Spatially variable syn- and post-Alleghanian exhumation of the central Appalachian Mountains from zircon (U-Th)/He thermochronology

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ABSTRACT

To assess spatial and temporal patterns of Phanerozoic orogenic burial and subsequent exhumation in the central Appalachian Mountains, we present mid-temperature zircon (U-Th)/He (ZH; closure temperature \(T_c = 140–200 ^\circ C\)) dates for 10 samples along a 225 km, strike-perpendicular transect spanning the Appalachian Plateau, Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces in West Virginia and western Virginia. Ranges of single-grain ZHe dates exhibit an eastward younging trend from 455–358 Ma in the Pennsylvanian Appalachian Plateau to 336–209 Ma in the Valley and Ridge, 298–217 Ma in the Blue Ridge, and 186–121 Ma in the Piedmont. Within the Pennsylvanian Appalachian Plateau, detrital ZHe dates are older than corresponding depositional ages, thus limiting postdepositional burial temperatures to less than 160 ^\circ C. These ZHe dates capture predepositional mid-Paleozoic cooling signatures, indicating provenance from either recycled Taconic or Acadian basin strata or mid-Paleozoic Appalachian terranes. Across the Valley and Ridge and western Blue Ridge provinces, reset Permian detrital ZHe dates feature flat date-effective uranium correlations that suggest rapid Alleghanian cooling initiating prior to 270 Ma. ZHe dates within the Valley and Ridge are more than 100 m.y. older than previously reported regional apatite fission-track dates, reflecting a protracted period of stable post-Alleghanian thermal conditions within the foreland. By contrast, post-Triassic single-grain ZHe dates in the interior Piedmont document rapid postrift cooling, likely resulting from both the relaxation of an elevated geothermal gradient and exhumation from rift-flank uplift. The spatial discontinuity between stable synrift thermal conditions in the Valley and Ridge and rapid cooling in the Piedmont suggests that rift-flank uplift and cooling were concentrated outboard of the foreland within the Piedmont province.

INTRODUCTION

Continent-continent convergence and postorogenic rifting induce differential exhumation across an orogen (e.g., Tucker and Slingerland, 1994; Arne et al., 1997; Lock and Willett, 2008); however, reconstructing the timing, rates, and spatial variability of exhumation during and immediately after these geologic processes is often difficult. During orogen development, exhumation typically depends on the magnitude of crustal loading, which drives rapid erosion of thickened crust and rugged topography within active mountain belts (Reiners and Brandon, 2006). During postcollisional rifting, exhumation is regulated by lithospheric thinning and edge-driven asthenospheric convection, which can cause rift-flank uplift, erosion, and subsequent exhumation. The magnitude of exhumation generally decreases away from the rift margin (Steckler, 1985; Buck, 1986), though extensional faulting can still result in rapid exhumation hundreds of kilometers inboard of the margin, as seen along the modern Red Sea Rift (Szymanski et al., 2016). Exhumation during both orogen development and rifting is regulated by key structural and lithospheric dynamics, and thus reconstructing the exhumation record provides essential geologic information about the spatial and temporal evolution of an orogen (McQuarrie and Ehlers, 2018).

Within the central Appalachian Mountains, the timing and rates of exhumation driven by the late Carboniferous–Permian Alleghanian orogeny and subsequent rifting of the Atlantic Ocean either are not known or remain relatively unconstrained (e.g., Roden, 1991; Evans, 2010). Across the foreland, maximum thermal indicators convey first-order information about the quantity and spatial patterns of postdepositional exhumation. For instance, the surficial exposure of more thermally mature sedimentary rocks toward the east (Ruppert et al., 2010; Repetski et al., 2014) indicates that the magnitude of postdepositional exhumation increased toward the hinterland, assuming a spatially consistent geothermal gradient. However, deciphering the timing, rates, and therefore precise mechanisms responsible for this pattern of differential exhumation requires reconstructing the thermal history of surface rock.

