Rapid eruption of the Columbia River flood basalt and correlation with the mid-Miocene climate optimum

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Flood basalts, the largest volcanic events in Earth history, are thought to drive global environmental change because they can emit large volumes of CO$_2$ and SO$_2$ over short geologic time scales. Eruption of the Columbia River Basalt Group (CRBG) has been linked to elevated atmospheric CO$_2$ and global warming during the mid-Miocene climate optimum (MMCO) ~16 million years (Ma) ago. However, a causative relationship between volcanism and warming remains speculative, as the timing and tempo of CRBG eruptions is not well known. We use U-Pb geochronology on zircon-bearing volcanic ash beds intercalated within the basalt stratigraphy to build a high-resolution CRBG eruption record. Our data set shows that more than 95% of the CRBG erupted between 16.7 and 15.9 Ma, twice as fast as previous estimates. By suggesting a recalibration of the geomagnetic polarity time scale, these data indicate that the onset of flood volcanism is nearly contemporaneous with that of the MMCO.

INTRODUCTION
The Columbia River Basalt Group (CRBG) is the youngest, smallest, and best-preserved continental flood basalt. It erupted ~210,000 km$^3$ of lava in the Pacific Northwest, United States, between ~17 and 5 million years (Ma) ago. Forty-three distinct stratigraphic members with volume estimates have been defined using regional correlations based on detailed mapping, geochemistry, and paleomagnetic data (1). While many flood basalts have been implicated in mass extinction events (2), the CRBG is not associated with a mass extinction event and its total volume is up to an order of magnitude smaller than other flood basalts. However, single members yielded comparable volumes of lava (thousands of cubic kilometers) to single formations of large igneous provinces implicated in mass extinctions [for example, Deccan Traps (3)] and therefore may have had comparable short-term climate impacts (4). The ~17 to 15 Ma mid-Miocene climate optimum (MMCO) is marked by high-latitude sea surface temperatures 4° to 6°C above background temperature (5) and is associated with vertebrate migrations and increased species origins (6). In paleoclimate records, the MMCO is marked by a benthic δ$^{18}$O minimum, a benthic δ$^{13}$C maximum, an ice sheet extent minimum (7), and a variety of pCO$_2$ (partial pressure of atmospheric CO$_2$) proxies, which indicate a possible doubling of atmospheric CO$_2$ levels to greater than 400 parts per million (ppm) (8–10). Given the apparent timing of both events, many studies have suggested that the environmental perturbations of the MMCO are connected to CRBG eruptions (1, 8, 11), but high-precision geochronologic data that link the two events are lacking (7).

While most flood basalt provinces are thought to relate to mantle plume–driven processes, models for the origin of the CRBG include a mantle plume source (12) as well as subduction-related processes such as slab tear (13) or slab rollback (14). Central to this debate is the fact that the CRBG was erupted during a period of active regional volcanism, including subduction volcanism of the Cascade arc, rhyolitic volcanism of the Yellowstone–Snake River Plain hotspot track, the High Lava Plains of central Oregon, and bimodal volcanism related to Basin and Range extension in northern Nevada (Fig. 1). The CRBG began erupting from a north-trending linear fissure system in eastern Washington, eastern Oregon, western Idaho, and northern Nevada, in a back-arc setting between the Cascades and Rocky Mountains. Volcanism progressed from south to north, and the regional tectonic and geomorphic setting guided flows hundreds of kilometers from east to west (1). An improved understanding of the timing of CRBG eruptions, the volumetric rates at which they were emplaced, and the rate at which they propagated geographically through the province are essential constraints on geodynamic models for the CRBG origin.

Here, we aim to test the hypothesis that there is a temporal relationship between CRBG eruptions and the MMCO by establishing an accurate and precise age model for the eruption of the CRBG. Decades of study have produced a high-resolution stratigraphic framework for the CRBG. The 350 tholeiitic basalt to basaltic andesite flows of the CRBG are divided into five formations: the Steens (31,800 km$^3$; 15.3% of the total volume), Imnaha (11,000 km$^3$; 5.3%), Grande Ronde (150,100 km$^3$; 72.3%), Wanapum (12,175 km$^3$; 5.9%), and Saddle Mountains Basalts (2424 km$^3$; 1.2%), which are composed of a total of 43 stratigraphic members, containing 1 to 20 lava flows each (1). Magnetic field reversals were ongoing during the eruption of the CRBG. While the magnetic stratigraphy first was developed in the field using a portable fluxgate magnetometer during mapping efforts (1), some detailed modern paleomagnetic data have since been published (15, 16). The Steens Basalt erupts during a reversal from reversed to a normal polarity interval [sometimes referred to as R$_k$ and N$_0$ (17)], which continues through the Imnaha Basalt. The Grande Ronde Basalt is marked by two couplets of magnetic field reversals (locally defined magnetostratigraphic units are known as R$_1$, N$_1$, R$_2$, and N$_2$). The N$_2$ normal magnetozone continues through the majority of the Wanapum Basalt, which exhibits a final reversed interval (1, 18, 19).

The majority of ages published on the CRBG have uncertainties that preclude the development of an unambiguous chronology for the timing and duration of CRBG volcanism. For example, in a review of K-Ar and $^{40}$Ar/$^{39}$Ar geochronology for the CRBG, a preferred chronology was developed with eruption of the Steens Basalt at 16.9 to 16.7 Ma, the Imnaha Basalt at 16.7 to 16.0 Ma, the Grande Ronde Basalt at 16.0 to 15.6 Ma, the Wanapum Basalt at 15.6 to 15.0 Ma, and the Saddle Mountains Basalts in several distinct events between 15 and 6 Ma (4). This eruptive age model is based on geochronologic
analyses with large uncertainties (>1 Ma) that make adherence to stratigraphic order difficult to address, and the result is that it is inconsistent with the geomagnetic polarity time scale (GPTS) (4, 20). For instance, this age model suggests a normally magnetized interval lasting ~600 thousand years (ka) through the Imnaha Basalt, which exceeds the duration of any normal chron occurring around 16 Ma in different calibrations of the GPTS (20). Other inconsistencies are discussed in greater detail in Results. New high-precision $^{40}\text{Ar}^{39}\text{Ar}$ dates derived from feldspar phenocrysts in silicic tuffs interbedded in the Steens Basalt have revised its eruptive duration to ~16.75 to 16.54 Ma and propose that the Steens magnetic field reversal occurred at 16.603 ± 0.028 Ma (21) [dates recalculated with Fish Canyon sanidine age of Kuiper et al. (22); see the Supplementary Materials]. These new data highlight the potential that additional precise geochronology has to resolve the timing and duration of CRBG volcanism and its correlation to the GPTS and MMCO.

