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Key Points:

- Early Picture Gorge Basalt (PGB) flows are reverse-polarity and represent an initial phase of Columbia River Basalt Group volcanism
- Existing radiometric argon dates defining the timeline of PGB eruption conflict with the magnetic polarity timeline
- The PGB records the vertical-axis rotation of Central Oregon since 16 million years ago

Supporting Information:

Supporting Information may be found in the online version of this article.

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New Paleomagnetic Constraints on the Eruption Timing, Stratigraphy, and Post-Emplacement Deformation of the Picture Gorge Basalt Within the Columbia River Basalt Group

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Abstract The Picture Gorge Basalt (PGB) is part of the Miocene Columbia River Basalt Group (CRBG). The PGB, which outcrops in eastern Oregon, is considered coincident in time with the voluminous Grande Ronde Basalt. New radiometric ages have expanded the age-range of the PGB, suggesting it began erupting prior to the Steens Basalt to its south and continued until after cessation of the Grande Ronde Basalt eruptions, an interval of 1.5 Ma. However, the existing paleomagnetism of the PGB implies this eruption timeline is an overestimate. To reconcile the radiometric and paleomagnetic timescales for the PGB, we conducted a paleomagnetic study on sections of the PGB to construct a detailed, high-quality magnetostratigraphy. Our data indicate the stratigraphically lowest lava flows in the PGB are of reversed polarity, revealing a new paleomagnetic transition with the PGB and a reversed (R)–normal (N)–reversed (R) sequence. This suggests one of two timeline possibilities for PGB volcanism: (a) eruptions began and during through CRBG polarity chrons R0–N0–R1, penecontemporaneous with Steens Basalt, or (b) eruptions began and persisted during CRBG polarity chrons R1–N1–R2. Our work supports a longer interval of PGB volcanism than was suggested by previous paleomagnetic data but is at odds with the suggestion that PGB eruptions lasted through the entire main CRBG. We favor a scenario wherein PGB eruptions begin with R0 and continue into the R1 paleomagnetic interval. The paleomagnetic results also record a $\sim 18^\circ$ vertical-axis rotation of east-central Oregon after ~ 16 Ma with respect to stable North America.

Plain Language Summary The Picture Gorge Basalt (PGB) is a small part of a large volcanic province in western North America that erupted 17–16 million years ago. The record of Earth's magnetic field frozen into these rocks has been used to correlate and map the sequences of lava flows throughout western North America. The PGB records multiple periods when the magnetic field was either north-seeking, like today, or in a reversed configuration. Some age dates on the lava flows of the PGB do not match well with the magnetic record when compared with the global magnetic record which the PGB can be correlated with. We suggest based on magnetic correlation, chemistry, and age data that the PGB is part of the earliest phase of the volcanic province. The area of central Oregon where the PGB erupted has also undergone a large rotation as compared with the North American continent since the volcanic activity occurred in this area.

1. Introduction

The vast ($>100,000$ km³, Ernst, 2014), rapidly accumulated (often <1 Myr, Kasbohm et al., 2021), lava stratigraphy and intrusive systems which characterize large igneous provinces (LIPs) represent the highest intensity sustained intervals of volcanic activity throughout Earth history. A better understanding of LIP eruption tempo and duration helps characterize the global environment, volcanic activity at different scales, and the regional tectonic interplay within LIP footprints (Ernst, 2014).

The Columbia River Basalt Group (CRBG) is a Miocene LIP, which was erupted in the Pacific Northwest, USA (Reidel et al., 2013; Swanson et al., 1979; Figure 1). It is the smallest continental flood basalt yet comprises an estimated 210,000 km³ of lava (Reidel et al., 2013). The hundreds of lava flows which make up the CRBG are divided on the basis of mapping, geochemistry, geochronology, and paleomagnetic data into seven major formations: the formally named Steens, Imnaha, Grande Ronde (GRB), and Picture Gorge (PGB) Basalts and the informally named Prineville Basalt make up the main eruptive phase, with a comparatively small volume ($\sim 7\%$)

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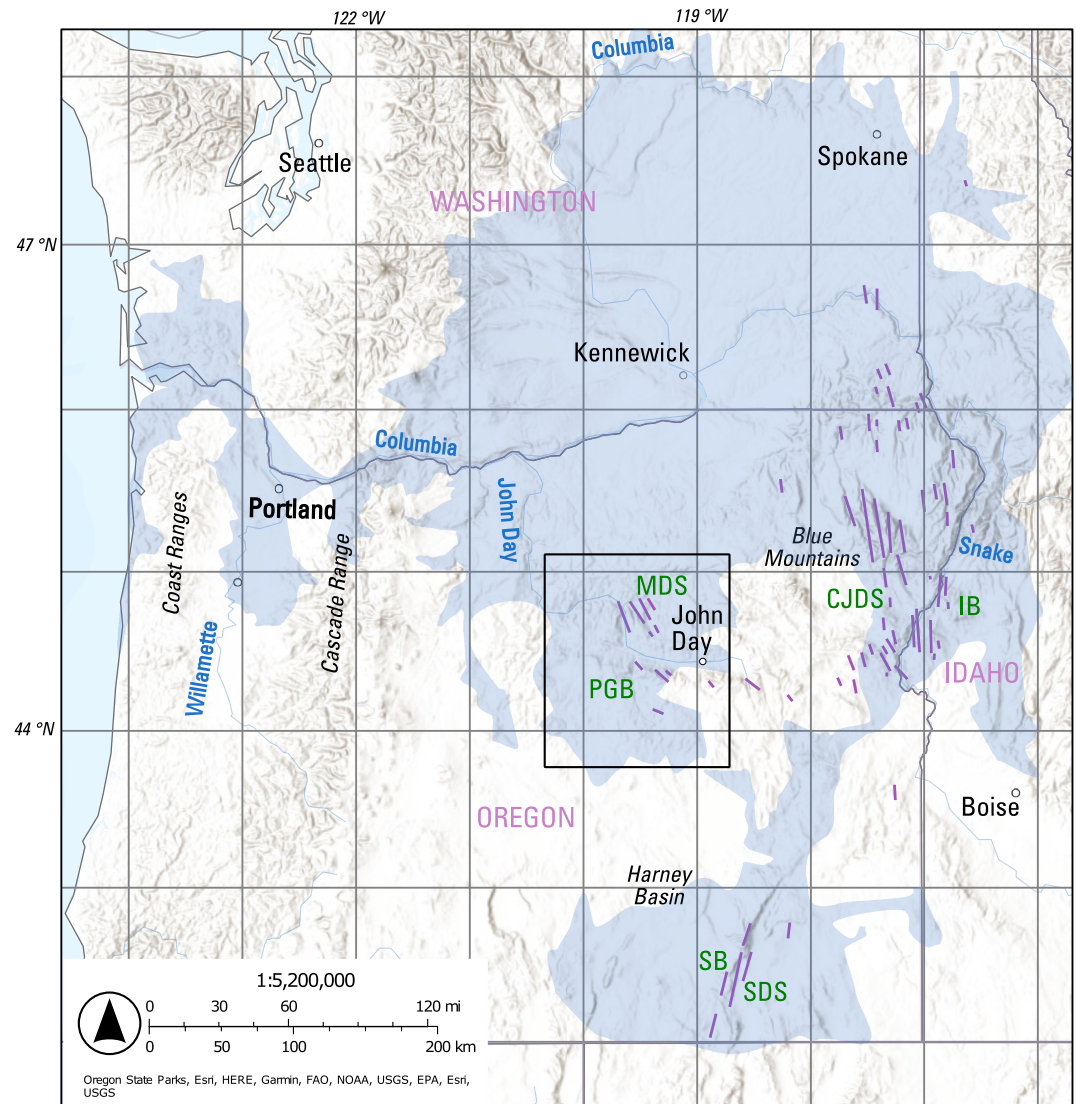


Figure 1. Regional view of the Columbia River Basalt Group (CRBG) extent across Cascadia. Blue shading indicates the CRBG footprint based on 1:100K state geologic-map compilations. The Northern Nevada rift volcanics in Nevada and Lovejoy Basalt in California, although associated with the CRBG, are not shown as part of the footprint. General locations of major early CRB eruptions are indicated in green: PGB = Picture Gorge Basalt, IB = Imnaha Basalt, SB = Steens Basalt. Major vent systems for CRBG (after Morriss et al., 2020) are shown schematically with purple lines: CJDS = Chief Joseph Dike Swarm, MDS = Monument Dike Swarm, SDS = Steens Dike Swarm. Central box marks the inset area shown in Figure 2.

of Wanapum and Saddle Mountains Basalts emplaced over extended periods of >200 kyr (majority of Wanapum; Kasbohm & Schoene, 2018) and ~10 Myr (Reidel et al., 2013) thereafter. Uranium-lead zircon dates from Kasbohm and Schoene (2018) indicate ~95% of the CRBG erupted volume, including all the Grande Ronde Basalt, erupted between 16.7 and 15.9 Ma, with a revised estimate of 83% of the volume erupted in 720 kyr based on the combination of U-Pb and Ar/Ar geochronology presented in Kasbohm et al. (2023). The Prineville Basalt (0.3%) and PGB (1.1%) are much smaller in volume than other parts of the main eruptive phase and have been for a long time considered coincident in time with one or two magnetozones within the larger Grande Ronde Basalt (Reidel et al., 2013).

However, radiometric data now indicates the PGB might have lasted through the entirety of “main-phase” CRBG eruption and is therefore at least in part older than the GRB (Cahoon et al., 2020, 2023). The PGB is also mostly restricted to east-central Oregon, although recent work focusing on the PGB (Cahoon et al., 2020, 2023) has

suggested it has a significantly larger distribution, volume, and duration than previously thought. The most notable mapped relationship of PGB with GRB is intercalated flows at the Butte Creek section in Buckhorn Canyon, Oregon (45.057°N, 120.368°W) (Nathan & Fruchter, 1974). This locality lies outside the John Day and north of the Blue Mountains uplift—a paleogeographical boundary during PGB eruption (Nathan & Fruchter, 1974). The other major relationship of the two basalts is at a paraconformity north of Dale, Oregon (45.111°N, 118.974°W), where a PGB flow lies underneath a GRB flow mapped as normal polarity, the flows separated by a 3-m thick silt layer (Nathan & Fruchter, 1974, present study). Cahoon et al. (2023) also describe PGB beneath GRB at the Castle Rock, Horseshoe Bend, and Pole Creek locales in the Malheur River gorge area, Oregon (their Figure 7).

The regional CRBG main-phase magnetostratigraphy begins with the Steens Basalt recording reversed polarity (R0), then continues through 5 changes in polarity. In short form, the polarity intervals are labeled R0–N0–R1–N1–R2–N2. The Grande Ronde Basalt—representing most volcanic activity in the CRBG (~85%)—erupted during the R1–N1–R2–N2 magnetic polarity chrons. Determination of magnetic polarities with portable fluxgate magnetometers was the best way to reliably determine GRB stratigraphy during early study (Swanson et al., 1979). This pioneering magnetostratigraphy continues to hold up well (Reidel et al., 2013) although chemostratigraphy has become increasingly essential in modern studies of the CRBG (Hooper, 2000; Reidel et al., 1989; Sawlan, 2018; Wells et al., 2020).

Paleomagnetic studies in Cascadia have demonstrated vertical-axis rotation of areas in the Cascades forearc, but the Columbia Plateau east of the Cascade Range is thought to be stable, particularly in southeast Washington and northeast Oregon (see Dominguez & Van der Voo, 2014; Magill et al., 1982). In southern-central Oregon, however, paleomagnetic and geochronological work on the Steens Basalt (Jarboe et al., 2008, 2010) illustrated ~14° of clockwise rotation relative to a stable reference pole. This contrasts with an earlier study which suggested tectonic stability of the Steens Basalt (Mankinen et al., 1987). The reference pole used by Mankinen et al. (1987) comprised most of the then extant CRBG data from central to eastern Oregon, including work on the PGB by Watkins and Baksi (1974).