Mid- to low-temperature thermochronology serves as a powerful tool to constrain time-temperature paths, yet within the central Appalachian Mountains, a thermal history gap spanning the late Carboniferous–Permian Alleghanian orogeny to Triassic–Jurassic rifting exists within prior thermochronologic data sets. In postorogenic settings, low-temperature apatite fission-track (AFT; closure temperature \(T_c = 80–120 ^\circ C\)) and apatite (U-Th)/He (AHe; \(T_c = 40–90 ^\circ C\); Farley and Stockli, 2002) thermochronology typically can be applied to determine the synorogenic and synrift rates and spatial patterns.
of exhumation (e.g., Ehlers and Farley, 2003; Enkelmann and Garver, 2016). However, the central Appalachian Mountains have been consistently exhuming along a passive margin for greater than 180 m.y., and low-temperature (<120 °C) thermochronology does not capture higher-temperature thermal histories of orogen development (e.g., Spotila et al., 2004; McKeon et al., 2014; Shorten and Fitzgerald, 2019). Furthermore, mid-temperature detrital zircon fission-track (ZFT; \( T_c = 140–200 °C \); Reiners, 2005) thermochronology to target the thermal history gap between the AFT and ZFT thermochronometers, which corresponds to exhumation driven by the late Paleozoic Alleghanian orogeny in the western Appalachians and Triassic–Jurassic rifting in the eastern Appalachians. Addressing the thermal imprint of these events informs the broader understanding of transitions from active orogen growth to postrift passive-margin sedimentation, refines existing thermal constraints, and demonstrates the utility of mid-temperature detrital ZHe dating in deciphering the burial and exhumation histories of ancient fold-and-thrust belts.

We present ZHe data for 10 samples along an orogen-perpendicular transect across the central Appalachian foreland and orogenic core (Fig. 2, A-A‘), spanning the Appalachian Plateau, Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces within Virginia and West Virginia. We began by drawing first-order inferences from basic depositional constraints and single-grain ZHe date-effective uranium concentration (eU) correlations. Next, we exploited existing structural, thermochronologic, and maximum thermal data to perform inverse thermal modeling of the ZHe data set. Finally, we constructed an overview of the transect-parallel trends in the timing and rates of exhumation. Our results constrain spatially variable and geologically reasonable syn- and postrAleghanian orogeny exhumation rates and augment the existing trove of structural and geochronologic data in the Appalachian Mountains.

## GEOLOGIC AND METHODOLOGIC BACKGROUND

### Geologic Background

Along our orogen-perpendicular transect (Fig. 2, A-A‘), the westernmost Appalachian Plateau and Valley and Ridge physiographic provinces collectively form the Appalachian foreland, which consists of siliciclastic sequences that were deposited during the Late Ordovician Taconic orogeny, the Middle to Late Devonian Acadian orogeny, and the late Carboniferous–Permian Alleghanian orogeny (Drake et al., 1988; Hatcher et al., 1989; Osberg et al., 1989; Etensohn, 2008; Hatcher, 2010). Syntectonic basin strata are onlapped by carbonate, shale, and sandstone sequences that were deposited during periods of tectonic quiescence, and they are underlain by a Cambrian–Late Ordovician synrift and passive-margin succession and series of foreland basin sequences (Read, 1989). Toward the east, the Blue Ridge and Piedmont physiographic provinces comprise the largely crystalline core of the Alleghanian orogen. Here, we detail a brief overview of the geologic setting of each province to provide a foundation for the interpretation of thermochronology results.

The Appalachian Plateau hosts subhorizontal autochthonous Paleozoic strata in the western region of the Appalachian foreland basin (Fig. 2). The eastern portion of the plateau exhibits long-wavelength (~15 km), low-amplitude (~200 m) folds formed during the convergence of Laurentia and Gondwana at the late stages of the Alleghanian orogeny (Cardwell et al., 1968; Hatcher, 2010). The western region of the plateau exposes subhorizontal Pennsylvanian and early Permian sedimentary rocks derived from the Alleghanian highlands that experienced shortening along the Burning Springs thrust and layer-parallel shortening (Root, 1998; Whitaker and Bartholomew, 1999). The province is bordered to the east by the Allegheny structural front, which is the westward boundary of Alleghanian thrust faulting in the adjacent Valley and Ridge Province (Gwinn, 1964; Mitra, 1987).

The Valley and Ridge Province forms an archetypal thin-skinned fold-and-thrust belt within the eastern half of the Appalachian foreland basin (Fig. 2;...
Gwinn, 1964; Perry, 1978; Kulander and Dean, 1986; Wilson and Shumaker, 1992; Evans, 2010; Hatcher, 2010; Lammie et al., 2020). Deformation is expressed as a roof rock sequence of long-wavelength (~15 km), high-amplitude (>2 km) folds in Ordovician through Carboniferous strata (Rader and Wilkes, 2001). The roof sequence is underlain by a duplex of Cambrian through Ordovician carbonate rocks that form antiformal stacks spatially correlated with folds in the overlying roof strata (Evans, 1989). While few emergent faults exist in the western Valley and Ridge Province, the North Mountain thrust fault in the easternmost Great Valley subprovince juxtaposes Cambrian–Ordovician carbonate sequences atop the folded Ordovician–Mississippian root sequence (Kulander and Dean, 1988; Evans, 1989, 2010).