RESULTS

Here, we use U-Pb zircon geochronology by chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS), which can achieve the precision (~0.1%) and accuracy required to address the issues with previous age models outlined above. Because basalts are generally too low in Si and Zr to saturate isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS), which can achieve the precision (~0.1%) and accuracy required to address the issues with previous age models outlined above. Because basalts are generally too low in Si and Zr to saturate zircon, we follow the sampling strategy of Schoene et al. (23) by collecting silicic volcanic ash from between basalt flows and dating them by U-Pb geochronology on single zircon crystals. These ash beds were sourced from contemporaneous regional silicic volcanism, and deposits include ash-bearing paleosols (referred to as "redboles" in the remainder of this paper), interflow volcaniclastic sediments, and pumice-bearing airfall tuff (Fig. 2 and fig. S1). Zircons separated from these samples (fig. S2) were dated by CA-ID-TIMS at Princeton University.

Data from eight horizons within the CRBG, reported as $^{206}\text{Pb}/^{238}\text{U}$ dates from single zircons taken from a population of dated grains with 95% confidence intervals, are shown in Fig. 3. Dates on single crystals within each sample spread beyond analytical uncertainty, a common observation in volcanic ash beds, because zircon can retain radiogenic Pb at temperatures of >900°C. A spread in crystallization dates beyond analytical uncertainty can reflect growth of zircon in the magmatic system before eruption, incorporation of pre-eruptive zircon from the volcanic edifice during eruption, or inheritance from the rock hosting the magmatic system (24, 25). In light of these potential sources for complex zircon populations deposited within the CRBG ashes, we use the youngest single concordant analysis, excluding low-precision analyses, as an estimate for the age of the ash (Fig. 3) (26). This approach is tested by dating a large number of zircons from each sample to obtain multiple analyses that overlap with the youngest grain and further requiring that samples from stratigraphically higher positions in the CRBG are in chronological order. A growing database of zircon geochronology from a variety of tectonic settings, using a variety of U-Pb analytical methods, shows that the youngest zircon analysis from continuous age population overlaps with weighted mean ages calculated from multiple grains for each sample, although we prefer the youngest zircon age as the more conservative interpretation. Our dates from the Steens Basalt show excellent agreement with ages derived from high-precision $^{40}\text{Ar}^{39}\text{Ar}$ sanidine geochronology (Fig. 3) (21).

Our zircon ages improve estimates for the timing and duration of each formation of the CRBG stratigraphy (Fig. 3) and indicate that 95% of its total volume erupted in 758 ± 66 ka (fig. S3). The upper 72% of the Steens Basalt volume erupted between 16.653 ± 0.063 Ma and 16.589 ± 0.031 Ma. The latest Steens eruptions occurred concurrently with Imnaha Basalt eruptions, which we have dated at 16.572 ± 0.018 Ma. While we currently do not have an estimate for the onset of the overlying Grande Ronde Basalt, four samples from its upper half fall in stratigraphic order and show its termination by 16.066 ± 0.040 Ma. Two samples from the bottom and top of the Wapshilla Ridge Member of the Grande Ronde Basalt, which comprises 20% of the total CRBG volume, gave dates overlapping within uncertainty of 16.288 ± 0.039 Ma and 16.254 ± 0.034 Ma. These ages come from a single stratigraphic section, and the age of the upper bound is indistinguishable at the 95% confidence interval from the age from a redboles that is in the same stratigraphic position but is found 44 km away (16.210 ± 0.043 Ma). Finally, the lower 77% of the Wanapum Basalt finished erupting before 15.895 ± 0.019 Ma (Fig. 3). Our dated samples bracket 95% of the eruptive history of the CRBG, and these data show that the CRBG erupted 2.4 times faster than the previous estimates (4). Our ages agree with the relative chronology of the existing stratigraphic framework (1) and bolster regional correlation through geochemical and paleomagnetic data.

Fig. 1. Map of CRBG and regional volcanism. The map shows the areal extent of each formation of the CRBG, and the legend provides the volume contribution of each formation. Stars represent geochronology sample collection sites; dashed lines enclose areal extent of source dike swarms. The Prineville Basalt (PVB) and Picture Gorge Basalt (PGB) are coeval with the Grande Ronde Basalt, represent 1.4% of the total CRBG volume, and are grouped with the Grande Ronde Basalt for all volume estimates presented here (1).
Combined with detailed volume estimates for each member of the CRBG (1), our new zircon ages yield effusion rates throughout the eruptive history of the CRB and provide a timeline for the release of CO$_2$, SO$_2$, and other gases into the atmosphere. For the main phase of eruption (Steens, Imnaha, and Grande Ronde Basalts), we calculate an average effusion rate of $0.334 \pm 0.042 \text{ km}^3/\text{year}$, which is double the previous estimate of $0.178 \text{ km}^3/\text{year}$ for the same interval (12). During the eruption of the Wanapum Basalt, the rate slows to $0.055 \pm 0.014 \text{ km}^3/\text{year}$, whereas during the Wapshilla Ridge Member, the average rate calculated is $1.18 \text{ km}^3/\text{year}$, with a minimum rate of $0.376 \text{ km}^3/\text{year}$. However, because our ages for the top and bottom of this voluminous member in a single stratigraphic section overlap, effusion rates were likely far greater than the average values. A potential constraint for the maximum rate can be derived from previous estimates for the minimum duration of the $1300 \text{ km}^3$ Roza Member to be 14 years (29), and the ca. 100 years or more needed to develop thin redbole horizons (30). Because there are at least 18 (and as many as 28) lava flow units in the Wapshilla Ridge Member (31) and 8 more redboles between the samples we dated, we estimate that peak eruption rates could be as high as 20 to 40 km$^3$/year for a duration of thousands of years.