The rotational history of Oregon as recorded in Miocene volcanic rocks has consequences in modern times. Syntheses of paleomagnetic data with GPS measurements (Wells & McCaffrey, 2013) provide a framework model on which to evaluate recent movement on faults (Wells et al., 2020). Since CRBG flows reach across the entire width of the Pacific Northwest, from Idaho to offshore (Reidel et al., 2013) and are thus widespread strain markers, detailed paleomagnetic studies on these lava flows are key to kinematic reconstruction of movement and deformation.

Our new paleomagnetic results sample the full eruptive sequence of the PGB—better placing this subunit within CRBG magnetostratigraphy—and allow us to test the hypothesis of protracted volcanic activity during main-phase CRBG formation. Our results provide modern high-quality CRBG paleomagnetic data at a flow-by-flow, stratigraphically constrained level. While this approach has been used to study the Steens Basalt, modern quality data of this type is lacking for all other CRBG formations. The most recent work on the CRBG (Dominguez & Van der Voo, 2014), while incorporating modern demagnetization protocols, did not take full advantage of the stratigraphic constraints for this LIP. Paleomagnetism provides an additional parameter of comparison to both the magnetostratigraphy established for the rest of the CRBG as well as the global geomagnetic field via the Geomagnetic Polarity Time Scale (GPTS). Additionally, our work provides a modern assessment of post-CRBG deformation in central Oregon.

2. The Picture Gorge Basalt

The PGB was erupted from the north-northwest-trending Monument dike swarm (Figures 1 and 2; Fruchter & Baldwin, 1975; Thayer & Brown, 1966). Geologic mapping of the area shows that the PGB's maximum thickness of 570 m occurs along the axis of its exposed feeder dike swarm (Bailey, 1989a; Thayer & Brown, 1966). The volume of the PGB has been estimated at 2,400 km³ (Tolan et al., 1989), 3,300 km³ (Bailey, 1989a), and most recently as 3,500–8,000 km³ (Cahoon et al., 2023). This latest upper estimate would place the PGB at ~4% of the total volume of the CRBG. The greater volume range was arrived at by nearly doubling the areal extent of the PGB, and using estimated thicknesses for chemical types and subunits (Cahoon et al., 2023). The greatest uncertainty in this method is likely related to the chosen thicknesses.

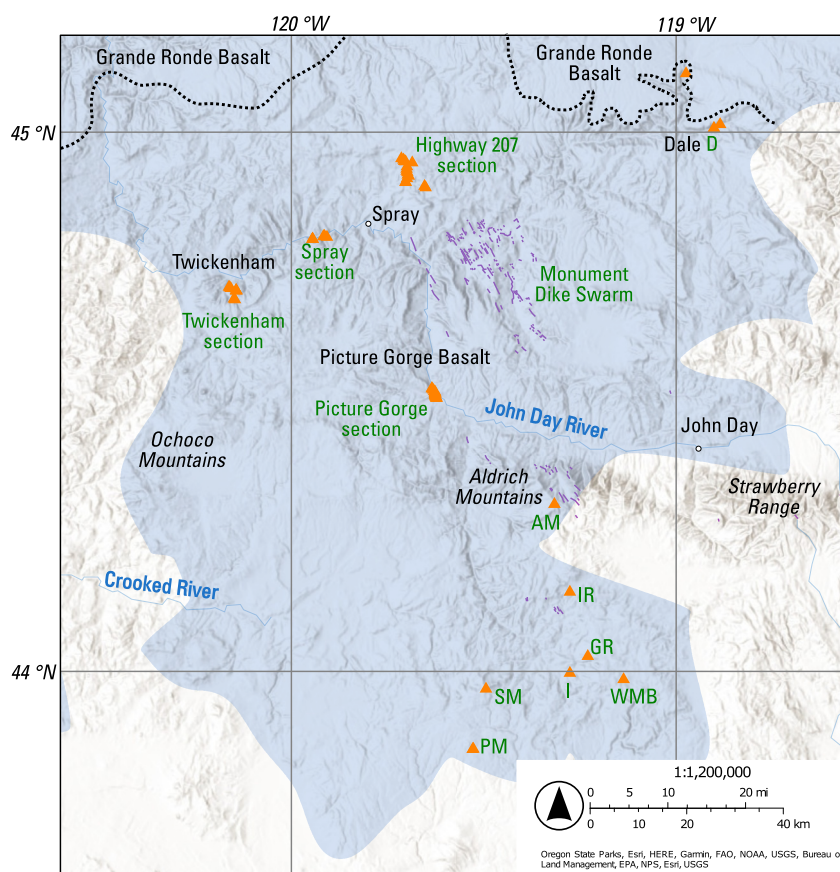


Figure 2. Location map of Picture Gorge Basalt (PGB) with orange triangles indicating paleomagnetic sampling sites. Green text indicates major lava flow sections. Place/town/geographical features names are indicated in black. Paleomagnetically sampled lava flows/intrusions were dated by Cahoon et al. (2020, 2023) and are labeled as follows: *D* = Dale flow, *AM* = Aldrich Mountains dike, *GR* = Gilbert Ridge dike, *IR* = Inshallah Ranch dike, *I* = Izee flow, *WMB* = West Myrtle Butte flow, *SM* = Snow Mountain flow, and *PM* = Ponderosa mine flow. Purple lines show mapped Monument Dike Swarm (Thayer & Brown, 1966). Dashed lines in upper section of map illustrate the general boundary of the PGB with the Grande Ronde Basalt.

Nathan and Fruchter (1974) described the general stratigraphy of the PGB, and Watkins and Baksi (1974) studied its paleomagnetism from a limited set of oriented core samples and conducted K-Ar geochronology experiments (Figure 2), defining the PGB N and R magnetozones at the Picture Gorge type section near John Day in central Oregon (Figure 2). The magnetozones of Watkins and Baksi (1974) are consistent with fluxgate measurements made throughout the other PGB sections (Nathan & Fruchter, 1974). Subsequent reevaluation of radiometric dates (Baksi, 1989) estimated the eruption of the type section to have occurred between 15.9 and 16.3 Ma (16.1 ± 0.2 Ma). The N-to-R upsection reversal within the Picture Gorge type section is typically considered coincident with the N1–R2 reversal in the Grande Ronde Basalt (Reidel et al., 2013); we reevaluate this assignment in this paper. Cahoon et al. (2020) employed the $^{40}\text{Ar}/^{39}\text{Ar}$ method on PGB flows and dikes, finding radiometric data ranging from 17.23 ± 0.04 to 16.06 ± 0.14 Ma. The work of Cahoon et al. (2020, 2023) argues a much longer duration of PGB eruption, with $^{40}\text{Ar}/^{39}\text{Ar}$ dates ranging from ~ 17.2 to ~ 15.8 Ma, versus the previous date of 16.1 ± 0.2 Ma (Baksi, 1989). These new geochronological results and their interpretation, however, have been challenged by Baksi (2022), who suggested the radiometric dates were unreliable based on alteration of the basalt and statistics of age calculation.

Bailey (1989a) described in detail the three-informal-member framework for the PGB, previously established by Swanson et al. (1979): the oldest Twickenham Basalt, the Monument Mountain Basalt, and the youngest Dayville Basalt. Geochemistry and petrology of the PGB, compared to other units within the CRBG, has seen relatively limited study (Bailey, 1989b; Brandon et al., 1993; Carlson, 1984; Wolff & Ramos, 2013; Wolff et al., 2008). The

PGB generally has lower titanium and incompatible trace elements contents than other main-phase CRBG formations (Cahoon et al., 2023), but larger large-ion-lithophile element to high-field-strength element ratios (Wolff et al., 2008). The PGB has some overlap in Sr-Nd-Pb isotopic space with the Steens Basalt (Wolff & Ramos, 2013).

3. Paleomagnetic Methods

We collected samples following standard paleomagnetic practices (Butler, 1992; Tauxe, 2010). Each of our paleomagnetic sites consists of multiple (usually 8) 1-inch diameter cylindrical samples up to 12 cm long drilled in situ with a gasoline-powered, water-cooled, diamond-bit coring drill. We oriented the samples in the field with a Pomeroy orienting device holding a Brunton magnetic compass set to zero declination; a built-in sun compass was also used for orienting when possible. Magnetic compass orientations were then corrected using either the sun compass measurements or International Geomagnetic Reference Field declination at the site location if the sun was not available. Standard paleomagnetic specimens were prepared from our oriented samples and these specimens were analyzed in the U.S. Geological Survey Paleomagnetism Laboratory in Menlo Park, Calif., using a cryogenic magnetometer with an automated sample handling system. A specimen from each sample was demagnetized using a stepwise alternating field from in-line coils; selected twin specimens also were demagnetized using stepwise thermal methods. Our paleomagnetic measurements took place in a magnetically shielded room.

Our paleomagnetic sampling covered the entire PGB sequence from the Twickenham Basalt flows (oldest) to the Dayville Basalt flows (youngest) at 4 sections with stratigraphic context and ordering. The sampled sections consisted of 18 sites in flows of the PGB type section, 7 sites in flows along Highway 19 west of the town of Spray, Oregon, 17 sites in flows along Highway 207 northeast of Spray, and 11 sites in flows near Twickenham, Oregon (Figure 2; Table 1). Additionally, we collected paleomagnetic data at other isolated flows and dikes dated by Cahoon et al. (2020, 2023; Figure 2) that were not directly stratigraphically associated with the PGB. In total, 518 independently oriented paleomagnetic samples were taken at 64 sites. Several sites were intentionally repeated within the same lava flow to assess the stability of the magnetic signal across multiple outcrops and/or the degree of overprinting present in samples collected close to an overlying flow.

We determined mean paleomagnetic directions recorded at each site (Table 1). Characteristic magnetic directions were calculated using line or great-circle plane fits to data (Figure 3) on vector-component diagrams (Kirschvink, 1980), which were then averaged at the site level using conventional Fisher (1953) statistics. The Python package Pmagpy (Tauxe et al., 2016) was used for analyses. Structural corrections were applied to paleomagnetic data from substantially tilted lava flows. These corrections involved both field assessment and remote examination of digital topographic data and satellite imagery (QT Modeler) and are available in Table S1 in Supporting Information S1. The paleomagnetic data for these Miocene volcanic rocks are in general straightforward; <5% of analyzed specimens were discarded due to poor magnetic stability, post-cooling movement, or inextricable lightning-induced remanence. Measurement-level paleomagnetic data are archived and available in the digital repository of the MagIC database (Pivarunas et al., 2025).