The Blue Ridge Province is a topographically prominent massif that forms the western half of the crystalline core of the Appalachian orogen (Fig. 2). The Blue Ridge exposes a west-verging anticlinorium that is thrust atop Cambrian–Ordovician carbonates of the Valley and Ridge Province by the Blue Ridge thrust (Tollo et al., 2004). The axis of the Blue Ridge antiform consists
of Grenville-aged (ca. 1.2–1.0 Ga) igneous and metamorphic basement rocks intruded by Neoproterozoic plutons and overlain by Neoproterozoic metasedimentary rocks of the Lynchburg Group, Neoproterozoic metavolcanics rocks of the Catoctin and Swift Run Formations, and Cambrian metasedimentary rocks and siliciclastic strata of the Chilhowee Group (Rader and Evans, 1993). The Blue Ridge is bounded to the east by an ~750-km-long, northeast-striking system of subparallel Alleghanian right-slip mylonitic shear zones, including the Bowens Creek fault (Gates, 1987) and Mountain Run fault (Fig. 2; Pavlides et al., 1983; Pavlides, 1987, 1989, 1994; Evans and Milici, 1994). The Blue Ridge is also truncated in the east by a southeast-dipping, brittle normal fault that forms the western boundary of the Triassic Scottsville Basin (Roberts, 1928; Bailey et al., 2014).

The Piedmont Province is the low-relief eastern half of the Appalachian crystalline core, and it consists of an amalgamation of mostly peri-Gondwana terranes that were thrust over the Laurentian margin during the Acadian and Taconic orogenies. These terranes contain Mesoproterozoic to Neoproterozoic right-slip shear zones, many of which utilized preexisting zones of weakness such as ophiolitic melange complexes. These right-slip systems include the Brookneal fault zone, the Shores melange zone (Brown, 1988), the Chopawamsic fault along the eastern margin of the Western Piedmont terrane (Gates et al., 1986), and the Spotylvania fault zone along the eastern margin of the Chopawamsic terrane (Bailey et al., 2004).

### Detrital Zircon (U-Th)/He Thermochronology and Maximum Thermal Indicators

Mid-temperature ZHe thermochronology is a powerful tool used to reconstruct the timing and rates of orogenic exhumation, constrain provenance, and determine maximum burial conditions (e.g., Reiners, 2005; Cecil et al., 2006; Powell et al., 2016). Careful interpretation of ZHe data requires an accurate characterization of 4He diffusion kinetics, which depend strongly on the time-evolving accumulated radiation damage, and to a lesser extent on grain size and shape (Reiners et al., 2002; Nasdala et al., 2004; Guenthner et al., 2013). Thermal histories may generate positive correlations between date and grain size and/or date and aspect ratio owing to the dependence of 4He diffusion on grain dimensions and anisotropic c-axis (fast) versus a-axis (slow) zircon 4He diffusion (Reiners and Farley, 2001; Anderson et al., 2020). Grain size and crystal morphology can cause tens of degrees Celsius difference in the effective Tc defined as the temperature of the sample at the calculated date (Dodson, 1973). Radiation damage is often the dominant control on 4He diffusivity and can lead to >100 °C differences in effective Tc, especially in protracted thermal settings (e.g., Johnson et al., 2017; Baughman and Flowers, 2020).

The total accumulated radiation damage of a grain depends on the effective uranium concentration (eU, the weighted alpha productivity, where eU = [U] + 0.235 × [Th]), and the time since a grain has cooled beneath the zircon radiation damage annealing zone (~250–350 °C; Ginster et al., 2019). Thus, eU is a useful damage proxy for samples with a shared thermal history. At low radiation damage, caused by low eU concentrations and/or minimal damage accumulation time, 4He diffusivity decreases with progressive damage accumulation, which increases the effective Tc (Guenthner et al., 2013). As damage accumulation continues to increase, 4He diffusivity reaches a minimum and crosses the damage percolation threshold, after which a precipitous drop in Tc is observed (Nasdala et al., 2004; Reiners, 2005; Guenthner et al., 2013). These radiation damage effects manifest as spans of ZHe dates correlated with eU, as individual grains possess disparate effective closure temperatures that each access different portions of the sample’s thermal history, and that collectively capture rates of cooling along the time-temperature (t-T) path. Rapid exhumation through the zircon helium partial retention zone (PRZ) will cool grains through their individual "closure temperatures" at a similar time, thereby producing a flat date-eU correlation. In contrast, once sufficient damage has accumulated for zircon to cross the damage percolation threshold, slow exhumation, isothermal holding within the PRZ, or reheating and partial 4He loss can yield a steep, negative date-eU correlation.