The eruptive pulse for the Wapshilla Ridge Member is an order of magnitude higher than average effusion rates calculated for other large igneous provinces associated with mass extinction events: $1$ to $2 \text{ km}^3/\text{year}$ for the Deccan Traps (23), $3$ to $5 \text{ km}^3/\text{year}$ for the Central Atlantic Magmatic Province (32), and 1 to $4 \text{ km}^3/\text{year}$ for the Siberian Traps (33). However, records from other flood basalts do not have the stratigraphic resolution to calculate effusive rates during high flux pulses compared to long-term average rates. More generalized models for the total climatic impact during flood basalt eruption will be dependent on delineating the timing of eruption pulses, such as the Wapshilla Ridge Member, from background fluxes.

**DISCUSSION**

Our age model provides quantitative constraints that must be satisfied by any geologic or geodynamic model for CRBG volcanism. In
particular, the mechanism must be consistent with (i) eruption duration of ~750 ka from 16.65 to 15.90 Ma; (ii) an average effusion rate of 0.334 ± 0.042 km²/year, with pulses of >1 km²/year; (iii) simultaneous eruptions at Steens Mountain and the Imnaha Basalt vents 300 km away; and (iv) an average linear geographic propagation rate of eruption of 0.37 ± 0.08 m/year to the north, given distances between the vents sourcing Imnaha through Wanapum eruptions. These criteria alone may be currently insufficient to fingerprint a mantle plume or subduction-related origin of the CRBG, both of which allow eruptions to occur in this time frame (13, 34). The geographic propagation rate of 0.37 ± 0.08 m/year for CRB volcanism is also compatible with either model: A small plume head has been modeled to spread at 0.2 to 0.3 m/year (35), while the proposed slab tear is modeled to propagate at 0.45 m/year (13). This northward propagation rate is about three times faster than those calculated for the McDermitt and High Rock dike swarms that propagate to the south of Steens Mountain (0.12 and 0.14 m/year, respectively) (36), showing that the potential radial propagation from Steens Mountain did not occur at the same velocity radially. Further modeling with our new quantitative constraints is required to better understand the process that allowed CRBG eruption.

Determining the relative timing of CRBG volcanism and the MMCO requires independent chronologies that are equally precise. However, the early- and mid-Miocene is one of the most problematic periods in the Neogene for establishing precise independent chronologies in marine sediments due to the difficulty in obtaining undisturbed stratigraphic sections that yield reliable magnetostratigraphy, biostratigraphy, astronomical tuning, and radiometric ages (20). All time scales proposed for the mid-Miocene depend directly or indirectly on correlation with the GPTS, for which there are currently several proposals, the most recent being the Geologic Time Scale (GTS) 2012 (20). GTS 2012 was derived from the seafloor anomaly profiles of the Antarctic and Australian plates and assuming a relatively constant spreading rate tuned to give a 23.03-Ma age for the Oligocene-Miocene boundary (20). GTS 2012 rejected an astronomically tuned record of mid-Miocene 39Ar and magnetostratigraphy from ODP (Ocean Drilling Program) site 1090 in the subantarctic south Atlantic, whose record extends from the Oligocene-Miocene boundary to ~15.9 Ma, because the tuned record yields ages for chron boundaries that do not meet the assumption of constant seafloor spreading rates in the Pacific (20). The most recent age model for the CRBG (4) attempts to reconcile 40Ar/39Ar geochronology with GTS 2012. However, the resulting age model is inconsistent with the existing GPTS and is in need of refinement (Fig. 4).

Our new age model for the CRBG permits a more robust correlation of CRBG magnetostratigraphy with existing proposals for the GPTS (Fig. 4). However, this exercise also indicates that some previous proposals for the GPTS, including GTS 2012, are in error. For example, the most recent age model for the CRBG has the Imnaha Basalt, which is entirely normally polarized, erupting through several magnetic reversals and thus is not permissible. Similarly, the existing age model places the Grande Ronde Basalt, which records two reversed and two normal intervals, within a single normal chron. By comparison, in our proposed correlation illustrated in Fig. 4, the Imnaha Basalt erupted entirely during chron C5Cn.3n, while the Grand Ronde Basalt erupted during C5Cn.2r-C5Cn.1n, consistent with observed magnetostratigraphy in the basals.

Using this baseline correlation with the GPTS, we can refine four proposed reversal ages (Fig. 4). Our ages in the Upper and Lower Steens bracket the “Steens Reversal” (between magnetozones R₀ and N₀, and chronos C5Cr and C5Cn.3n), which can be conservatively constrained to 16.637 ± 0.079/0.089 Ma (95% confidence intervals given for internal uncertainty/decay constant uncertainty). This estimate compares favorably with the estimate of 16.603 ± 0.028/0.36 Ma obtained through recent 40Ar/39Ar sanidine geochronology (21). Our samples from the base and top of the Wapshilla Ridge Member constrain the timing and provide a minimum duration for C5Cn.1r, to begin no later than 16.288 ± 0.039/0.046 Ma, and to end no earlier than 16.210 ± 0.043/0.047 Ma, because the Wapshilla Ridge Member comprises the majority of volume of the second reversed magnetostratigraphic unit of the Grande Ronde Basalt (R₃) (31). The end of C5Cn.1n (N₀) is well constrained by our age of 15.895 ± 0.019/0.026 Ma for the top of the transitionally magnetized Roza Member, which immediately overlies the normally magnetized Frenchman Springs Member, especially given previous estimates that the Roza Member erupted in as little as 14 years (29). Our initial data do not identify any significant hiatuses in eruptions—no more than ~200 ka elapse between any two of our samples, during which volcanism is known to be ongoing, although we do not present zircon data from these intervals (fig. S3). Therefore, high-precision geochronology can be used to bound the ages of magnetically characterized CRB flows and to further refine the record of mid-Miocene magnetic field reversals.
Our proposed GPTS is also consistent with the astronomically derived age model for the magnetic reversal stratigraphy at IODP (Integrated Ocean Drilling Program) site U1335 in the equatorial Pacific (Fig. 4) (37), indicating an independent verification for our proposed age model for the GPTS.