3.1. Tectonic Tilt Correction

Post-eruptive tectonic deformation has variably affected our study area, with evidence for 0–14° tilting. Measuring paleohorizontal in the field was difficult due to the thickness of lava flows and height of outcrops. Therefore, we used a remote sensing approach to estimate post-eruptive deformation. For most sites, QT Modeler software (Applied Imagery) was used to interpret lava flow tilt by digitizing several points on continuous or correlative cliff bands for paleomagnetically analyzed lava flows based on oblique views of satellite imagery and 10-m-resolution topographic data (U.S. Geological Survey, 2023). At the Picture Gorge type section, the same technique was used with 1-m-resolution LiDAR topographic data (Oregon Department of Geology and Mineral Industries - Oregon LiDAR Consortium, 2023). QT Modeler software was used to find the best-fit plane (dip and dip direction) to each collection of points, typically 7 to 14 points, to estimate the orientation of each lava flow (Table S1 in Supporting Information S1). Some flows analyzed for paleomagnetism in this study were not remotely evaluated for tilt due to similar apparent orientation to underlying or overlying flows or to relatively poor exposure across the landscape that precluded confident three-point orientation assessments. Tectonic

Table 1
Paleomagnetic Data From Sites Within the Picture Gorge Basalt

Site	Lat	Lon	<i>N</i>	Dec	Inc	Dec _{tc}	Inc _{tc}	<i>a</i> ₉₅	Kappa	Dip direction	Dip	Section	Notes	DG
P211	44.81017	240.09208	10	12.3	53.6	14.0	55.2	1.8	692	155	2	a5		16
P227	44.81159	240.08260	8	10.7	62.1	13.0	63.7	2.5	512	155	2	a4		15
P228	44.81136	240.08570	7	323.0	68.4	321.8	70.4	2.1	794	155	2	a3	Same DG as c2	<u>12</u>
P213+	44.80644	240.05493	8	157.0	26.5	157.0	24.5	9.1	38	155	2	a2	Combined with P2249, same DG as d3	<u>3</u>
P212+	44.80644	240.05493	9	209.4	−75.7	216.3	−76.8	4.3	145	155	2	a1	Combined with P229	2
P226	45.11101	241.02555	8	12.5	55.6	12.5	55.6	5.4	108	—	—	No	Paraconformity with GRB	—
P225	45.01766	241.11393	8	359.0	60.1	359.0	60.1	3.1	328	192	0.5	e3	No tc	—
P224	45.01047	241.09779	8	352.6	49.6	352.6	49.6	2.3	584	192	0.5	e2	No tc	—
P223	45.00967	241.09876	8	352.9	64.4	352.9	64.4	6.8	67	192	0.5	e1	D flow, 17.02 ± 0.03	—
P2243	44.71120	239.85642	4	31.8	63.3	35.7	63.9	3.2	1,121	140	2	d10		26
P2244	44.71143	239.85623	8	4.5	63.7	7.5	65.1	2.4	531	140	2	d9	Same DG as b7	<u>17</u>
P2245	44.71165	239.85590	8	14.1	57.6	16.8	58.7	4.2	178	140	2	d8	Same DG as b6, c4, a5	<u>16</u>
P2246	44.71152	239.85543	6	33.2	50.7	35.6	51.2	2.5	741	140	2	d7		13
P2234	44.69457	239.85282	7	20.0	80.5	31.4	81.3	2.9	443	140	2	d6		8
P2233	44.69598	239.85056	8	348.0	64.2	350.1	65.9	3.9	208	140	2	d5		7
P2223	44.71555	239.84225	8	29.3	49.7	31.5	50.4	7.6	54	140	2	d4	Same DG as b2	<u>6</u>
P2224	44.71690	239.83909	7	152.5	32.9	152.2	30.9	8.3	54	140	2	d3	Same DG as a2	<u>3</u>
P2225+	44.71798	239.83738	10	205.5	−52.9	208.0	−53.7	4.1	140	140	2	d2t	Combined with P2226	1
P2242	44.94751	240.31355	8	222.7	−54.1	222.7	−54.1	10.2	34	—	—	c16	Same as b17	<u>38</u>
P2247	44.90367	240.34625	8	217.6	−77.3	217.6	−77.3	5.3	116	—	—	c15		36
P2241	44.90116	240.34874	9	27.9	74.8	27.9	74.8	4.5	130	—	—	c14a		31
P2216	44.95220	240.29121	8	351.5	66.3	351.5	66.3	3.6	243	—	—	c14		30
P2235	44.81136	240.08570	8	10.5	51.7	10.5	51.7	3.6	243	—	—	c13		28
P2217	44.95480	240.28600	9	8.0	63.6	8.0	63.6	2.8	344	—	—	c12		27
P2218	44.94995	240.29251	9	24.0	63.4	24.0	63.4	3.8	189	—	—	c11	DG 25	<u>25</u>
P2248	44.94889	240.29615	9	26.5	62.4	26.5	62.4	5.1	104	—	—	c10	DG 25	<u>25</u>
P2219	44.94020	240.30016	9	24.3	64.0	24.3	64.0	2.6	396	—	—	c9	DG 25	<u>25</u>
P2220	44.93579	240.29959	8	355.4	69.0	355.4	69.0	1.9	844	—	—	c8		23
P2221	44.93191	240.29964	8	15.7	65.3	15.7	65.3	3.7	221	—	—	c7		22
P2222	44.92904	240.30108	8	1.1	69.2	1.1	69.2	1.8	971	—	—	c6		21
P2214	44.92477	240.30244	7	326.0	64.9	326.0	64.9	2.0	885	—	—	c5		18
P2213	44.92279	240.30487	8	13.2	56.4	13.2	56.4	3.2	308	—	—	c4	Same DG as b6, d8, a5	<u>16</u>
P2211	44.91811	240.29994	8	19.3	55.4	19.3	55.4	2.6	466	—	—	c3		15
P2215	44.91099	240.29674	8	316.9	70.3	316.9	70.3	2.2	615	—	—	c2	Same DG as a3	<u>13</u>
P2210	44.91136	240.29646	7	184.0	79.9	184.0	79.9	7.4	68	—	—	c1		4
CB7177	44.51222	240.37663	8	177.7	−38.4	176.3	−51.8	5.6	97	183	13.5	b18		39
CB7169	44.51299	240.37695	8	207.6	−43.4	215.1	−55.3	4.8	133	183	13.5	b17	Same as c16	<u>38</u>
CB7161	44.51362	240.37632	8	206.0	−52.5	216.5	−64.5	3.2	295	183	13.5	b16		37
CB7153	44.51458	240.37531	8	175.1	−54.3	170.8	−67.6	6.2	81	183	13.5	b15		35
CB7145	44.51542	240.37415	7	91.6	37.0	101.7	36.1	7.5	55	183	13.5	b14		34
CB7129	44.51635	240.37387	7	20.9	4.3	21.7	17.1	5.4	126	183	13.5	b13		33
CB7121	44.51770	240.37336	8	14.3	50.9	19.4	64.0	4.4	163	183	13.5	b12		32
CB7113	44.51878	240.37325	8	359.4	40.6	358.3	54.1	4.4	161	183	13.5	b11		29

Table 1
Continued

Site	Lat	Lon	N	Dec	Inc	Dec_tc	Inc_tc	α_{95}	Kappa	Dip direction	Dip	Section	Notes	DG
CB7105	44.51940	240.37345	8	15.6	49.3	20.8	62.3	2.8	386	183	13.5	b10		24
CB7137	44.51959	240.37368	8	6.8	51.1	8.6	64.6	3.0	337	183	13.5	b9		20
CB7097	44.52053	240.37374	6	353.8	52.1	349.4	65.3	10.9	39	183	13.5	b8		19
CB7089	44.52092	240.37347	8	3.3	50.8	3.4	64.3	3.9	208	183	13.5	b7	Same DG as d9	<u>17</u>
CB7081	44.52255	240.37230	8	13.8	44.6	17.5	57.8	3.5	253	183	13.5	b6	Same DG as c4, d8, a5	<u>16</u>
CB7073	44.52360	240.37358	8	320.2	74.9	260.4	79.6	7.0	64	183	13.5	b5		12
CB7065	44.52493	240.37051	7	23.0	36.4	27.8	48.9	4.4	191	183	13.5	b4		11
CB7057	44.52742	240.36732	8	13.0	63.5	22.5	76.6	2.9	364	183	13.5	b3		10
CB7049	44.52981	240.36534	7	26.9	41.5	33.7	53.5	3.8	248	183	13.5	b2	PG flow, 17.14 ± 0.04 , same DG as d4	<u>7</u>
CB7041	44.53041	240.36502	7	21.2	61.4	35.2	73.7	4.5	179	183	13.5	b1		5
P214	44.31495	240.68311	8	19.3	55.3	19.3	55.3	4.2	178	—	—	No	AM dike, 16.88 ± 0.06	—
P215	44.15153	240.72370	8	24.5	69.3	24.5	69.3	2.7	432	—	—	No	IR dike, 16.70 ± 0.09	—
P216	44.00054	240.72404	8	32.2	63.4	21.4	62.9	2.7	437	302	5.5	No	Izee flow, 16.62 ± 0.07	—
P217	43.98821	240.86301	11	307.9	−14.5	307.9	−14.5	8.2	32	—	—	No	WMB flow, 16.22 ± 0.06	—
P218	44.03168	240.76989	9	3.7	65.1	3.7	65.1	2.3	504	—	—	No	GR dike, 16.06 ± 0.14	—
P219	43.97071	240.50547	12	54.8	60.1	52.5	59.4	4.6	93	352	1.5	No	SM flow, 16.96 ± 0.07	—
P2252	43.85862	240.47310	6	150.4	−44.1	150.5	−45.6	10.0	57	147	1.5	No	PM flow, 16.18 ± 0.05	—
P2253	43.85786	240.47116	8	176.5	−67.0	178.3	−68.3	3.9	199	147	1.5	No	PM, upper	—

Note. Site = identifier for unique paleomagnetic collection area, Lat = site latitude, Lon = site longitude (WGS84 datum), N = total number of samples used in final analysis, Dec = paleomagnetic declination, Inc = paleomagnetic inclination, Dec_tc = paleomagnetic declination tilt-corrected for measured flow attitude, Inc_tc = paleomagnetic inclination tilt-corrected for measured flow attitude, α_{95} = cone of 95% confidence about the mean direction, kappa (κ) = precision parameter (Fisher, 1953), Dip Direction = direction that flow dips in, if applicable, Dip = angle of flow with horizontal, if applicable, Section = code applied to flows sampled in stratigraphic sequence: first letter refers to location, number refers to stratigraphic position. a: Spray, b: Picture Gorge, c: Highway 207, d: Twickenham, e: Dale. Notes = applicable information, such as ages or noted combined sites. DG = directional group that poles were assigned to, see Figure 6. Declinations and inclinations in bold type are those used for calculation of mean directions and subsequent analyses. DGs that are underlined are those that represent multiple flows.

deformation, despite the attempts to mitigate it, probably introduces a few degrees of error into our paleomagnetic assessments at any given site, overall error is less given the variable orientation of flows.

The Picture Gorge section, the south-dipping limb of an eroded anticline, is the most deformed of any sampling area in this study. The average dip direction was just west of south (azimuth 187.2°), with an average dip angle of 13.6° . For individual flows, dip directions ranged from azimuth 178.1° – 194.9° and dips ranged from 11.5° to 16.5° . Broadly, dip of flows slightly steepened up-section. An ESE-striking, subvertical (89° SSW dip) fault with an interpreted south-down vertical offset of ~ 12 m cuts the upper part of the section. The two steepest dips— 16.1° and 16.5° —were locally found at two thick cliff bands mid-section, although tracing one of these cliff bands regionally and fitting a plane across a wider area yields a more moderate 12.8° dip with 183.3° dip-direction that is consistent with our average dip and dip-direction. We interpret this local deviation of $\sim 3^\circ$ in dip magnitude likely reflects a local, low-relief ($\sim 3^\circ$) paleo-channel margin where relatively thicker PGB flows accumulated. We therefore tilt-correct paleomagnetic directions from all sites at the Picture Gorge section back to horizontal, assuming a dip direction of 187.2° and dip of 13.6° .

At other sections, high-resolution lidar topographic data were not available. However, flow units are visible in high-resolution satellite imagery and their orientations were estimated in conjunction with 10-m topographic data.