Thermal modeling software, HeFTy v.1.9.3 (Ketcham, 2005), tracks time-evolving zircon 4He diffusion kinetics using the zircon radiation damage accumulation and annealing model (ZRDAAM; Guenthner et al., 2013), and it can constrain the various thermal histories that satisfy ZHe date, eU, and grain-size data. Within HeFTy, thermal history paths can be further constrained through the integrated vitrinite reflectance model of Nielsen et al. (2017), and by constructing t-T constraint boxes that force thermal paths through known geologic constraints, such as depositional ages or U-Pb crystallization dates. However, interpretation and thermal modeling of ZHe dates from sedimentary rocks are complicated by the fact that detrital zircons do not necessarily share the same predepositional thermal history, as grains may have different provenance. Consequently, grains from a single sample may have variable inherited damage accumulation and/or 4He retention prior to deposition, such that for some thermal histories, it may be inappropriate to model grains together. For samples that may lack a shared predepositional thermal history, we considered a range of damage and 4He inheritance histories to explore the role and complexity that variable t-T histories may have on detrital ZHe data patterns, particularly for ZHe dates that were not fully reset by postdepositional thermal conditions (Guenthner et al., 2014; Powell et al., 2016). We also carefully interpreted our model outputs in the context of known flaws in the ZRDAAM, which may under- or overestimate 4He diffusivity depending on specific sample and thermal history characteristics.

Within basins, maximum thermal indicators, including vitrinite reflectance (VR), conodont alteration indices (CAI), and fluid inclusion microthermometry, form an additional method to determine maximum burial conditions, reconstruct eroded overburdens, and model thermal histories (Epstein et al., 1977;
An integrated approach combining thermochronology with maximum thermal indicators serves as an effective method with which to reconstruct the thermal history of a sedimentary basin, as each technique targets distinct characteristics of a t-T path (e.g., Kamp et al., 1996; Crowhurst et al., 2002; Reed et al., 2005; Evans et al., 2014; Shorten and Fitzgerald, 2019). For instance, burial temperatures derived from maximum thermal indicators can further refine rates of thermochronologically calculated cooling by forcing t-T paths through a specific temperature. Similarly, thermochronology can constrain the timing of peak thermal conditions using maximum thermal data, and regional-scale isograd maps created from maximum thermal data can provide estimates of overburdens and/or geothermal gradients that aid in the interpretation of thermochronologic data.

Prior Thermal Constraints

Sedimentary samples within the Appalachian foreland and western half of the Blue Ridge Province experienced a thermal history encompassing deposition at surficial temperatures, reheating by burial, and subsequent exhumation and cooling, which can be reconstructed using both maximum thermal indicators and thermochronology. In contrast, thermal history paths for primarily crystalline samples within the Piedmont and Blue Ridge Provinces exhibit cooling from metamorphic temperatures and, owing to their crystalline lithology, are reliant on thermochronology for thermal history reconstructions. Here, we provide an overview of prior thermal constraints and identify gaps targeted by our ZHe data set.

Within the central Appalachian foreland, the magnitude of postdepositional overburden exerts a primary control on maximum postdepositional thermal conditions. In the Appalachian Plateau, Pennsylvanian VR isograd maps exhibit an eastward increase in thermal maturity, thereby suggesting greater burial depths toward the hinterland (Ruppert et al., 2010). VR and fluid inclusion microthermometry data suggest that maximum burial temperatures reached ~150 °C immediately west of the Allegheny deformation front (Reed et al., 2005; Evans, 2010; Ruppert et al., 2010). Within the Valley and Ridge Province, maximum thermal conditions display significant spatial and stratigraphic variability related to the development of thrust duplexes, deposition in “piggyback basins,” and the passage of warm orogenic fluids (Zhang and Davis, 1993; Evans, 2010; Repetski et al., 2014). However, maximum thermal conditions in presently exposed Valley and Ridge rocks likely exceeded those experienced by Appalachian Plateau rocks.