Given the inconsistencies described above for the GPTS, demonstrating a link between the eruption of the CRBG and the MMCO requires a careful assessment of the age models used to develop proxy records across the MMCO. For example, the δ¹³C proxy record for pCO₂ at ODP site 761 indicates that atmospheric CO₂ increases at 16.5 Ma (8), which agrees well for our suggested timing of the onset of voluminous Grande Ronde Basalt volcanism. However, the age model for site 761 (38) depends on biostratigraphic (39) or isotopic events (40) tied to calibrations of the GPTS (41) that we have shown to be inaccurate. Recent work describing the δ¹³C and δ¹⁸O records from IODP site U1337 identifies the onset of the MMCO at 16.9 Ma (42), which precedes our timing for all CRBG eruptions. This site has an age model derived from an astronomical solution (43) without radiometric age control or a magnetostratigraphy, thus adding subjectivity to the chosen isotopic tie points used to calibrate the tuning (44) and making correlation with our eruptive record difficult.

One way forward is to use proxy records from sites that contain reliable magnetostratigraphy (37, 45). Benthic δ¹⁸O values—a proxy for deep-ocean temperature—from sites 1090 (46) and U1335 (37) (Fig. 5) indicate that the decline in δ¹⁸O values began during what is interpreted as C5Cr, reaching a nadir (the MMCO) during C5Cn.3n-C5Cn.1r. While it is currently difficult to validate the identification of C5Cr, reaching a nadir (the MMCO) during C5Cn.3n-C5Cn.1r.

The time lag between the cessation of volcanism and a return to cooler climatic conditions could be understood as a consequence of the long response time of negative feedbacks within the global carbon cycle that regulate atmospheric CO₂ and Earth’s temperature on geologic time scales. These feedbacks include interactions between temperature, the chemical weathering of continental silicate minerals, and the burial of CO₂ in marine carbonate sediments (48). While the sensitivity of the silicate weathering feedback remains poorly understood, recent estimates for response times vary from ~200 to 500 ka (49) and are consistent with the stabilization of atmospheric CO₂ (that is, return to baseline conditions) on ~1 million year time scales.

Our age model of CRBG emplacement shortens the duration of volcanism from 1.9 Ma (4) to 750 ka and correlates the onset of CRBG volcanism and the onset of the MMCO to within ~100 ka.

**Fig. 5. Correlation of the CRBG with the MMCO.** (A) A compilation of proxy records exhibiting the MMCO (47), with age constraints as reported in each study. Although ages are susceptible to uncertainties in the mid-Miocene time scale, the magnitude of the isotopic signals is not. (B) To compare zircon geochronology results for CRBG eruptions to paleoclimate proxy records of the MMCO, it is necessary to bypass age models tied to outdated calibrations of the GPTS. The robust magnetostratigraphy of sites 1090 (45, 46) and U1335 (37) allows correlation of these isotopic records to our CRBG eruption chronology and refined GPTS. The area of each colored rectangle corresponds to the volume of each formation (1) (S, Steens Basalt; I, Immaha Basalt; GR, Grande Ronde Basalt; W, Wapakum Basalt), with width constrained by zircon ages (slanted boundary indicates that the onset of Steens Basalt volcanism is not yet constrained); polarity of the basalt flows is taken from Reidel (1) and references therein. Yellow shading compares global proxy data at 17 to 16 Ma (lacking an age model based on absolute geochronology) with volcanic events occurring 17 to 16 Ma, while the light blue shading highlights the onset of the MMCO in both records with the drop in δ¹⁸O.
shorter duration of CRBG volcanism implies higher average CO$_2$ emissions and higher peak CO$_2$ concentrations during volcanism, to be compared with marine proxy records. However, current proxy records for atmospheric CO$_2$ during the MMCO are too coarse for a close comparison to the eruptive history of the CRBG, further inhibiting the ability to assess whether or not the CRBG caused the MMCO. Furthermore, establishing a quantitative link between CRBG volcanism and changes in the global carbon cycle and atmospheric CO$_2$ is hampered by uncertainties in the amount of CO$_2$ emitted by flood basalts from dissolved mantle carbon in addition to “cryptic” sources, such as organic or inorganic sediments volatilized through contact with basaltic flows or sills (7). Armstrong McKay et al. (7), using a main phase CRBG eruptive duration of 900 ka, model that 4090 to 5670 Pg of emitted carbon can yield the observed changes in benthic $\delta^{13}$C and atmospheric CO$_2$, although this amount includes a substantial component of cryptic degassing beyond the expected volatile release of subaerial basalt flows. Future studies should focus on further revision of the mid-Miocene time scale and a high-resolution climate proxy record spanning the 700-ka duration of CRBG volcanism to explore the extent to which the timing of CRBG volcanism agrees with changes in atmospheric CO$_2$. Such studies will lead to an improved understanding of the MMCO and more general models linking volcanism to climate change and could be crucial for understanding why some flood basalts apparently result in mass extinctions and others do not.

**MATERIALS AND METHODS**

Methods are as described by Schoene et al. (23) and Samperton et al. (50).

**Zircon separation and preparation**

Zircons were separated from their host rock through standard methods of crushing as well as gravimetric and magnetic separation techniques using a Bico Braun “Chipmunk” jaw crusher, disc mill, hand pan, hand magnet, Frantz isodynamic separator, and methylene iodide. Zircons from the least magnetic and most dense mineral separate were transferred in bulk to quartz crucibles and annealed in a muffle furnace at 900°C for 48 hours after Mattinson (51). After annealing, 20 to 40 zircon grains from each sample were photographed (fig. S2) and picked in reagent-grade ethanol for analysis. Given the low radiogenic Pb content of the samples, cathodoluminescence images were not obtained. Euhedral grains with a range of morphologies were selected, while those with visible cracks, inclusions, and cores were avoided. Individual grains were transferred using stainless steel picking tools to separate 3-ml Savillex Hex beakers containing distilled acetone and taken to the clean laboratory for analysis.