The flows sampled near Spray, Oregon, had a slight, roughly eastward dip as assessed in the field, although variable over multiple kilometers along the river-side road. Two prominently outcropping cliffs were measured at these drill sites both north and south of the river, which yielded a consistent dip direction of 155.0° , while dips ranged from 1.5° to 3.5° , averaging 2° . The thick, transitionally magnetized flow (site P213) above the reversely magnetized flow (P212) had slightly different dip direction of 107.7° , while retaining the same dip. However, near

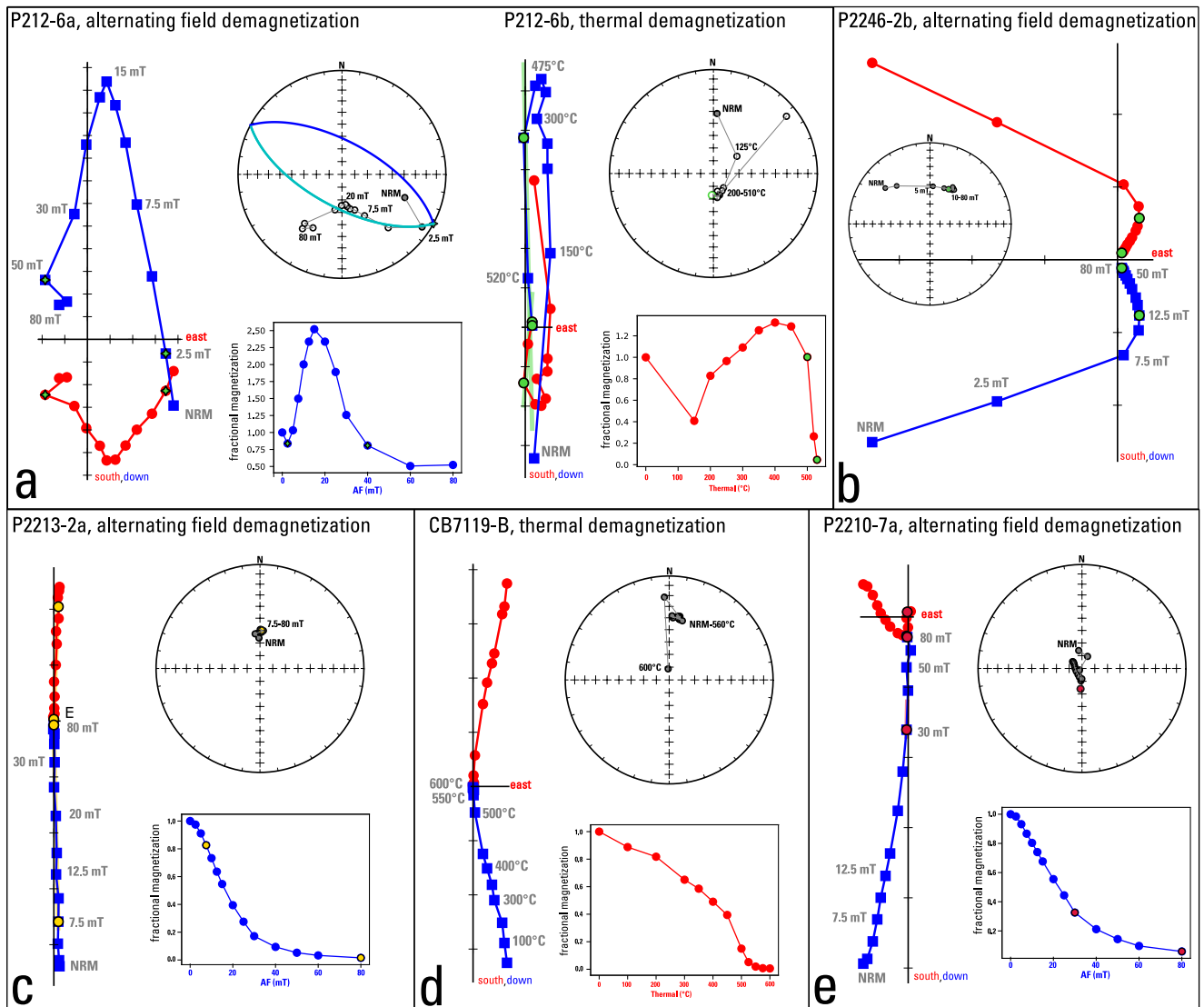


Figure 3. Paleomagnetic data from the Picture Gorge Basalt (PGB). Data are shown in geographic coordinates on vector component plots, measurement-level equal area plots, and magnetization-magnitude plots (principally constructed using PmagPy software; Tauxe et al. (2016). Endpoints of line or plane fits to data are shown as colored markers on vector component and magnetization-magnitude plots. These data are also available at an archived data repository (Pivarunas et al., 2025). The (a) upper left plots show paleomagnetic data from two specimens (P212-6a and P212-6b) from the same core. These are from the lower reversed-polarity section of PGB and illustrate the large secondary normal component, as well as the success of both alternating-field (AF) and thermal demagnetization methods in removing it, with the latter method yielding better results. The (b) upper right plot group shows an example of a large but low-coercivity component removed from a characteristic normal-polarity specimen with AF demagnetization (P2246-2b). The (c) lower left (P2213-2a) and (d) middle plot groups illustrates the stability of characteristic magnetizations using both AF and thermal methods. These well-behaved univectorial magnetizations were common throughout the PGB. The (e) lower right diagram (P2210-7a) illustrates successful AF demagnetization of an excursions direction (nearly vertical).

Service Creek, this flow (above site P229 here) had a more consistent dip direction of 159.6°, with a 2.3° dip. Generally, sites at the Spray section could be corrected back to horizontal assuming a dip direction of 155° and dip of 2°. However, given how shallow this interpreted dip is, we find it unsatisfactory to correct for something that could represent an original gradient.

Tectonic influence on the sub-horizontal flows sampled near Twickenham was difficult to assess in the field, particularly for the very thick lower flows. In QT Modeler, satellite imagery and 10-m topographic data were used to fit three planes, at a lower, middle, and upper flow. These yielded dip direction and dip estimates of 136°/2°, 143°/2°, and 140°/3°, respectively, with an average of 140°/2°. These numbers are comparable to those from the Spray section, ~20 km to the northeast. While we could therefore correct all sites at the Twickenham section back

to horizontal assuming a dip direction of 140° and dip of 2° , this shallow dip may reflect an original lava gradient, and we do not correct for it.

The Highway 207 flows appear undeformed when viewed in the field. Multiple attempts to fit planes to these flows using QT Modeler yielded sub-horizontal attitudes with dips of 0° – 2° . Dip directions are inconsistent between different flows. Therefore, we regard the Highway 207 section as essentially flat-lying and have not performed any tilt-correction on those data.

To summarize, the Picture Gorge section has been tilt-corrected using lidar-derived plane fits, while other sections and flows have been evaluated using plane fits derived from the integration of satellite imagery and 10-m topographic data but not tilt-corrected for the possible minor tectonic deformation. The Highway 207 section has not been corrected as we judged it to be essentially sub-horizontal based on multiple plane fits. Besides the type section flows, only one other flow (site P216, near Izee) was corrected for $\sim 5.5^\circ$ of southward dip. We provide the requisite information for future evaluation of our estimations for the planar orientations of lava flows (Table S1 in Supporting Information S1).

4. Paleomagnetic Results

4.1. Spray Section

We sampled 5 gently eastward-dipping lava flows exposed in sequence close to the town of Spray, Oregon (Figure 4a). These lava flows are described as a reference section for the Twickenham Basalt (Swanson et al., 1979). The basal flow in the Spray sequence, exposed from Service Creek to near Spray has reversed polarity. We sampled separate outcrops of this basal flow, at Service Creek (site P229) and a few kilometers west of Spray (site P212). The reversed characteristic magnetization is revealed at both sites only after a large normal polarity overprint is removed (Figure 3). At site P2249, 0.5 m below the contact with the overlying transitional direction flow, the reversed polarity flow (site P2249) is completely overprinted with the transitional direction seen a few meters above at site P213. This overprint is distinct from the normal polarity overprint, which masked the reversed polarity in site P212 a few meters below the contact. This is consistent with other CRBG paleomagnetic results (e.g., Audunsson & Levi, 1988), which showed a comparably short distance of magnetic resetting below the Roza lava flow. The transitional polarity flow, which has a shallow, down-inclination southerly direction, is followed by a sequence of 3 normal flows exposed sequentially up section.

4.2. Twickenham Section

We sampled 10 lava flows near the town of Twickenham, Oregon (Figure 4b). The oldest flows in the PGB are found here within the Twickenham Basalt subunit (Nathan & Fruchter, 1974; Swanson et al., 1979). The bottom four flows are especially coarse-grained and up to 70–90 m thick (Bailey, 1989a; Nathan & Fruchter, 1974), with pegmatoidal zones like the older flows exposed near Spray (Lindsley, 1960). This section is at least 600 vertical meters thick, from the basal flow to the ridgetop, which would render it thicker than the mapped sections of Bailey (1989a). The bottom-most flow sampled, second from the base of the section, is of reverse polarity and was sampled at two sites. This flow is followed by a transitional flow with a paleomagnetic direction identical to the shallow, down-inclination southerly direction seen in the Spray section. The rest of the sampled flows in the section are of normal polarity. There are multiple additional unsampled lava flows above our sampled sequence. Since these are natural exposure, some horizontal differences in sampling were employed, and flow boundaries are always clear, some thin flows may have been missed in the sampled sequence.

4.3. Highway 207 Section

We sampled 16 subhorizontal, conformable lava flows exposed in sequence along Highway 207 (Figure 4c). This section is 453 m in thickness based on elevations of the base to top flows and has at least 16 flows in it; some thin flows or flows without clearly exposed boundaries may have been missed. The stratigraphic ordering of flows becomes less clear in the top 4 flows, however, the reversed polarity flows are certainly above the normal polarity flows. Since the basal flows are neither coarse-grained nor abundantly phyrlic, we judge them as the Monument Mountain Basalt, and not the more recognizable Twickenham Basalt. The basal flow has a down-inclination, southerly transitional direction that is distinct from the transitional direction found in the Spray section. This is followed by 13 normal polarity flows and capped by two reversed polarity flows. There are two interbeds in

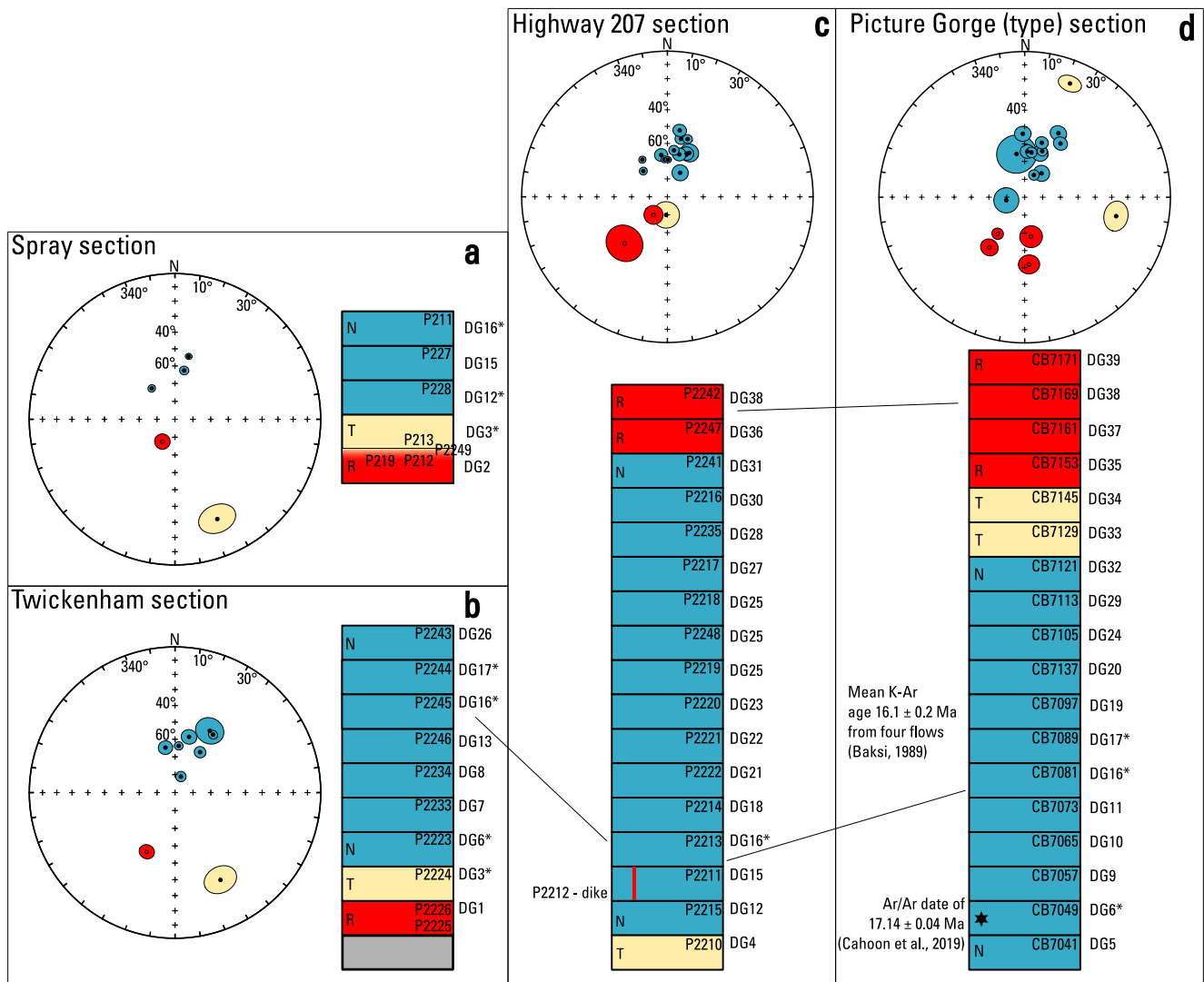


Figure 4. Stratigraphic columns for Picture Gorge Basalt sections, along with equal-area stereoplots showing tilt-corrected paleomagnetic directions (Table 1). Columns are schematic; thickness of boxes do not represent the actual thickness of individual flows. Unique site indicators as labeled. Blue boxes (label of “N”) indicate flows of normal polarity, red boxes (label of “R”) indicate flows of reversed polarity, tan boxes (label of “T”) indicate transitional polarity flows. Color scheme from columns is same for equal-area stereoplots. Columns and stereonet are from: (a) the Spray section, (b) the Twickenham section, (c) the Highway 207 section, and (d) the Picture Gorge (type) section. Asterisks on Directional Group (DG) designations indicate flows interpreted as spanning multiple sections. Selected correlations are shown with lines.