Within the Valley and Ridge and Appalachian Plateau Provinces, existing ZFT, AFT, and AHe thermochronologic dates bracket a significant temporal gap in the t-T history. Higher-temperature ZFT dates within the central and northern Appalachian foreland are not reset or partially reset by postdepositional reheating (Fig. 2, small circles; Lakatos and Miller, 1983; Johnsson, 1985, 1986; Roden et al., 1993; Montario and Garver, 2009; Naeser et al., 2016), corroborating maximum thermal indicators, but providing little information about the postdepositional exhumation history. By contrast, lower-temperature AFT and AHe thermochronometers are fully reset, but they generally capture only post- Triassic exhumation (Roden, 1991; Roden et al., 1993; Blackmer et al., 1994; Boettcher and Milliken, 1994; Reed et al., 2005; Shorten and Fitzgerald, 2021). These data sets typically exhibit an eastward younging trend (Fig. 2, diamonds), and they have been interpreted to reflect differential cooling during a mid-Cretaceous pulse of exhumation. Within the southern Pennsylvania Appalachian basin, Blackmer et al. (1994) modeled AFT and VR data to infer that post-Alleghanian thermal conditions were relatively stable, but this stability may have been preceded by a rapid late Permain cooling pulse. However, the thermal signature of the late Carboniferous–Permian Alleghanian orogeny is not directly captured within these thermochronologic data. Our mid-temperature ZHe data set falls between the temperature sensitivities of the AFT and ZFT thermochronometers and bridges the corresponding thermal history gap.

Within the central Appalachian Blue Ridge and Piedmont Provinces, existing thermochronology is limited, but it suggests a thermal discontinuity corresponding to orogen-perpendicular changes in lithology and structure. In particular, ZFT dates from Naeser et al. (2016) displayed a sharp eastward younging trend perpendicular to the strike of the Blue Ridge Province, from Precambrian (617–582 Ma) ZFT dates not reset by burial within Cambrian Chilhowee Group samples to significantly younger mid- to late Paleozoic dates from the eastern crystalline core of the Blue Ridge (Fig. 2, small circles). Within the interior of the Piedmont Province further north in Maryland, higher-temperature muscovite (Tc = 500 ± 50 °C) and hornblende (Tc = 400 ± 50 °C) 40Ar/39Ar dates document cooling following the Taconic and Acadian orogenies (Kunk et al., 2005). In the Piedmont and Newark rift basin of Pennsylvania and Maryland, synrift (ca. 220–180 Ma) titanite fission-track (Tt = 265–310 °C; Coyle and Wagner, 1998) and ZFT dates indicate a thermal pulse during rifting, potentially driven by a steepening of the thermal gradient up to 60 °C/km (Roden and Miller, 1991; Kohn et al., 1993; Steckler et al., 1993) along with localized reactivation of Paleozoic transpressional faults and Triassic extensional faults.

METHODS

We collected 10 samples along a 225-km-long, orogen-perpendicular transect across the Appalachian foreland basin and orogenic interior of West Virginia and western Virginia (Fig. 2; Table 1), spanning the Appalachian
Plateau, Valley and Ridge, Blue Ridge, and Piedmont physiographic provinces. The elevation of sampling sites varied from 317 m in the Piedmont to 1291 m in the Appalachian Plateau. Table 1 presents a summary of geological information for all samples. Samples CA1, CA2, and CA3 consist of coarse sandstones collected from the Pennsylvanian Pottsville Group in the Appalachian Plateau interior, while sample CA4 is a sandstone from the Devonian Hampshire Formation in the easternmost Appalachian Plateau. Within the Valley and Ridge Province, samples CA5, CA6, and CA9 are Silurian sandstones, while sample CA10 is an Ordovician sandstone from the Martinsburg Formation. Sample CA7 from the Blue Ridge Province is phyllite of the Cambrian Chilhowee Group, and sample CA8 from the Piedmont Province is quartzofeldspathic schist of the Laurentian-affinity Potomac terrane (Hughes et al., 2014).