**U-Pb zircon ID-TMS analysis**

Single zircon grains were loaded into 200-μl Savillex “micro”-capsules with 100 μl of 29 M HF + 15 μl of 3N HNO$_3$ for a single leaching step in high-pressure Parr bombs at 185°C for 12 hours to remove crystal domains affected by Pb loss (51). Grains were rinsed after leaching in 6 N HCl, MQ H$_2$O, 3N HNO$_3$, and 29 M HF before spiking with EARTHTIME (202$^Pb$-208Pb, 233$^U$-235$^U$) tracer and addition of 100 μl of 29 M HF + 15 μl of 3N HNO$_3$ (52, 53). Zircons were then dissolved to completion in Parr bombs at 210°C for 48 hours. Dissolved zircon solutions were subsequently dried down, dissolved in 100 μl of 6N HCl, and converted to chlorides in Parr bombs at 185°C for 12 hours, after which solutions were dried again and brought up in 50 μl of 3N HCl. The U-Pb and trace element aliquots were then separated by anion exchange chromatography using 50-μl columns and AG-1 X8 resin (200 to 400 mesh, chloride from Eichrom) (54) and dried down with a microdrop of 0.015 M H$_3$PO$_4$. The dried U and Pb aliquot was loaded in a silica gel emitter (55) to an outgassed zone-refined Re filament.

Isotopic determinations were performed using an IsotopX Phoenix-62 TIMS at Princeton University, with Pb analysis performed in a peak-hopping mode on a Daly photomultiplier ion-counting detector. A correction for mass-dependent Pb fractionation was applied in one of two ways. For double-Pb spiked analyses (202$^Pb$-205$^Pb$, ET2535), a cycle-by-cycle fractionation correction was calculated from the deviation of measured 202$^Pb$/205$^Pb$ from the known tracer 202$^Pb$/205$^Pb$ [0.99924 ± 0.00027 (1σ)]. For single-Pb spiked analyses (205$^Pb$, ET3535), a Pb fractionation of 0.182 ± 0.041% per atomic mass unit (amu) was used, as determined by repeat measurements of NBS982 at Princeton. A Daly photomultiplier dead time of 28.8 ns was used, as determined by repeat measurements of National Bureau of Standards (NBS) standards. Corrections for interfering isotopes under masses 202, 204, and 205 were made cycle by cycle by measuring masses 201 and 203 and assuming that they represent 201$^BaPO_4$ and 203$^TI$ and using natural isotopic abundances to correct for 202$^BaPO_4$, 204$^BaPO_4$, 205$^BaPO_4$, and 205$^TI$.

UO$_2$ measurements were performed in static mode on Faraday cups with a bulk U fractionation correction calculated from the deviation of measured 233$^U$/235$^U$ from the known tracer 233$^U$/235$^U$ [0.995062 ± 0.000054 (1σ)], and an oxide composition of 16O/18O of 0.00205 was used (56). Data reduction was performed using the programs Tripoli and U-Pb Redux (57, 58) and the decay constants of Jaffey et al. (59). All Pb was attributed to laboratory blank with a mean isotopic composition determined by total procedural blank measurements (see table S1 for values). Two different blank models were generated to assess data collected before [Outliers Culled (OC)] and after [Side Filaments (SF)] January 2017, when the laboratory began heating side filaments before collecting data on the mass spectrometer, which was found to reduce interferences. Uncertainties in reported U-Pb zircon dates are at the 95% confidence level and exclude tracer calibration and decay constant uncertainties. Correction for initial 230$^Th$ disequilibrium in the 206$^Pb$/238$^U$ system was made on a fraction-by-fraction basis by estimating (Th/U)$_{zircon}$ using (Th/U)$_{zircon}$ determined by TIMS and a mean (Th/U)$_{zircon-magma}$ partition coefficient ratio of 0.19 ± 0.11, which encompasses the range of values for (Th/U)$_{zircon-magma}$ partition coefficients obtained from glasses from a variety of volcanic settings (60). Uncertainties for the resulting (Th/U)$_{magma}$ were also calculated on a fraction-by-fraction basis, propagating the uncertainty in the (Th/U)$_{zircon-magma}$ partition coefficient. Overall, these corrections for 230$^Th$ disequilibrium affected our results by no more than ±10 ka compared to an alternative approach using a constant (Th/U)$_{magma}$ of 3.5 ± 1.0 (see the Supplementary Materials).

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/9/eaa8223/DC1

Supplementary Materials and Methods

Fig. S1. Geochronology sample photos.

Fig. S2. Zircon photos.

Fig. S3. Thickness and volume versus age plots.

Fig. S4. Concordia plots for U-Pb ID-TMS-geochronological data.
REFERENCES AND NOTES


15. A. R. Domínguez, R. Van der Voo, Secular variation of the middle and late Miocene geomagnetic field recorded by the Columbia River Basalt Group in Oregon, Idaho and Washington, USA. Geophys. J. Int. 197, 1299–1320 (2014).


Supplementary Materials for

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The PDF file includes:

Supplementary Materials and Methods
Fig. S1. Geochronology sample photos.
Fig. S2. Zircon photos.
Fig. S3. Thickness and volume versus age plots.
Fig. S4. Concordia plots for U-Pb ID-TIMS geochronological data.
Fig. S5. Alternate age interpretations.
Legend for table S1.
Table S2. Alternate age interpretations.
References (61–66)

Other Supplementary Material for this manuscript includes the following:

(available at advances.sciencemag.org/cgi/content/full/4/9/eaat8223/DC1)

Table S1 (Microsoft Excel format). U-Pb isotopic data.
MATERIALS AND METHODS

Sample Descriptions
Samples dated in this study were collected from roadcuts or natural exposures in Washington, Oregon, and Idaho in summers 2015 and 2016. Detailed sample descriptions are provided here, in stratigraphic order from oldest to youngest. Outcrop photographs are provided in fig. S1, and zircon photographs are provided in fig. S2.