between the first and second and fourth and fifth flows with the first interbed having a noticeable reddened color. A 1.5-m-thick dike with reversed polarity cuts the normal polarity third flow in the sequence. This dike has an identical paleomagnetic direction to the second-from-the-top reversed polarity flow (site P2247) supporting the original supposition of Nathan and Fruchter (1974) that this is the feeder dike for an upper R-polarity flow. Unlike at the type section, we did not find transitional flows between the N–R zones.

4.4. Picture Gorge Section

We sampled 18 tilted-to-the-south lava flows exposed at the type section in PGB along Highways 19 and 26 (Figure 4d). The sequence begins in the Monument Mountain Basalt subunit, with the oldest Twickenham Basalt subunit missing (Bailey, 1989a; Cahoon et al., 2023; Swanson et al., 1979). Our sampling at the type section confirms the original framework of N–R (Watkins & Baksi, 1974). The only difference is that our detailed sampling indicates a sequence of 12 normal polarity lava flows from the beginning of the section, rather than the 9 recognized earlier. The unique paleomagnetic directions from these additional flows confirm that these are robust

additions to the PGB sequence. The second-from-the-base normal polarity flow was dated by Cahoon et al. (2020) at 17.14 ± 0.04 Ma. The normal polarity and date for this flow are inconsistent with the GPTS, since its date would place it during a reversed polarity chron (discussed further below). The normal polarity flows record substantial swings in paleomagnetic direction, with inclinations ranging from 50 to 80°. After the normal polarity flows, two transitional lava flows are followed by four reversed polarity lava flows. Multiple reddened interbeds are noticeable in the sequence.

4.5. Site Averaging and Summary Data

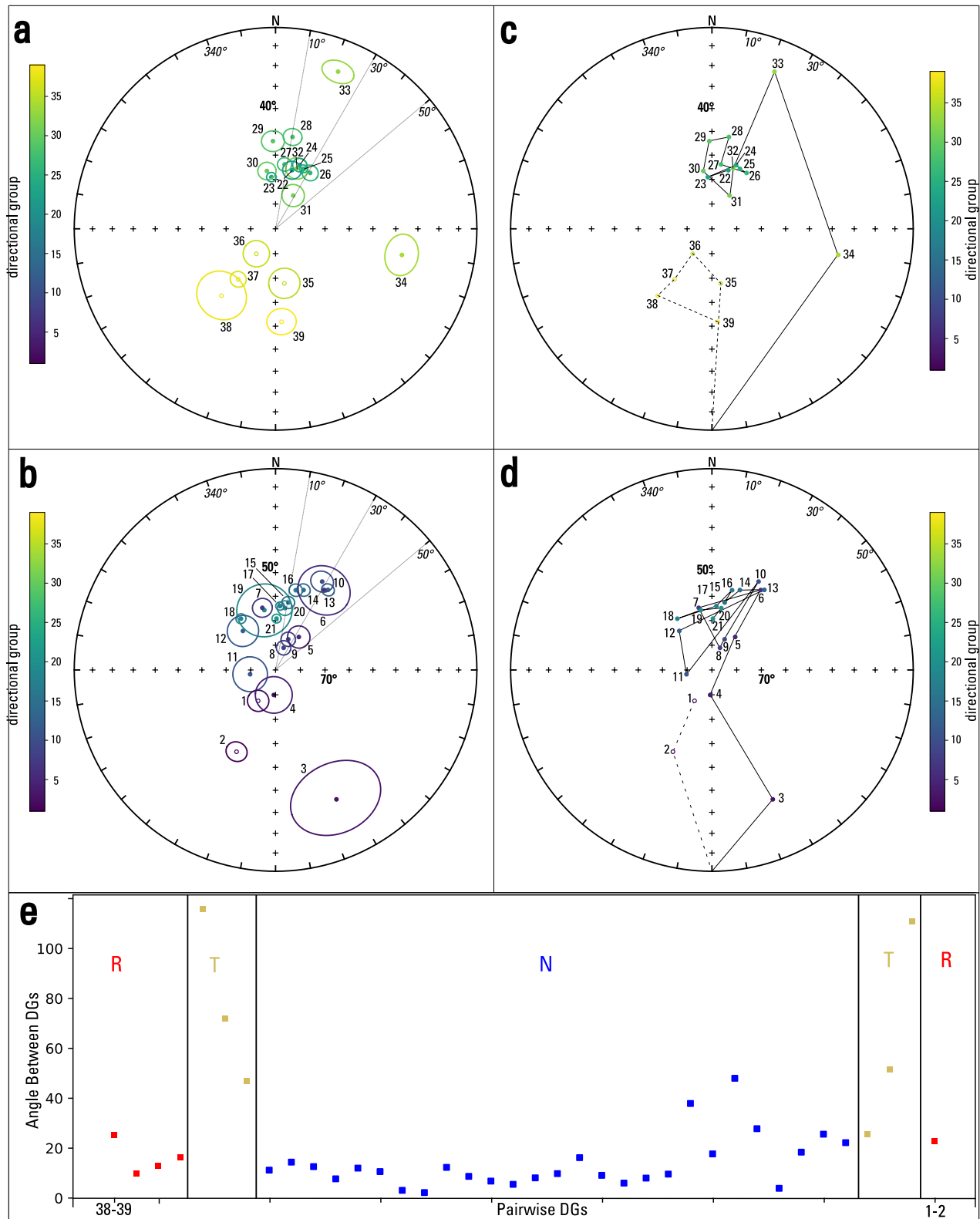
We correlated the four studied sections and constructed a total composite magnetostratigraphic sequence for the PGB using 39 paleomagnetic directions. Paleomagnetic directions were combined based on paleomagnetic directional similarity of flows at similar stratigraphic locations within different sections or serially correlated flows from the same section (Figure 5, see Mankinen et al., 1985 for discussion). We judged that at least 7 flows have been sampled at multiple sections. These comparisons were based on paleomagnetic data along with location within the section and are conservative. Future geochemical study of these sections, paired with the paleomagnetic data, would provide an additional axis of comparison. We did not use data from non-stratigraphically linked flows/dikes for our composite magnetostratigraphic sequence.

Our sequence (Figure 5) illustrates the paleosecular variation (PSV) recorded throughout the main eruptive interval of the PGB. Our ordering does not represent the actual path of the geomagnetic field, rather, it is our best estimate of the outline of a path based on our stratigraphic ordering. Multiple 10s of degrees of looping angular changes between successive events, such the DG 6–10 or DG 10–13 loops, provide an example of how similar paleomagnetic directions do not necessarily indicate synchronous emplacement. The reversed-normal-reversed sequence is clear, with transitional magnetizations recorded by multiple flows at each reversal. The angular distance between DGs—which is a crude proxy for time—tends to decrease with time in the normal polarity interval and exhibits small rises and falls. Large angular distances are seen during polarity transitions, consistent with rapid movement of the ancient magnetic field at those times.

We calculated a mean direction, from 45 non-transitional flows/directional groups—i.e., 45 independent samplings of the ancient geomagnetic field (Table S2 in Supporting Information S1). This calculation does incorporate isolated dated flows and dikes. The mean PGB paleomagnetic direction has $D = 9.8^\circ$, $I = +64.5^\circ$, with statistical parameters $\alpha_{95} = 3.4$, $\kappa = 41$. These data have both polarities, pass a reversals test (McFadden & McElhinny, 1990) at the “C” level and represent sporadic sampling of the geomagnetic field over >100 kyr of time. The paleomagnetic pole calculated from the associated VGPs is 083°N , 303°E ($A_{95} = 5^\circ$, $K = 19$). The age for this pole ranges from ~ 16.7 to 16.0 Ma.

4.6. Correlation of Dated Units With the Geomagnetic Polarity Time Scale

We compare dated but stratigraphically isolated flows with the GPTS (Figure 6) to assess compatibility. Accurate K/Ar or $^{40}\text{Ar}/^{39}\text{Ar}$ dating of CRBG lavas is extremely challenging due to glass (commonly with cryptic alteration), fine-grained textures, and a lack of potassium-bearing phenocrysts. Following an assessment of recently published data (Cahoon et al., 2020, 2023) we note a reduction method that may have led to inclusion of data with disturbed argon isotopes. Typically, the term “plateau age” implies simple correction with atmospheric argon ($^{40}\text{Ar}/^{36}\text{Ar} = 298.56 \pm 0.31$, Lee et al., 2006; or 295.5, Nier, 1950 used here). However, a common visualization tool sometimes used to plot age spectra uses a $^{40}\text{Ar}/^{36}\text{Ar}$ value derived from an inverse isochron intercept instead of the accepted atmospheric ratio. This practice is more robust if the full uncertainty of the inverse isochron intercept is propagated through the age equation and can yield a result identical to the isochron age (Schaen et al., 2021). In the present case, the ages reported would be better described as inverse isochron results, not plateau ages. Inverse isochron results can be reliable but do imply more complexity than concordant results containing only radiogenic and atmospheric argon. Many of the inverse isochron intercepts used are lower than atmospheric (<298.56) which is a common result of ^{39}Ar recoil (Fleck et al., 2014), which complicates results. To test these published results we sampled flows and dikes dated by the $^{40}\text{Ar}/^{39}\text{Ar}$ method from Izee, West Myrtle Butte, Dale, Snow Mountain, and Ponderosa Mine and dated dikes at Aldrich Mountain, Gilbert Ridge, and Inshallah Ranch; these ages are listed alongside our paleomagnetic results in Table 1. The matchup of the dates and associated polarities to the GPTS is poor; the majority (5/9) of these radiometric ages, when paired with paleomagnetic data, do not match the expected timescale polarity. As to the other four ages, two of these age-