ZHe analyses were conducted at the University of Colorado at Boulder Thermochronology Research and Instrumentation Laboratory (CU TRaIL). Analyzed single zircon grains were isolated using standard mineral separation techniques, and 3–4 suitable grains per sample were handpicked, photographed, and measured under a Leica M165 binocular microscope with an attached calibrated digital camera (Fig. S1† displays photomicrographs of analyzed zircon grains). Individual grains were put into a Nb packet and placed into an ASI Alphachron He extraction line under vacuum (3 × 10⁻⁸ torr). To extract He gas, packets were heated twice with a diode laser to 800–1100 °C. Released He was purified using SAES getter methods, spiked with ³⁷He, and measured using a Balzers PrismaPlus GM6220 quadrupole mass spectrometer. After degassing, grains were treated with ³⁹U and ⁴⁰Th tracers and dissolved using an acid vapor HF and HCl dissolution method. U and Th were measured on an Agilent 7900 quadrupole inductively coupled plasma–mass spectrometer (ICP-MS). Orthorhombic and ellipsoidal geometries were used for alpha-ejection corrections to account for He ejected from grain edges (Ketcham et al., 2011), and for zircon mass, volume, and concentration calculations for euhedral and ellipsoid grain morphologies, respectively. Single-grain ZHe date error represents 2σ propagated analytical uncertainty. For rounded sedimentary grains yielding ZHe dates older than depositional ages, special correction factors have been developed to account for abrasion during transport and deposition (Rahli et al., 2003). However, as Appalachian foreland basin strata have been subject to multiple episodes of basin recycling (e.g., Eriksson et al., 2004; Park et al., 2010), it is unreasonable to pinpoint when abrasion occurred, and thus we only applied standard ellipsoidal alpha-correction factors to non-reset rounded grains.

### Results

Single-grain ZHe data are shown in Figure 3 and reported in Table 2. Single-grain ZHe dates exhibit a clear younging trend toward the east, from 455–373 Ma in the westernmost Appalachian Plateau sample (CA1) to 186–121 Ma in the easternmost Piedmont sample (CA8; Fig. 4). West of the Allegheny structural front, detrital ZHe dates predates or span depositional ages, whereas east of the front, detrital ZHe dates postdate depositional ages. ZHe dates do not display a clear single-grain date-aspect ratio or date-elevation relationship (Figs. S2 and S3 (see footnote 1)).

Single-grain ZHe dates of Middle and Lower Pennsylvanian sandstones from the Appalachian Plateau Province (CA1, CA2, CA3) range from 455 to 358 Ma, predates depositional ages (Fig. 4, blue circles), and generally feature negative date-eU correlations (Fig. 3, orange circles). Sample CA1 displays a negative, gently sloped date-eU correlation spanning from 435 Ma at 148 ppm eU to 373 Ma at 2012 ppm eU (Fig. 3A, orange circles), whereas sample CA3 yields a slightly steeper negative date-eU correlation from 432 Ma at 602 ppm eU to 398 Ma at 991 ppm eU (Fig. 3A, bold orange circles). Sample CA2 exhibits

| Sample | Single-grain zircon (U-Th)/He date range* (Ma) | Elevation (m) | Latitude (°N) | Longitude (°W) | Unit/formation† | Depositional period | Lithology | Physiographic province |
|--------|-----------------------------------------------|--------------|--------------|---------------|----------------|-------------------|-----------|-----------------------|
| CA1    | 455–373                                       | 317          | 38.6111      | 80.5656       | Kanawha Formation, Pottsville Group | Middle Pennsylvanian | Sandstone | Appalachian Plateau    |
| CA2    | 425–373                                       | 477          | 38.4805      | 80.4541       | New River Formation, Pottsville Group | Late Pennsylvanian  | Sandstone | Appalachian Plateau    |
| CA3    | 433–358                                       | 797          | 38.6171      | 80.1076       | Kanawha Formation, Pottsville Group | Middle Pennsylvanian | Sandstone | Appalachian Plateau    |
| CA4    | 376–234                                       | 1291         | 38.4758      | 79.6998       | Hampshire Formation | Devonian  | Sandstone | Appalachian Plateau    |
| CA5    | 336–296                                       | 1089         | 38.4247      | 79.5986       | Catawba Sandstone | Silurian  | Sandstone | Appalachian Plateau    |
| CA6    | 296–209                                       | 794          | 38.3582      | 79.5496       | Tuscarora Sandstone | Silurian  | Sandstone | Appalachian Plateau    |
| CA7    | 298–217                                       | 531          | 38.0405      | 78.8738       | Chilhowee Group | Cambrian  | Phyllite | Blue Ridge             |
| CA8    | 186–121                                       | 111          | 37.9839      | 78.3109       | Potomac terrane | N.A.†    | Quartzofeldspathic schist | Piedmont  |
| CA9    | 323–244                                       | 677          | 37.5422      | 80.3538       | McKenzie Formation, Clinton Group | Silurian  | Sandstone | Appalachian Plateau    |
| CA10   | 280–248                                       | 925          | 38.0495      | 79.7949       | Martinsburg Formation | Ordovician | Sandstone | Appalachian Plateau    |