CRB1625 (42.67542°N, 118.68724°W, elevation 2255 m)
This sample was collected from a ~0.5 m thick redbole between two Lower Steens Basalt flows, (based on the stratigraphy of Johnson et al. (61)) on the western side of Steens Mountain. The fine red sediment overlay a brecciated flow top and contained abundant vitreous microphenocrysts, black round lithic fragments, and subangular fragments of basaltic pumice up to 1 mm in size.

Fewer than 100 zircons were separated from this sample, and many of these grains are rounded and appear detrital. Some grains are euhedral, and ranged from equant to a high aspect ratio. Many grains are tinted orange, while some are clear. Forty grains were selected for analysis, and 19 were successfully dated. For this sample and the other samples described below, grains that were not successfully dated were lost at some stage of zircon chemistry prior to dating, or were dated and either did not fall on the Concordia line or exhibited a ratio of radiogenic Pb to common Pb that was ≤1. Six of these grains were ca. 16.7 Ma, with a dispersion of 120 ka, while the other 13 are inherited. Both the Mid-Miocene and inherited grains exhibited a range of morphologies. The youngest grains were often euhedral, and ranged from equant to an aspect ratio of at least 4:1. While some of the young grains were glassy and transparent, others were opaque. While a few of the analyses exhibited elevated common Pb content (>1 pg), others had low common Pb (<0.3 pg) but also low radiogenic Pb content (<1 pg), yielding generally less precise zircon ages for this sample than for the others in this study.
CRB1624 (42.66626°N, 118.56479°W, elevation 2966 m)
This sample was collected from a ~0.5 m thick redbole interbedded between Upper Steens Basalt flows (61) at the East Rim Lookout on Steens Mountain. The sampled horizon was a fine pink sediment infilling a brecciated flow top, and contained abundant vitreous microphenocrysts with few dark round lithic fragments.

Hundreds of zircons were obtained from this sample, with a range of morphologies. Generally, grains were angular to subangular, with fewer round detrital grains. The grains ranged from equant to higher aspect ratios, though few were acicular. Most of the grains are orange, while a few are clear and glassy. Twenty-three grains were selected for analysis, and 11 were successfully dated. The youngest grains appear to be the most euhedral, and range in size from <100 to over 300 μm. All of the grains were found to be ca. 16.6 Ma, with a dispersion of <70 ka. The precision of these analyses is attributed to high radiogenic Pb content (up to 34 pg) of the grains and low common Pb content (often <0.3 pg) in the analyses.

CRB1586 (44.83067°N, 116.90138°W, elevation 641 m)
This sample was collected from a ~0.5 m thick bed of lapilli tuff interbedded between columnar Immaha Basalt flows on route 71 south of Brownlee Dam in Idaho. Accretionary lapilli are mm-cm scale and exhibit concentric banding around lithic nuclei.

Fewer than 50 zircons were separated from this sample, and are found to be glassy, somewhat blocky, and ranging in morphology from equant to tabular. Most of the grains are around 100 μm in length. Twenty-three grains were selected for analysis, and of these, 14 were successfully dated. One grain was found to be inherited, while the other 13 are dated to ~16.6 Ma, with a dispersion of 120 ka. The youngest and most precise grains are among the largest analyzed, and have a high radiogenic Pb content (1-6 pg).

CRB1634 (46.05072°N, 117.23906°W, elevation 538 m)
This sample was collected from a redbole in the lower flows of the Wapshilla Ridge Member of the Grande Ronde Basalt, on Rattlesnake Grade in southeastern Washington. The redbole infills topography on the underlying brecciated flow top, with a maximum thickness of 0.3 m, but
The redbole contains a few mm-scale light and dark lithic fragments, with some vitreous phenocrysts.

Hundreds of zircons were obtained from this sample, ranging in size from 50-250 μm. Most are orange in color but a few are clear. Half of the zircons presented an acicular morphology, 20% appeared equant, and the rest have a medium aspect ratio. Twenty-four zircons were selected for analysis, and eleven were successfully dated. All zircons were found to be ca. 16.3 Ma, with a dispersion of 160 ka. The youngest grains appear somewhat wide, clear, and euhedral, and the most precise analyses came from zircons with the greatest amount of radiogenic Pb (1-2 pg).

**CRB1556 (46.08543°N, 117.17870°W, elevation 1145 m)**

This sample was collected from the same stratigraphic section as CRB1634, from a 0.6 m thick redbole between lava flows of the Meyer Ridge Member, immediately overlying the Wapshilla Ridge Member. The horizon was most coherent in its upper half, and displayed few vitreous phenocrysts and rare lithics.

The sample yielded 19 zircons, and all were picked for analysis; 7 were successfully dated. The zircons were either <100 μm and equant or larger and more tabular. A few were euhedral with pointy edges, while others appeared fragmented at the edges. The youngest, most precise analyses came from the largest grains. Even though these grains were not euhedral, they possessed the greatest amount of radiogenic Pb (1-2 pg). The grains exhibit a dispersion of 150 ka around ca. 16.3 Ma.

**CRB1519 (46.44171°N, 117.39066°W, elevation 701 m)**

This sample was collected from a redbole found under a lava flow of the Meyer Ridge Member and overlying a lava flow Wapshilla Ridge Member, representing the same stratigraphic interval as CRB1556 but found 44 km away on US-12 east of Pomeroy, WA. The sample is fine-grained, with abundant vitreous microphenocrysts and few angular lithic fragments.

Hundreds of zircons were separated from this sample, and they appear mostly clear and glassy, with a few orange grains. Most present typical aspect ratio, while 10% are acicular and a few
grains are equant. Many grains are subangular, with pointy tips slightly worn down. Twenty-one grains were selected for analysis, and 10 were successfully dated. Two of the zircons analyzed were inherited, and appear somewhat opaque; five zircons were ca. 16.2 Ma but an age dispersion of 400 ka, outside the range of analytical uncertainty. The youngest grains each have one euhedral tip, are longer than 100 μm, and the most precise analyses were for zircons with a higher radiogenic Pb content (2-4 pg).