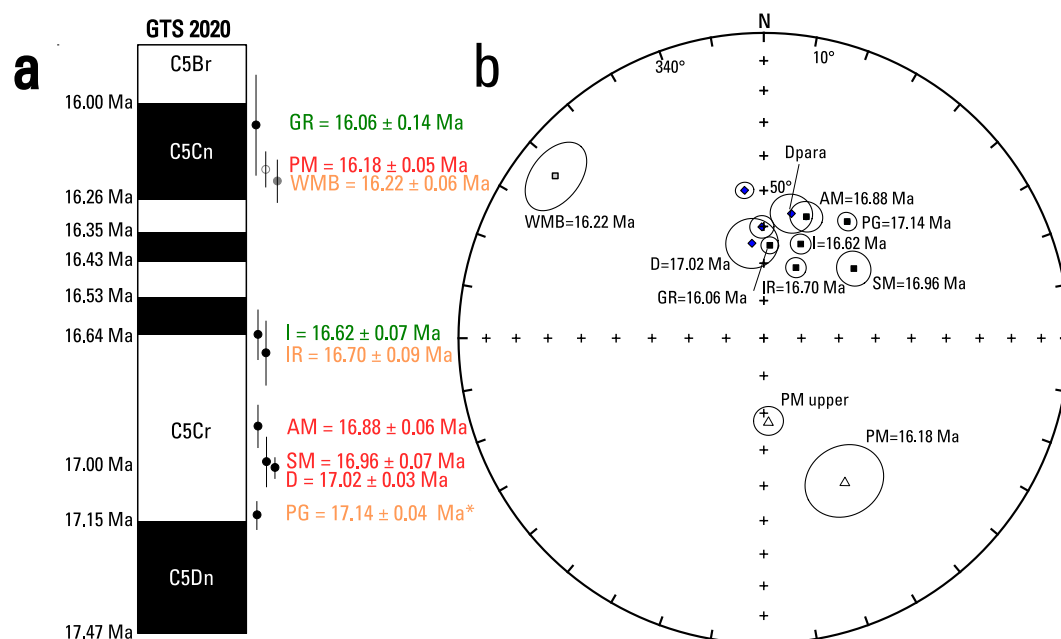


Figure 6. (a) Lava flow $^{40}\text{Ar}/^{39}\text{Ar}$ ages relative to the Geomagnetic Polarity Time Scale (Kochhann et al., 2016; Ogg, 2020; Raffi et al., 2020), age bars are 2-sigma after Cahoon et al. (2020, 2023). Filled circles indicate normal polarity lava flows, open reversed-polarity, and gray transitional polarity. Colors indicate match with timescale polarities: red for no match, orange for possible match near boundary, and green for match, b, equal-area projection of site-level directions. Quoted ages after Cahoon et al. (2020, 2023), abbreviations as used therein. *D* = Dale flow, *AM* = Aldrich Mountains dike, *GR* = Gilbert Ridge dike, *IR* = Inshallah Ranch dike, *I* = Izee flow, *WMB* = West Myrtle Butte flow, *SM* = Snow Mountain flow, *PM* = Ponderosa mine flow, and *PG* = Picture Gorge flow. *Dpara* = Dale wayside paraconformity, where a Picture Gorge Basalt flow is separated from the Grande Ronde Basalt by several meters of sediment.

polarity pairs do match the expected sequence and another two are permissible when age uncertainty is considered.

Two matches with the GPTS are from the lava flow at Izee and the dike at Gilbert Ridge. The Izee flow, like basalt flows of similar age in the area, is a ridge-capping unit atop basement Mesozoic terranes (Dorsey & LaMasquin, 2007; White et al., 1992). Cahoon et al. (2020) reported a 16.62 ± 0.07 Ma plateau age, favoring the analysis with an inverse isochron age of 16.57 ± 0.09 Ma. This flow has a normal paleomagnetic direction, which is consistent with the GPTS and its associated date. The Izee flow is tilted at 5° to the SSW, which we have corrected back to the implied paleo-horizontal. The dike at Gilbert Ridge also has a normal polarity direction. This is permissible with the GPTS given its reported age of 16.06 ± 0.14 Ma (Cahoon et al., 2020), but the inverse isochron age of the chosen analysis is 15.86 ± 0.80 Ma, which spans several reversals as well as the majority of the main-phase CRBG. The paleomagnetic direction is ordinary enough that we are not confident of the dike's relation to the normal polarity sequence in the PGB magnetostratigraphy.

Two dates which fit the timescale polarity within uncertainty are from a dike and a lava flow south and southeast of type area respectively. The Inshallah Ranch dike has a normal paleomagnetic direction which, within uncertainty, fits both its reported age (16.70 ± 0.09 Ma) relative to the GPTS and its inverse isochron age of 16.70 ± 0.19 Ma. The Inshallah Ranch dike has been associated with the nearby Izee flow based on age, texture, and geochemistry (Cahoon et al., 2023); we find this correlation paleomagnetically permissible given that both have moderate-steep down inclinations and easterly declinations. The West Myrtle Butte flow outcrops as low-

Figure 5. Composite path of field direction changes using data from all sections sampled. Left-side equal area stereoplots (a, b) show mean-directions with 95% confidence limits. Right-side equal area stereoplots (c, d) show mean directions connected by lines in stratigraphic sequence. Directional sequence numbers run from 1 to 39, where higher numbers are younger in the sequence. (a) is the younger/upper sequence (1–20), (b) is the older/lower sequence (21–39). Open symbols indicate paleomagnetic directions on the upper hemisphere of equal-area projection; solid symbols indicate paleomagnetic directions on lower hemisphere. (e) Shows angular distance between successive directional groups, younging to the left.

slung benches of basalt along a Forest Service road. This lava is reported at 16.22 ± 0.06 Ma, concordant with its inverse isochron age of 16.22 ± 0.06 Ma (Cahoon et al., 2020). It has a transitional paleomagnetic direction; if its date is considered together with the associated uncertainty, it may be associated with the C5Cn.1r to C5Cn.1n polarity reversal. We again mention the Picture Gorge type section flow, although it does not fall into the “not stratigraphically constrained” category. While its date, given uncertainty, could fall into C5Dn, this scenario implies an unevidenced hiatus of 500 kyr in between the second and third flows within the PGB type section, which then fortuitously resumed erupting during another normal chron.

Data for the remaining flows and dikes do not exhibit good matches with the polarity time scale. The Dale flow is ~80 km northeast of the Picture Gorge section and outcrops above a tuff dated at 33 Ma (Brown, 2017). The Dale flow is the base of a section of PGB lavas and was reported at 17.02 ± 0.03 Ma (Cahoon et al., 2020), with an inverse isochron age of 17.02 ± 0.06 Ma, though with an extremely subatmospheric $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 225 ± 17 . We sampled both the dated flow as well as the two flows immediately above it. All three flows yield normal paleomagnetic directions, which is inconsistent with the date of ~17 Ma when compared with the GPTS (Figure 6). The paleomagnetic direction of the dated flow, when compared to our composite magnetostratigraphy, might correspond to the early part of the normal polarity interval. Only a few Quaternary normal faults cut the area between Picture Gorge and Dale, Oregon, thus this correlation is unlikely to be substantially affected by differential tectonism. North from Dale on the road to Ukiah, a PGB flow is exposed in a quarry separated from an overlying Grande Ronde Basalt flow by a paraconformity (Nathan & Fruchter, 1974); this PGB flow is also of normal polarity. The Snow Mountain flow is an isolated ridge-capping flow at high altitude (>2,200 m). The flow has a reported date of 16.96 ± 0.07 Ma, an inverse isochron age of 16.97 ± 0.12 , and its paleomagnetic direction is of normal polarity, although its far-easterly declination is inconsistent with other sampled flows in the PGB. This could indicate differential clockwise rotation of this area—somewhat feasible given the obvious uplift—relative to other sections of the PGB. The normal polarity and date for this flow are inconsistent with the GPTS, since its date would place it during a reversed polarity chron (C5Cr). The Ponderosa Mine flow is coarsely crystalline at a sunstone mine in southern Oregon (Cahoon et al., 2023; Johnston et al., 1991). Atop the coarsely crystalline flow is a fine-grained PGB-like flow. The lower, coarse-grained flow is dated at 16.18 ± 0.05 Ma with a 16.18 ± 0.08 inverse isochron age. This lower flow has a somewhat shallow reversed polarity direction and the upper flow has a regular reversed polarity direction. The flow's age would place it in a normal polarity chron (C5Cn). Near Aldrich Mountain, an aphyric dike has a reported plateau age at 16.88 ± 0.06 Ma and inverse isochron result of 16.88 ± 0.08 Ma (Cahoon et al., 2020). The geochemical correlation of this dike is uncertain, but its age suggests association with the older Twickenham Basalt of the PGB (Cahoon et al., 2023). However, its paleomagnetic direction is normal, inconsistent with the GPTS. Rough correlation of its paleomagnetic direction with PGB magnetostratigraphy does support an early position in the normal PGB magnetozone; paleomagnetic directions later in the sequence do not share its combination of moderate-inclination and easterly declination.

In summary, over half the examined $^{40}\text{Ar}/^{39}\text{Ar}$ dates on the PGB do not align with the GPTS when paleomagnetic directions for the dated flows/dikes are considered (Figure 6) along with associated geological information. Considerations of the argon data confirm the paleomagnetically derived judgments, in that argon data which were in themselves unsatisfactory did not pass the paleomagnetic test, while more satisfactory argon data did. None of the oldest dates, in particular, have magnetic polarities compatible with their corresponding ages. The importance of continuous basalt sections in guiding interpretations cannot be overstated. Isolated flows are difficult to place contextually, especially if age constraints are not well known.

5. New Stratigraphic Context for the Picture Gorge Basalt

5.1. Columbia River Basalt Group Relationships

Our magnetostratigraphic results provide evidence of an extended interval of PGB volcanism during at least 3 CRBG magnetozones. The scenarios for continuous PGB volcanism during main phase CRBG eruption are that these magnetozones coincide with R2–N2–R3, R1–N1–R2, or R0–N0–R1. The first possibility lacks credence given ages from the overlying Mascall Formation (McLaughlin et al., 2016) as well as the mapped relationship of PGB–GRB relationship north of the Blue Mountains uplift where PGB underlies R2 GRB. We prefer the last option, where the PGB is a part of the early group of CRBG eruptions.

Since the geomagnetic field is a global phenomenon, our PGB magnetostratigraphy lets us leverage the GPTS to provide more precise ages (Figure 6, boundaries after Ogg, 2020; Raffi et al., 2020). The timing of these CRBG

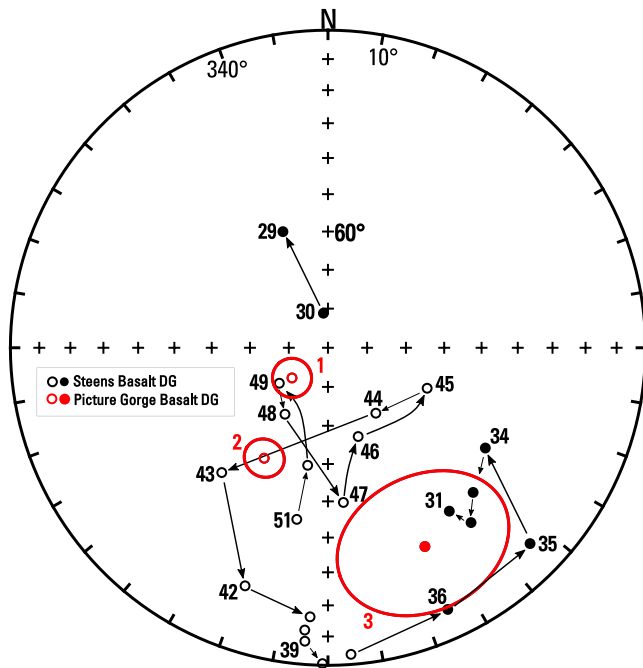


Figure 7. Comparison of geomagnetic field movement during the Steens reversal with geomagnetic field movement during the lower Picture Gorge Basalt (PGB) field reversal. Red datapoints correspond with new PGB data (with error ellipses), while black data are from the Steens Basalt (Mankinen et al., 1985), plotted without error ellipses. Numbers from Steens Basalt decrease as they go up in stratigraphy (i.e., 51 is the first/oldest and 29 is the last/youngest), whereas numbers of PGB data increase with stratigraphy (i.e., 1 is the first/oldest).

directional groups (DG) 1, 2, and 3 with the secular variation recorded in SB DG 51–31 (numbers after Mankinen et al., 1985). We also use the more detailed path of Jarboe et al. (2011), where flows from other sections of Steen Basalt filled some gaps in the path. Two reverse polarity flows (our 1 and 2) correspond with the reversed-polarity field from early within the Steens sequence. PGB DG 1 is similar to Steens DG 49, while PGB DG 2 falls on the path between Steens DG 44–DG43 (Mankinen et al., 1985), nearest to DG PS10/PN2 (Jarboe et al., 2011). The most unique element of this correlation is PGB DG 3, which is in a south-declination, down-inclination position visited twice during the Steens reversal (Jarboe et al., 2011). If one uses a probabilistic method such as that of Bogue and Coe (1981) to assess the probabilities of encountering these directions pair-wise or this sequence of directions, the probability that the shallow-down directional group (e.g., PGB DG 3) would recur at separate times (i.e., the “random” hypothesis) collapses to zero. While this seems to be strong evidence in favor of the correlation, similar patterns of directions during reversals in the western United States have been recognized (Bogue et al., 2017). Thus, our argument could possibly be an artifact. However, no other detailed transitional record from other candidate reversals in the Grande Ronde Basalt, such as R1–N1, provide a similar sequence of directions (Hooper et al., 1979; Watkins & Baksi, 1974). These records are less than satisfactory, and we recommend—and indeed are carrying out—a thorough PSV based paleomagnetic re-study of the Grande Ronde Basalt to fully test our hypothesis.

