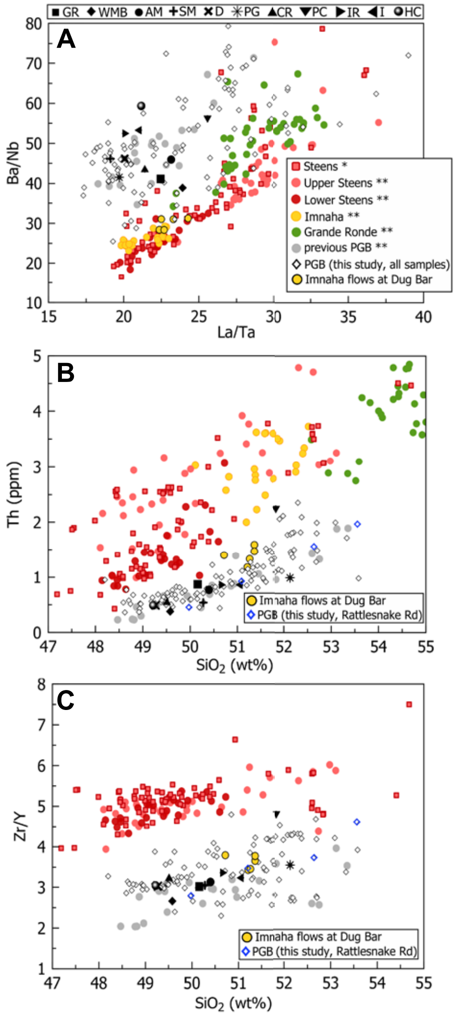

Figure 2. Geochemistry of our Picture Gorge Basalt (PGB, northwestern United States) study samples compared to the Steens Basalt data from Moore et al. (2018) (*) and all main-phase Columbia River Basalt Group (CRBG) units from Wolff and Ramos (2013) (**). For the Imnaha Basalt, only the American Bar subgroup samples are plotted, as only these Imnaha lavas occur in the study area of northeastern Oregon (Vic Camp, 2019, personal commun.). Dated sample locations are abbreviated as in Figure 1.

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

Sample location	Sample name	Age (Ma)	Error (±2σ)	MSWD	No. of steps
West Myrtle Butte (WMB)	CAH15-007	16.22	0.06	0.96	18
Aldrich Mountains (AM)	CAH15-023	16.88	0.06	1.10	22
Snow Mountain (SM)	CAH16-174A	16.96	0.07	0.85	23
Dale (D)	CAH17-200	17.02	0.03	0.86	14
Pole Creek (Malheur Gorge) (PC)	CAH16-065	16.72	0.03	1.84	15
Castle Rock (CR)	MC-76-16	16.23	0.09	0.90	25
Gilbert Ridge (GR)	MS-11-6	16.06	0.14	1.09	13
Inshallah Ranch (IR)	CAH16-138	16.70	0.09	0.80	24
Izee (I)	CAH16-148	16.62	0.07	1.82	22
Holmes Creek (HC)	CAH17-222A	17.23	0.04	2.25	5
Picture Gorge (PG)	CAH17-245	17.14*	0.04	2.95	16

Note: All ages are plateau ages unless otherwise specified (*), and within error of their inverse isochron age. MSWD—mean square weighted deviation.
*Weighted mean age.

PGB-like chemistry (see the Data Repository), but they were not correlated with PGB due to their distance from the type locality (Swanson et al., 1979). Furthermore, PGB samples contain lower SiO_2 (weight percent) and incompatible trace element concentrations than Grande Ronde Basalt (Fig. 2). We use these characteristics to identify basalts with PGB composition and distinguish them from other CRBG units.

Because some sample locations are >100 km from the nearest currently mapped PGB outcrop, we highlight additional locations in between (e.g., Rattlesnake Road; Fig. 1), where basaltic flows are geochemically identifiable as PGB (Fig. 2). All flows and dikes selected for geochronology reflect PGB chemical characteristics with one possible exception at Pole Creek (sample CAH16-065). Yet, this sample plots within the PGB field in Figure 2A and in additional parameter spaces (e.g., Nb, Rb, and K_2O/Yb versus SiO_2), along with other Pole Creek flows that are stratigraphically lower.