**CRB1533** (46.95243°N, 119.99783°W, elevation 227 m)
This sample was collected from 2 kg of 1-10 cm-scale pumice clasts embedded in the volcaniclastic sediments of the Vantage Interbed type locality in Vantage, WA (Stop 7 in Tolan et al. (62)). Phenocrysts in the pumice contained quartz and sanidine, and the sampled horizon consisted of 1.4 m of the total 5.6 m of the Vantage Interbed exposed at the outcrop. The Vantage Interbed lies over the Basalt of Museum of the Sentinel Bluffs Member of N2 of the Grande Ronde Basalt, and under the Basalt of Ginkgo of the Frenchman Springs Member of the Wanapum Basalt.

Several thousand zircons were obtained from this sample, and all are clear, prismatic, and euhedral. The zircons range in size from 50-300 μm, and about 10% are equant grains, while 10% of the grains are acicular. Forty zircons were selected for analysis, and 11 of these were successfully dated, with 9 grains found younger than 17 Ma. The age dispersion of these samples is greater than 500 ka, well beyond analytical uncertainty, suggesting pre-eruptive crystallization. The youngest grains appear to be the most acicular in morphology, and the most precise analyses are due to high radiogenic Pb content of 5-15 pg.

**CRB1506** (46.73914°N, 117.75500°W, elevation 470 m)
This sample was collected from 0.3 m of a fine white crumbly ash, with few round lithic fragments and glassy phenocrysts, interbedded between the overlying Basalt of Lolo and the underlying Basalt of Rosalia of the Priest Rapids Member of the Wanapum Basalt, on WA-127 southeast of Endicott, WA.
Hundreds of zircons were obtained from this sample, most of which are clear and subangular to subrounded. While a few zircons were angular, none were acicular. Thirty-five grains were selected for analysis, and 10 were successfully dated. Four of these were inherited, and the remaining six grains have a uniform age distribution within 2σ uncertainty, of ca. 15.9 Ma. The youngest and most precise dates were obtained from somewhat opaque, orange-tinted zircons that were euhedral, and had high radiogenic Pb content of 11-40 pg.

**S2 U-Pb Age Interpretations**

Given the physical characteristics of both rock samples and zircons, the geochronology samples for this study are interpreted to be volcanic in origin, and deposited by unrelated regional silicic volcanism during cessations in CRBG volcanism. The presence of phenocrysts, lithic fragments, and fragments of basaltic pumice found at the hand sample scale are consistent with ash deposits, and the euhedral and prismatic appearance of the zircons are consistent with magmatic textures, with little evidence for rounding seen in alluvial or eolian grains.

Full U-Pb isotope results are given in table S1, maximum thickness and volume versus age plots are given in fig. S3, and Concordia plots for each sample are given in fig. S4. All dates are presented with 2σ uncertainty, which represents internal errors only. In table S2, alternative age interpretations are also given with 2σ uncertainties of ±X/Y/Z. X is used for most of the geochronological uncertainty described in this paper, and indicates internal uncertainties only for comparison with U-Pb dates from labs using ET-(2)535 tracer solution. Y also incorporates tracer calibration uncertainties for comparison with other U-Pb dates determined with different tracer solution. Z includes full systematic uncertainties, including decay constants, to allow for comparison with other radioisotopic dates or astrochronologically-determined timescales that may be tied to other radioisotopic dates that are not derived from the U-Pb system (63, 64).

The ages we present in this study are influenced by how we dealt with the issue of Th/U disequilibrium in zircon, and our decision to present the single youngest, most-precise analysis as the age of each ashbed, rather than weighted means. Both of these decisions are discussed below, and ultimately, neither interpretation substantially affects our major conclusions about the timing and duration of CRBG eruptions.
Th/U disequilibrium correction in zircon
During zircon crystallization, $^{238}$U is preferentially incorporated into the crystal lattice over $^{230}$Th, an intermediate daughter product, causing the system to depart from secular equilibrium and ages to be underestimated. Often, a minimal correction is made to address this fractionation. Either zircons are assumed to crystallize from a magma with a uniform (Th/U), or a uniform partition coefficient between Th and U from the liquid is assumed, and then the (Th/U) of the magma is calculated on a fraction by fraction basis, using the model (Th/U) of each zircon determined from the $^{208}\text{Pb}/^{206}\text{Pb}$ ratios (65). Given the likelihood that the zircons in this study were crystallized from a variety of different magmatic systems, we prefer the constant partition coefficient approach for correcting Th/U disequilibrium. A recently published, comprehensive study (60) measures partition coefficients in zircon-glass pairs from a range of volcanic settings; volcanic glasses are assumed to display the same partitioning as the magma from which they crystallize. All measurements of Th/U partitioning in the study fell in the range of 0.06-0.3, so we use a conservative estimate of $0.19\pm0.11$ (2σ) to calculate (Th/U)$_{\text{magma}}$ for each zircon, using the $^{208}\text{Pb}/^{206}\text{Pb}$ obtained for each zircon during mass spectrometry. To assess the impact of this correction, we also reduce our youngest zircon ages (upon which our interpretations depend) with a constant (Th/U)$_{\text{magma}}$ of $3.5\pm1.0$ (2σ), which encompasses the majority of igneous liquids (table S2). We find that our preferred interpretation with a constant Th/U partition coefficient adjusts our dates by no more than 10 ka, and adds no more than 5 ka of uncertainty to each age.

Interpretation of zircon crystallization age spectra
The zircons dated from each geochronology sample displayed a dispersion in ages ranging from 40-500 ka (apart from inherited grains). We interpret this as geological scatter caused by pre-eruptive zircon crystallization or incorporation of zircons from older material in the same volcanic system (24), because the dispersion in most cases goes beyond analytical uncertainty. Therefore, the zircon that crystallized most recently should best time the eruption of the volcanic ash, and for this reason we interpret the youngest, most precise zircon dates as representing the age of the horizons in this study. Although Pb loss in zircons may sometimes cause U-Pb dates to be biased too young, chemical abrasion on young zircons nearly eliminates this effect. We find the pattern in our dataset of younging ages with increasing height in the CRB stratigraphy as
further evidence that Pb loss does not affect our conclusions, as its effects would vary with grain size and U-content, and not systematically with age.