The duration of the normal PGB magnetozones provides time constraints on the PGB eruption rate. This normal interval may either correspond with the N0 (C5Cn.3n) or N1 (C5Cn.2n) magnetozones (see discussion of CRBG magnetozones in Kasbohm & Schoene, 2018; Kasbohm et al., 2023). The duration of the polarity intervals is 83 and 105 kyr respectively, taken from the GPTS (Ogg, 2020; Raffi et al., 2020), who based this part of the timescale on the carbonate and astronomical records from IODP site U1335 in the Pacific Ocean (Kochhann et al., 2016). The modeled durations for the polarity intervals from Kasbohm et al. (2023) are 72 + 44/–35 kyr for N0 and 99 + 56/–55 kyr for N1. The total span of credible duration for these normal polarity intervals is thus 37–155 kyr. The normal interval in the PGB contains 26 directional groups and even more distinct flows

reversals has been constrained by a high-precision geochronological work. The R0–N0 reversal is placed at ~16.65 Ma (Kasbohm et al., 2023) by a dual-chronometer Bayesian model which agrees with $^{40}\text{Ar}/^{39}\text{Ar}$ data from Steens lava flows subject to Bayesian statistical analysis by Jarboe et al. (2010). The date of Mahood and Benson (2017) for the reversal is younger in comparison, at ~16.5 Ma. The next sequence of reversals is best constrained by the comprehensive dual-chronometer model of Kasbohm et al. (2023): N0–R1 at ~16.57 Ma, N1–R2 at ~16.46 Ma, and R2–N2 at ~16.37 Ma.

The typical placement for the PGB, absent the early reversed magnetozones, is coincident with N1–R2 Grande Ronde Basalt (Reidel et al., 2013). Recent $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology (Cahoon et al., 2020, 2023), however, suggests the earliest normal polarity PGB flows are >17 Ma, meaning coincidence with the N0–R1 magnetozones and the spread of new $^{40}\text{Ar}/^{39}\text{Ar}$ ages from the PGB (Cahoon et al., 2023) covers a span of 8 GPTS polarity intervals. However, our sampling of multiple sections and derivative composite magnetostratigraphy only shows 3 distinct intervals of polarity. The critique of the $^{40}\text{Ar}/^{39}\text{Ar}$ dates from Cahoon et al. (2020, 2023) by Baksi (2022) also suggested the type section PGB reversal is the N0–R1 reversal. This suggestion was based on a 16.44 Ma age from a tuff in the lowermost Mascall Formation (McLaughlin et al., 2016), this formation overlies the PGB. There also exists a 16.549 ± 0.007 Ma U–Pb date on zircon from an ash bed near the upper reversal of the PGB type section (Maverick et al., 2016) consistent with an R0–N0–R1 placement for the PGB.

We suggest, based on our paleomagnetic data, evaluation of age constraints, and geochemical considerations, that the timing of the lower PGB reversal corresponds with the Steens Basalt reversal sequence (Mankinen et al., 1985). The lower PGB reversal sequence is found in only a handful of thick flows in contrast with the dozens of thin flows which comprise the record at Steens Mountain and surroundings. We note similarity (Figure 7) between PGB

(Table 1; Figure 5). Using each directional group as a separate event, our paleomagnetic data imply the PGB erupted with an average recurrence interval of 1.4–6.0 kyr during this main phase interval, more specifically 1.4–4.5 kyr if the chron was N0. This is a minimum estimate but suggests more frequent eruptions than estimated by other workers (e.g., Bailey, 1989a; Sheldon, 2006), based on the total number of mapped PGB flows and the total duration of PGB emplacement. The volcanic activity, however, was unlikely to have occurred at a consistent frequency through time. For example, an upper portion of the Highway 207 section where 3 separate flows share an identical paleomagnetic direction suggests volcanic activity at times occurred at a rate greater than that of secular variation. The rises and falls of the DG angular distances (Figure 5e) might be crudely cyclic and represent pulses of volcanic activity. These pulses would be on the order of 10–20 kyr, and would be an interesting feature to search for in other detailed magnetostratigraphic data sets for LIPs. We interpret a rough consistency in eruptive behavior in that each polarity transition (average duration of ~7,000 years; Clement, 2004) is recorded by 2 transitional flows. An avenue for future work would involve the union of paleomagnetic directional data along with geochemical data in order to more finely divide the time between radiometric tie points.

PSV has been used to estimate time duration during LIP eruptions (Mankinen et al., 1985; Pavlov et al., 2019). In southern Oregon, workers at the Steens Basalt polarity transition used PSV to estimate a duration of $3,500 \pm 700$ years for the normal polarity interval and $5,000 \pm 1,000$ years for the reversed interval (Mankinen et al., 1985). For the PGB normal chron, we use a combination of these published approaches, taking into account both the time each directional group represents and the time between the directional groups. There are 28 normal DGs, each of which we estimate to comprise 300–400 years of volcanic activity (after Pavlov et al., 2019). The sum of the angular distance between each consecutive DG is 375° . We assume a PSV rate of $2^\circ/100$ years to be conservative (after low-end Holocene estimate of Hagstrum & Blinman, 2010). This provides a paleomagnetically based estimate of 27–30 kyr for the PGB normal chron, which is clearly well-under the “real” amount of time elapsed and thus we suggest that such methods may represent significant underestimations. The longer recurrence interval of PGB eruptions, versus the Steens Basalt, likely misses structure in the secular variation path, cutting across or missing loops.

The earliest PGB Twickenham Basalt and the Imnaha Basalt are similarly coarse-grained, plagioclase- and olivine-phyric flows (Bailey, 1989a), a textural feature they also share with the Steens Basalt. All three are somewhat primitive, with a maximum MgO >9 wt% (Wolff & Ramos, 2013). The Picture Gorge and Imnaha Basalts have been directly compared, geochemically (Carlson, 1984; Nathan & Fruchter, 1974), with particular similarities between the lowest American Bar chemical type of the Imnaha Basalt and the PGB (Streck et al., 2023). The Steens, Imnaha, and PGB might represent regionally separated but penecontemporaneous early CRBG volcanism. Radiometric dating of ash beds within the Steens and Imnaha Basalts (Kasbohm & Schoene, 2018; Kasbohm et al., 2023) show that these formations overlap in time.

An earlier beginning for PGB volcanism also necessitates re-examination of the relationship between the PGB and GRB. If these polarity intervals are coincident with the R0-N0-R1 CRBG magnetostratigraphy, then the interpretation of PGB-GRB equivalence at N1-R2 is either inaccurate or reflects a different phase of PGB eruption unconnected to its continuous interval of volcanism. The geochemistry and paleomagnetism of the Butte Creek section (Nathan & Fruchter, 1974), the only recognized locality where the PGB and GRB have been described as interfingering, may bear on this problem. The “PGB-type” eruptions north of the Blue Mountains uplift, which have dikes associated (Robinson, 1975), may not be time equivalent to the eruptions in the John Day Basin and south.

5.2. Post-Emplacement Tectonism

By comparing our calculated paleomagnetic pole (083°N , 303°E) for the PGB study area (44.7°N , 240.3°E) with the stable North American (NAM) reference pole (83.4°N , 163.6°E) from Gallo et al. (2023) at 17 Ma and the coordinates of our study area, we calculate $18^\circ \pm 7^\circ$ of clockwise rotation (Table 2). Our results are of similar magnitude to the $14.5^\circ \pm 6.4^\circ$ of clockwise rotation calculated by Jarboe et al. (2008) based on paleomagnetic results from the Steens Basalt. The previous study used a different NAM reference pole for 15 Ma from Besse and Courtillot (2002), although the difference in pole positions is negligible. These modern studies on well-characterized sections of early CRBG lavas in Oregon render the conclusion of post-Miocene deformation of Central Oregon unavoidable. Earlier work, however, chiefly in the Steens Mountain area and regional compilation results of Mankinen et al. (1987), has been used by Wells and Heller (1988) and Wells and

Table 2

Summary Paleomagnetic Pole Data From Central Oregon

Pole name	Nominal age	<i>N</i>	Plat	Plon	<i>K</i>	<i>A</i> ₉₅	Rotation	ΔR	Reference
Picture Gorge Basalt	17 Ma	45	83	303	19	5	18	7	This study
Picture Gorge section	17 Ma	14	84.7	352	20	9.2	15	10	Watkins and Baksi (1974)
Imnaha/Lower GRB	17 Ma	30	85	155	15	6.8			Hooper et al. (1979)
Steens Basalt	17 Ma	76	85.7	318.4	15	4.3	14.5	6.4	Jarboe et al. (2008)
Clarno Formation	45 Ma	46	83.9	277.6	9	7.4	16	10	Grommé et al. (1986)
Mitchell Inlier	90 Ma	11	80.4	359.4		5.2	37.3	6.6	Housen and Dorsey (2005)

Note. Reference poles used to calculate rotations at 17 Ma and 45 Ma come from Gallo et al. (2023); reference pole for 90 Ma comes from Housen et al. (2003). We note that the differences between the 17 and 45 Ma poles we chose, versus those used in previous studies (Steens Basalt used Besse & Courtillot, 2002, Clarno Formation used Diehl et al., 1983) results in nearly no difference in calculated pole position or apparent rotation.

McCaffrey (2013) to argue against significant rotation in this area. A possible reason for late recognition of Steens Basalt rotation was the reference pole employed (Mankinen et al., 1987), which included results from the PGB (Watkins & Baksi, 1974). If these early PGB results were subject to post 17-Ma rotation, as we believe they were, they masked recognition of the Steens Basalt rotation.