New Picture Gorge Basalt Ages

We first examine our oldest samples, which are from the previously mapped distribution of PGB (Brown and Thayer, 1966; Fruchter and Baldwin, 1975; Bailey, 1989). These ages are >17 Ma and represent PGB basal flows which immediately overlie Oligocene tuffs at the type locality of Picture Gorge (sample CAH17-245), Holmes Creek (sample CAH17-222A), and along the North Fork John Day River near the town of Dale (sample CAH17-200) (Fig. 1; Table 1). These PGB flows are the earliest flows of the CRBG (Fig. 3) and extend initiation of the CRBG to 17.23 ± 0.04 Ma.

A recent age of 16.97 ± 0.06 Ma from the base of Steens Mountain, now defined as the lower A Steens sequence, was previously the oldest age for the entire CRBG and extended Steens Basalt activity by 200 k.y. (Moore et al., 2018). We also obtained ages for the PGB just under 17 Ma, which includes an aphyric dike (sample CAH15-023, location AM) exposed at the southern edge of the Monument dike swarm (Fruchter and Baldwin, 1975), and a flow (sample CAH16-174A, location SM) located farther south at Snow Mountain (Fig. 1; Table 1).

The geochemical analyses allow us to extend the magmatic footprint of PGB lavas. South of the main Monument dike swarm and Aldrich Mountains, exposures of mid-Miocene basalt are abundant (i.e., locations IR, GR, SM, I, and WMB; Fig. 1A) but lack the lateral continuity of flows further north near the type locality (Brown and Thayer, 1966). This is likely the result of the paleotopography, subsequent erosion, and/or coverage by the 16.16 Ma Dinner Creek Tuff (unit 1) or younger widespread ignimbrites (e.g., Streck et al., 2015), contributing to these mid-Miocene basalts being excluded in earlier PGB map compilations, despite spatial overlap with the southern Monument dike swarm. Our youngest age (16.06 ± 0.14 Ma) came from one of these dikes (location GR; Fig. 1) and suggests that PGB volcanism lasted > 1 m.y., longer than any other CRBG main-phase unit.

Dated flows at locations previously correlated with Steens Basalt include those at Pole Creek in Malheur Gorge, and at Castle Rock adjacent to Malheur Gorge (locations PC and CR; Fig. 1). Our PGB sample at Castle Rock (sample MC-76-16, location CR) yields an age of 16.23 ± 0.09 Ma, consistent with exposure of the 16.16 Ma Dinner Creek Tuff unit 1 above (Cruz, 2017). At Pole Creek, our dated PGB flow (sample CAH16-065, location PC) directly underlies Grande Ronde Basalt and yields an age of 16.72 ± 0.03 Ma (Table 1; see Fig. DR1). This age fits within age relationships of Camp et al. (2003), but is not within 2σ uncertainty of a younger Steens Basalt plagioclase age at Pole Creek (16.45 ± 0.11 Ma, 1σ; Jarboe et al., 2010). While this plagioclase-phyric flow is interpreted to be the base of the Pole Creek section, it is not in direct stratigraphic continuity with our section where PGB represents the lowest stratigraphic exposures.

DISCUSSION

Initiation Footprint of CRBG Eruptions

Our new PGB $^{40}Ar/^{39}Ar$ ages indicate an earlier and longer eruptive phase compared to other main-phase units (Fig. 3). Our earliest PGB ages are slightly older than those of Steens and Imnaha Basalts, which initiated at 16.97 ± 0.06 Ma and 16.637 ± 0.08 Ma, respectively (Moore et al., 2018; Kasbohm and Schoene, 2018).

PGB flows that are most distal to the previously known distribution near the Monument dike swarm are located in Malheur Gorge at the Pole Creek and Castle Rock locations (Fig. 1). There, the previous CRBG stratigraphy included Steens, Imnaha, and Grande Ronde Basalts (Hooper et al., 2002; Camp et al., 2003); now, we also identify PGB flows, which are capped by Grande Ronde Basalt.

Our older and overlapping ages of PGB as compared to the oldest ages of Steens Basalt could result from a rapidly spreading plume head, not confined to Steens Mountain. This is consistent with large-scale geological and