Other geochronological studies often use a weighted mean of several zircon dates to constrain the age of a sample. This approach yields dates with lower uncertainty than the single crystal approach as well as greater assurance that the resulting age is not biased by a young outlier, but should only be used for homogeneous age populations where the only source of scatter is analytical uncertainty, which is not the case for all of our samples, and difficult to justify in most U-Pb datasets even if they overlap within analytical uncertainty. Additionally, including zircons beyond the youngest grain in the final age of the sample may bias the resulting age too old as a result of pre-eruptive crystallization. To assess how well the analytical uncertainty can explain the observed dispersion of crystallization ages, the mean square of weighted deviates (MSWD) may be calculated, and should be ~1, with deviance from 1 varying with the number of analyses included in the weighted mean (66). However, a dataset may still be subject to subtle geologic dispersion, even with an MSWD near 1 (65), resulting in weighted means that are biased too old.

We compare the single crystal ages presented in this study to weighted mean ages calculated for each sample in table S2 and fig. S5. First, we calculate the weighted mean for the youngest few zircons, whose dates overlap with the youngest date, where slight offsets may be caused by analytical uncertainty. We also calculate weighted mean ages using the maximum number of grains allowed to produce an acceptable MSWD near 1. We find that the more grains that are included in the weighted mean, the ages are biased older, though are more precise. Ultimately, as seen in table S2 and fig. S5, the decision to use the age of single crystals rather than weighted means ages does not substantially offset our ages, and does not have a major bearing on any of the conclusions presented in this paper. The single crystal approach appears to be the most conservative because it results in larger uncertainty for each age, while overlapping with the weighted mean ages.

Comparing with $^{40}$Ar/$^{39}$Ar geochronology

When compared to the most recent $^{40}$Ar/$^{39}$Ar geochronology results (21) for the Steens Basalt, we find a similar duration (150 ka compared with 210 ka) but timing 100 ka earlier. However,
when the $^{40}\text{Ar}/^{39}\text{Ar}$ ages are recalculated through the method of Renne et al. (64) using the more recent Fish Canyon sanidine age of 28.201 Ma (22) instead of 28.02 Ma (64), the recalculated range of 16.75-16.54 Ma matches favorably with our results.
**Supplementary Figures and Tables**

**Fig. S1. Geochronology sample photos.** Outcrop-scale and/or hand-sample scale photos of each geochronology sample are provided here, with stratigraphic younging from bottom to top (Photo credit: Jennifer Kasbohm, Princeton University).
Fig. S2. Zircon photos. Optical images of zircons under transmitted light are presented here, with stratigraphic younging from bottom to top. Zircons present a range of morphologies, but the majority are euhedral with sharp crystal terminations, indicating an igneous rather than detrital origin. The zircon yielding the youngest, most precise analysis for each sample is starred.
Fig. S3. **Thickness and volume versus age plots.** Detailed area and volume estimates for each member of the CRBG stratigraphy allows for plots of cumulative maximum thickness and volume versus age. Youngest zircon ages with 2σ uncertainty for the samples dated in this study are plotted here. Cumulative thickness and volume are color-coded by CRBG formation as labeled on the plots.
Fig. S4. Concordia plots for U-Pb ID-TIMS geochronological data. U-Pb isotopic data for each analysis is available in table S1. Each ellipse is labelled and represents a zircon analysis, with the width of the ellipse representing 2σ uncertainty. The red ellipses are those analyses that are included in the “Youngest Few Zircons” weighted means described in table S2, while the gray ellipses are not included in those weighted means. The shading around the Concordia line represents uncertainties in the U decay constants. Almost all ellipses overlap with Concordia, indicating closed-system behavior.
Fig. S5. *Alternate age interpretations.* Our preferred interpretation of single crystals representing the eruptive age of each sample does not substantially offset our results from using weighted mean ages. For each sample, we compare the age of the youngest sample to the a weighted mean age calculated from the youngest few grains, and to a weighted mean age calculated using the maximum number of grains that yield an acceptable MSWD near 1. Even though ages from single crystals exhibit higher $2\sigma$ uncertainty, we prefer the youngest zircon interpretation to avoid the effects of pre-eruptive zircon crystallization, as the weighted mean ages all appear biased slightly older. Calculated dates using the different interpretations are given in table S2.
Table S1. U-Pb isotopic data. Data acquired by CA-ID-TIMS is presented in a separate file, with various corrections as specified in the notes beneath the table.

Table S2. Alternate age interpretations. We compare our preferred data interpretation of using the youngest, most precise zircon date for the age of the sample, with a constant Th/U partition coefficient to alternative interpretations. The youngest zircon age with a constant partition coefficient shows no more than 10 ka offset from the youngest zircon age obtained using a constant \((\text{Th/U})_{\text{magma}}\). The youngest zircon age can also be compared to weighted mean ages calculated from the youngest few zircons or a weighted mean taken from the maximum number of grains allowing an acceptable MSWD of 1. The effects of these interpretations are described in the text and illustrated in fig. S5.

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<th>Sample</th>
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<th>const. partition coefficient uncertainty</th>
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<td>16.655 ± 0.062 0.070 ± 0.072</td>
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<td>3.15 ± 0.016 0.017 ± 0.024</td>
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<td>16.571 ± 0.016 0.017 ± 0.024</td>
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**Preferred Interpretation**
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<td>0.39</td>
<td>0.29</td>
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Table S1. U-Pb isotopic data.
Values for ET535 and ET2535 are found in ref. 31 and ref. 32. Two different blank models were used to reduce data - Outliers Culled model (OC), and Side Filaments (SF). Values are:

- Measured ratios corrected for fractionation, tracer and blank.
- Ratio of radiogenic Pb (including 208Pb) to common Pb.
- Total mass of radiogenic Pb.
- Corrected for initial Pa/U disequilibrium using initial fraction activity ratio 

### U-Pb isotopic data.

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Rapid eruption of the Columbia River flood basalt and correlation with the mid-Miocene climate optimum
Jennifer Kasbohm and Blair Schoene

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