Our results extend the area exposed to a similar magnitude of clockwise rotation from the Nevada border two hundred kilometers north (Figure 8a). Jarboe et al. (2008) suggested northward-decreasing Basin and Range extension as a driver for this clockwise rotation, reviving the suggestion of Magill and Cox (1981). Work on the Eocene Clarno Formation (CF) near our study area, by Grommé et al. (1986), found $16^\circ \pm 10^\circ$ of clockwise rotation using the Eocene reference pole (82.8°N , 170.4°E) of Diehl et al. (1983). The Eocene and Miocene (17 Ma) reference poles are quite similar. A simple model is that the 16–18° of rotation recorded in both the CF and PGB represents the same post-PGB rotation. But, having both Eocene and middle Miocene results from the

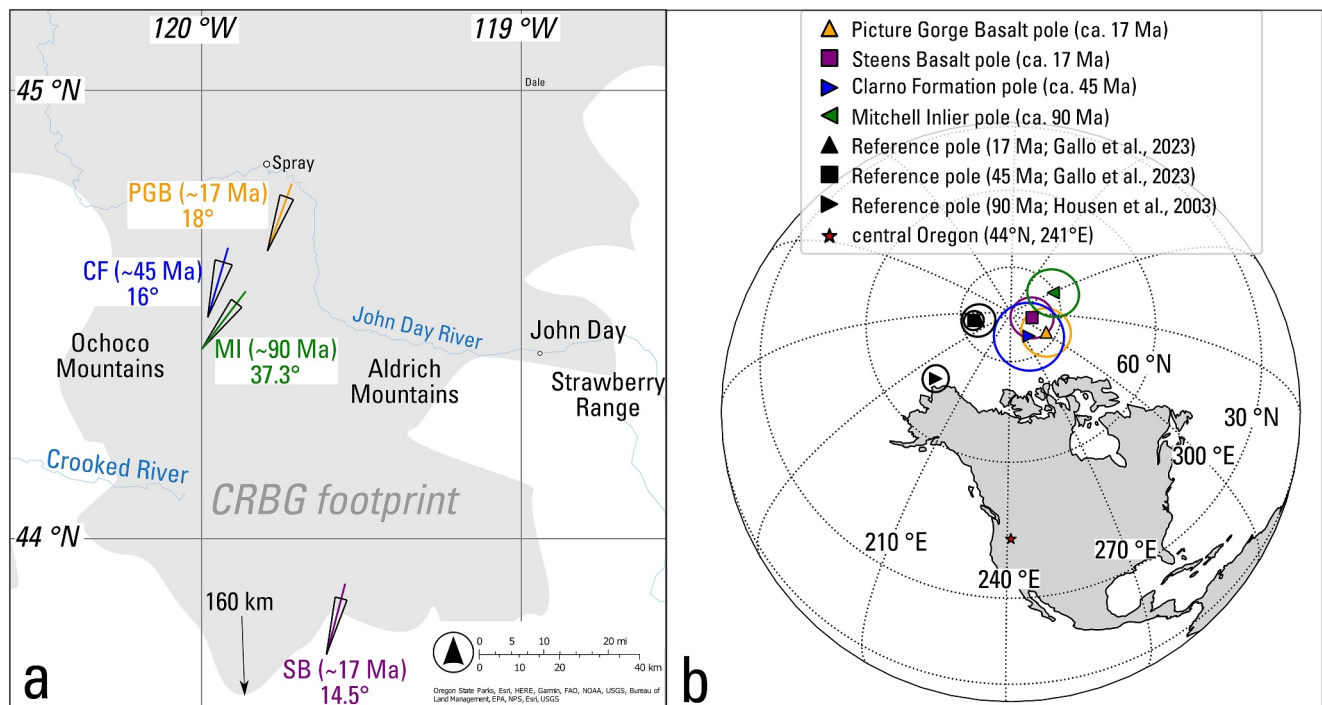


Figure 8. (a) Tectonic map of central Oregon showing paleomagnetic results from this and other studies: Jarboe et al. (2008), Grommé et al. (1986), and Housen and Dorsey (2005) and the apparent vertical-axis rotations. (b) Paleomagnetic poles from the studies mentioned plotted on an orthographic map along with reference poles (from Gallo et al., 2023; Housen et al., 2003).

same area gives us the ability to compare these rotational estimates. Since the CF study area is coincident with our PGB interpretations, the older data should indicate a commensurately greater rotation if the area has experienced long-term clockwise rotation. If we adjust the rotations within their uncertainties, the CF records a maximum of $\sim 26^\circ$ of clockwise rotation, while the PGB records a minimum of $\sim 12^\circ$ of rotation. This comparison suggests 14° of clockwise rotation occurred from ~ 40 to 17 Ma in Central Oregon, with 12° thereafter, yielding an aggregate rotation in the CF of 26° . If the Mesozoic results of Housen and Dorsey (2005) from central Oregon are considered, $\sim 37^\circ$ of total rotation has taken place in central Oregon since 90 Ma, at an apparently increasing rate through time (Figure 8b). The rates suggested are an average of $\sim 0.2^\circ/\text{Myr}$ from 90 to 45 Ma, then $\sim 0.5^\circ/\text{Myr}$ from 45 to 16 Ma, and a rate of $\sim 0.75^\circ/\text{Myr}$ from 16 to 0 Ma. Paleomagnetic data from western Oregon through the Cenozoic define a rotational rate of $1.19 \pm 0.1^\circ/\text{Myr}$ (Wells & McCaffrey, 2013), while modern GPS results illustrate current rotation of up to $2^\circ/\text{Myr}$ in Oregon (McCaffrey et al., 2007, 2013).

There are other possibilities to account for potential inaccuracy in the magnitude of clockwise rotation: non-averaged secular variation, the influence of structural corrections, or unreliable reference poles. As to the first, data from the CF (Grommé et al., 1986) and our study exhibit both reversed and normal polarities, with efforts made to mitigate serial correlation effects in the sequences of lava flows. The CF rocks are more deformed than the PGB rocks in most cases, with dips ranging from 0 to 37° and variable dip directions. Thus, the CF results are more heavily influenced by both the measurement and interpretation of structural corrections employed. Additionally, the CF data resulted from blanket demagnetization methods and analysis. The reference poles used in both studies are different by only a few degrees.

We note that the choice of reference pole influences results. It is possible that part of the PGB vertical-axis rotation is only apparent and is related to the reference pole itself. Gallo et al. (2023) noted that suitable data for North America are sparse to non-existent between 10 and 20 Ma and therefore their APWP for this interval is interpolated as part of sliding 21 Ma window. They used no CRBG paleomagnetic data in their compilation. We believe this total exclusion may be unnecessary and possibly bias the mid-Miocene component of their APWP.

To this end, we consider paleomagnetic results from northeast Oregon, southeast Washington, and Idaho (Hooper et al., 1979) from the Imnaha Basalt and lowest Grande Ronde Basalt as a comparison for our results from central Oregon. We note that this study did not use modern analytical techniques. A recalculation of their results from their Table 1 (we note that it appears that Table 1a is the blanket cleaned directions and Table 1b is the NRM's contrary to the labeling) yields a paleomagnetic pole at 85.0°N , 155.0°E ($A_{95} = 6.8^\circ$), calculated from 30 separate VGPs. If we then compare this IB/lower GRB paleomagnetic pole to that of Gallo et al. (2023), we see $2^\circ \pm 9^\circ$ rotation; in other words, indistinguishable from no rotation. Comparing the Imnaha Basalt and lower GRB pole to our pole yields $17 \pm 10^\circ$, less rotation than implied by comparison to the pole of Gallo et al. (2023) but similar within confidence limits. The Imnaha Basalt and lower GRB data, absent transitional directions, may not have fully averaged secular variation. An examination of Imnaha Basalt and GRB data should provide a more comprehensive North American reference pole for 16.5–17.0 Ma.

6. Conclusions

We have described a paleomagnetic reversal recorded within the lower main phase of the PGB. We suggest the PGB may have been contemporaneous with eruption of the Steens Basalt during the earliest phase of Columbia River Basalt Group (CRBG) volcanism rather than its historical placement during later Grande Ronde Basalt volcanism. Our finding of a lower zone of reversed polarity in the PGB partially supports a slightly extended interval of PGB volcanism, but we find that PGB volcanism is unlikely to have lasted through the entire main phase of the CRBG without significant hiatuses in its waning states, something we do not observe in our magnetostratigraphy. Although our data and correlations support a slightly earlier onset of PGB volcanism, the >17 Ma onset suggested by recent $^{40}\text{Ar}/^{39}\text{Ar}$ dates is inconsistent with our ages of PGB lavas based on paleomagnetic results. We instead suggest a ~ 16.7 – 16.4 Ma duration for “main-phase” PGB volcanism (Figure 9). In our preferred scenario, early CRBG eruptions were spatially widespread but roughly concurrent for the upper Steens and lower Picture Gorge Basalts, and possibly the Imnaha Basalt as well. The three units may best be viewed as overlapping in time (Figure 9). We revive earlier suggestions of significant clockwise rotation in central Oregon, based on our new paleomagnetic pole compared with a recent North American reference pole as well as a study-level pole from the stable CRBG plateau. The eastern CRBG plateau should be considered as a source of mid-Miocene paleomagnetic data suitable for North American reference APWPs. Paleomagnetic work at the level

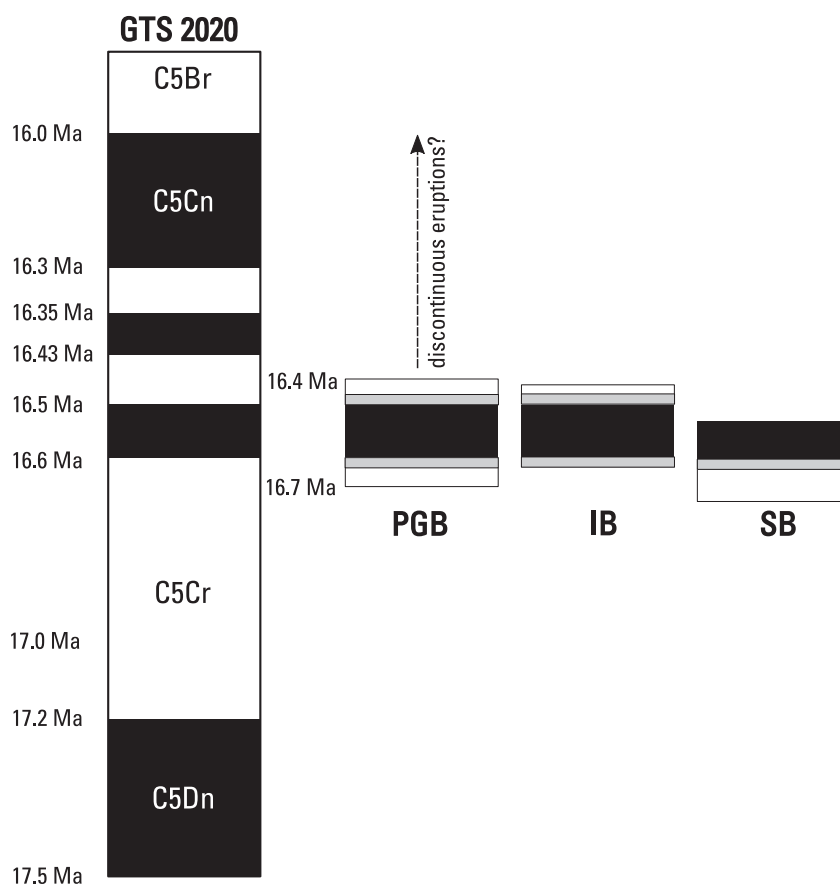


Figure 9. Comparison of the Geomagnetic Polarity Time Scale (GPTS) (Ogg, 2020; Raffi et al., 2020), mid-Miocene assignments after Kochhann et al. (2016) to our preferred model of early Columbia River Basalt Group (CRBG) eruptions of the Picture Gorge, Imnaha, and Steens Basalts based on their polarity. Black indicates normal polarity, white indicates reversed polarity, and gray indicates transitional polarity. Size of magnetozones is proportional for the GPTS, and schematic for the three illustrated CRBG formations. Polarity data for Picture Gorge Basalt comes from this study, Imnaha Basalt from Hooper et al. (1979) and description in Swanson et al. (1979), Steens Basalt from Jarboe et al. (2008), with thanks to the detailed studies of Mankinen et al. (1985, 1987).

of PSV—not simply magnetic polarity—from sections of flood basalts, when combined with reliable geochronological and geochemical data, may provide the best path forward for robust correlation and improvements in our understanding of eruption tempo.

Data Availability Statement

The paleomagnetic data used to develop our magnetostratigraphy and tectonic conclusions developed in this study are archived in the MagIC database (Pivarunas et al., 2025). Analyses were performed using the Python packages NumPy (Harris et al., 2020) and PmagPy (Tauxe et al., 2016), Figures were created using Matplotlib (Hunter, 2007) and Cartopy (Met Office, 2010).

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