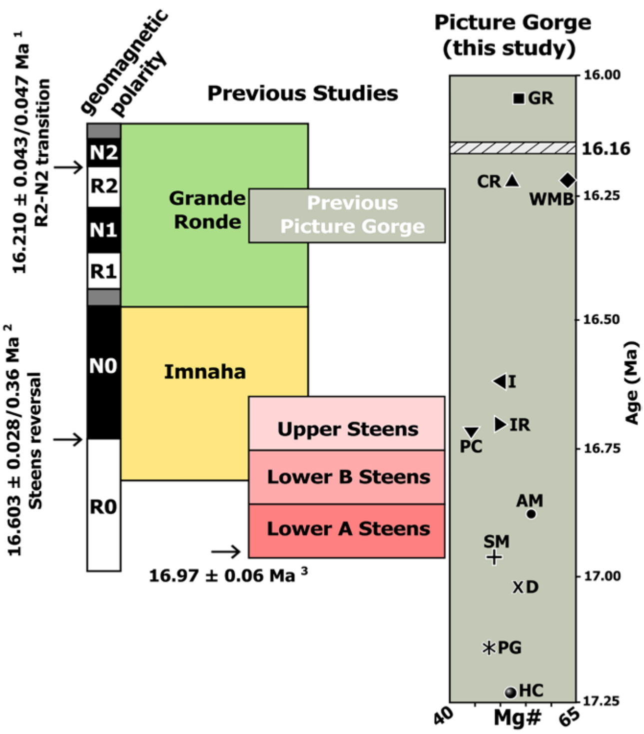

Figure 3. Stratigraphy of main-phase Columbia River Basalt Group (CRBG, northwestern United States) with our reported Picture Gorge Basalt (PGB) ages and associated Mg#. The 16.16 Ma unit is unit 1 of the Dinner Creek Tuff (Streck et al., 2015). Additional ages: 1—Kasbohm and Schoene (2018); 2—Mahood and Benson (2017); 3—Moore, et al. (2018). All $^{40}Ar/^{39}Ar$ dates were calculated using the Fish Canyon Tuff sanidine age of 28.201 ± 0.023 Ma, after Kuiper et al. (2008), and the U-Pb errors for the Kasbohm and Schoene (2018) age are reported as 95% confidence intervals given for internal uncertainty and decay constant uncertainty. Dated sample locations for this study are abbreviated as in Figure 1.

geophysical features that converge ~150 km east of the Monument dike swarm, potentially induced by stress imposed on the base of the crust due to inception of the Yellowstone plume (Glen and Ponce, 2002).

While mantle plume models illustrate that volcanism is most intense above plume tails (e.g., Morgan, 1981; Hill et al., 1992), the outward spreading of the plume at the base of the lithosphere can result in volcanism over a much wider extent, i.e., several hundred kilometers (e.g., Ernst et al., 2019, and references therein). In conjunction with an emerging new age distribution pattern for cogenetic CRBG rhyolites (Streck et al., 2017; Webb et al., 2018), our PGB ages and locations suggest that the earliest volcanism due to plume impingement occurred over a broad region, from Steens Mountain at the southern portion of the province north to the Monument dike swarm (Fig. 1).

Implications for Tapping the Mantle

PGB contains geochemical features that distinguish it from other CRBG main-phase units. The most notable are elevated ratios of large ion lithophile elements to HFSEs, the fingerprint of a subduction-modified mantle (Fig. 2; Fig. DR4) and the basis for arguing that PGB likely contains a backarc mantle component (Carlson, 1984; Wolff and Ramos, 2013). While this feature is present in all CRBG subunits, it is the most prevalent in PGB and has new significance in light of our ages, indicating the tapping of an evolving geochemical signal.

We propose that the initial pulse of PGB, and thus CRBG magmatism, was sourced from a shallower backarc-like mantle source, with a plume-like mantle progressively playing a greater role over time. Yet with PGB and Steens Basalt erupting nearly contemporaneously, the variation in geochemical traits might not reflect a solely temporal feature, but also a spatial characteristic that we are still detailing. Spatial and temporal geochemical zonation have been observed in other mantle plume systems (Hoernle et al., 2015, and references therein). This geochemical signal may extend east of the Wallowa Mountains to Dug Bar (Fig. 1A) if early basalt flows with PGB-like chemistry erupted locally instead of traveling great distances (Fig. 2; Fig. DR4).

CONCLUSIONS

We report the first $^{40}Ar/^{39}Ar$ ages for PGB, which range between 17.23 ± 0.04 and 16.06 ± 0.14 Ma. Ages demonstrate that PGB erupted earlier and longer than other CRBG main-phase units, and that CRBG volcanism initiated over a broad region that includes Picture Gorge. Our study also identifies outcrops of PGB beyond its currently published extent and necessitates increasing the distribution and ultimately the eruptive volume of PGB.

Combining ages with the strongest arc-like but depleted geochemical signal of PGB among CRBG units illustrates that the shallowest metasomatized backarc-like mantle was tapped first and concurrently, with later CRBG units (Steens and Imnaha Basalts) exhibiting an increased influence of a plume-like source. This newly identified temporal and spatial geochemical signal provides an added constraint for CRBG evolution models.

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