*3-4 zircon (U-Th)/He dates. †Cardwell et al. (1968) and Rader and Evans (1993). ²Not applicable.
a scattered date-eU correlation, although eU is bounded between 210 and 385 ppm, and the date-radius plot exhibits a positive date-radius trend (Fig. 3A, cross-hatched orange circles; Fig. S4 [footnote 1]). In contrast to Pennsylvanian strata, a Devonian sandstone (CA4) collected from the easternmost Appalachian Plateau, adjacent to the Allegheny structural front, features single-grain ZHe dates spanning the depositional age of the unit. Sample CA4 exhibits a steep, negative date-eU correlation from 357 Ma at 267 ppm eU to 233 Ma at 511 ppm eU (Fig. 3A, dotted orange circles).

Within the Valley and Ridge Province, single-grain ZHe dates (CA5, CA6, CA9, CA10) are Carboniferous through Triassic, postdate depositional ages, feature primarily flat, negatively trending date-eU correlations, and display a slight eastward年轻的 trend in single-grain date ranges, from 336–298 Ma (CA5) to 296–209 Ma (CA6; Fig. 4). Samples CA6 and CA10 exhibit flat date-eU correlations between 250 and 300 Ma and 197 and 767 ppm eU (Fig. 3B). Sample CA6 yielded an anomalously young zircon grain date of 209 Ma at 197 ppm eU. Photomicrographs indicate the presence of a large inclusion, and this grain is therefore excluded from subsequent interpretation (Fig. S1 [footnote 1]). Sample CA5 exhibits slightly older Carboniferous single-grain dates and a slightly positive date-radius correlation (Fig. 3B, cross-hatched blue circles; Fig. S4), while sample CA9 exhibits a negative date-eU correlation from 323 Ma at 206 ppm eU to 244 Ma at 552 ppm eU (Fig. 3B, blue circles).

Blue Ridge Province sample CA7 yielded four single-grain dates that range from 298 to 217 Ma and exhibit a positive, then gradually negative, ZHe date-eU correlation (Fig. 3C, red circles). To the east, Piedmont Province sample CA8 yielded four single-grain dates that range from 186 to 121 Ma, feature a flat, gradually negative date-eU correlation, and display a weak positive date-radius correlation (Fig. 3C, purple circles; Fig. S4).

**DISCUSSION**

**Controls on ⁴He Diffusivity and Thermal Conditions**

Radiation damage exerts a primary control on ⁴He diffusivity within our ZHe samples. Negative date-eU correlations for samples CA2, CA3, CA5, CA8, and CA10 are consistent with sufficient damage accumulation as to cross the zircon damage percolation threshold, such that increased damage causes increased ⁴He diffusivity and a lower effective $T_C$ (Reiners, 2005). Samples CA1, CA4, and CA7 display parabolic date-eU correlations, suggesting that accumulated damage within individual grains spans the damage percolation threshold (Guenthner et al., 2013). Regional and within-sample date-eU correlations will be interpreted in detail within subsequent sections. While grain size and aspect ratio cause up to 10 °C difference in $T_C$ (Reiners et al., 2002; Anderson et al., 2020), these effects are likely masked by the strong control of radiation damage on diffusivity. Nonetheless, two samples (CA2 and CA6) lacking significant spread in eU exhibit positive date-radius correlations (Fig. S4), and minor data dispersion within other samples may be explained in part by effects of grain radius and morphology on ⁴He diffusion.

For Appalachian foreland samples, we infer that ZHe dates primarily reflect cooling during orogen development and subsequent exhumation. However, tectonically elevated geothermal gradients and warm orogenic fluids may form a supplementary control on both ZHe dates and maximum thermal indicators. Nonetheless, no samples were collected from the Devonian interval identified as a region of warm orogenic fluid flow by Evans and Battles (1999), and Pennsylvanian VR, Devonian VR, Devonian CAI, and Ordovician CAI isograd maps do not feature anomalous west-bulging salients across our transect (Ruppert et al., 2016).
| Sample | Geometry* | Length (μm) | Width (μm) | Radius† (μm) | Mass (μg) | U (ppm) ± | Th (ppm) ± | Sm (ppm) ± | eUj (ppm) | He (nmoi/g) ± | Th/U | Uncorrected date (Ma) ± | ε* | R** | Corrected date (Ma) ± |
|--------|-----------|-------------|-------------|--------------|-----------|------------|------------|------------|-----------|----------------|------|----------------|-----|------|-------------------|
| CA1    | R         | 101.8       | 46.1        | 27.1         | 0.5       | 538.0      | 16.5       | 281.8      | 7.2        | 8.0           | 1.5  | 605.2           | 885.3 | 6.1  | 0.52              | 265.1 | 7.3  | 0.57              | 455.4 | 23.5 |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA2    | R         | 107.4       | 47.2        | 26.5         | 0.4       | 1863.9     | 21.1       | 632.8      | 7.4        | 56.7          | 46.7 | 2027.2         | 2368.1 | 11.6 | 0.34              | 214.1 | 2.4  | 0.57              | 373.5 | 8.1  |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA3    |            |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA4    | R         | 134.2       | 83.3        | 47.0         | 2.3       | 434.7      | 10.0       | 257.9      | 7.8        | 4.2           | 0.4  | 495.3           | 677.1 | 2.0  | 0.59              | 248.1 | 5.0  | 0.75              | 329.7 | 13.2 |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA5    |            |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA6    |            |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA7    |            |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA8    |            |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA9    |            |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
| CA10   |            |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |
|        |           |             |             |              |           |            |            |            |            |                |      |                 |      |      |       |      |      |       |      |      |      |

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*E—euhedral, R—rounded.

†Equivalent spherical radius.

²Effective uranium concentration weighting Th and U for alpha productivity, where eU = [U] + 0.235 × [Th].

*²Analytical uncertainty based on measurement of U, Th, Sm, He, and grain dimensions.

**Alpha correction factor of Ketcham et al. (2011), assuming euhedral orthorhombic or ellipsoidal geometry.
et al., 2010; Repetski et al., 2014), which have been interpreted as regions of orogenic fluid flow in the Anthracite Basin of southwest Pennsylvania and elsewhere in the foreland (Zhang and Davis, 1993; Evans and Battles, 1999).

Thermal Modeling

Inverse thermal modeling of ZHe data was performed using the ZRDAAM (Guenthner et al., 2013) implemented in HeFTy v1.9.3 (Ketcham, 2005). Figure 5 displays inverse thermal model results for all samples. A comprehensive description of our modeling approach and sources of external data is detailed in Table S1 (footnote 1). We applied four types of thermal constraints in which t-T paths were forced to take into account zircon U-Pb crystallization dates, depositional ages, reheating constraints, and prior low-temperature thermochronology.

First, models began at a temperature of 400 °C at 1250–950 Ma, a temporal range coeval with the Grenville orogeny and corresponding to a significant peak in zircon U-Pb date probability distributions within sampled formations (Reed et al., 2005; Park et al., 2010). While previously reported U-Pb dates for Silurian and Cambrian samples fall exclusively (>99%) within this Grenville time span, Middle and Lower Pennsylvanian, Upper Devonian, and Ordovician samples (CA1–CA4 and CA10) harbor a significant population (~10%–30%) of Paleozoic or pre-Grenville zircon grains, suggesting grain provenance from multiple source terranes. Thermal modeling based on a radiation damage and annealing model, however, requires shared predepositional thermal histories. To evaluate predepositional thermal histories, we created forward-model inheritance “envelopes” (e.g., Guenthner et al., 2014; Powell et al., 2016) predicting ZHe dates for variable durations of radiation damage accumulation across a range of geologically reasonable burial depths (Figs. S6 and S7 [footnote 1]). Most grains for Appalachian Plateau samples CA1–CA4 fall between the 320 and 500 Ma inheritance lines at a geologically reasonable burial temperature of 140 °C, suggesting that grains began accumulating radiation damage during this interval. Similarly, ZHe dates from sample CA10 fall near the 950 Ma inheritance line at burial temperature of 190 °C. These models demonstrate that within-sample variability in predepositional thermal histories is limited and unlikely to significantly alter thermal history interpretations.

Second, models required a surficial temperature of 20 °C during the depositional range of the formation. Third, models incorporated t-T constraint boxes requiring postdepositional reheating. Within Pennsylvania Appalachian Plateau samples (CA1–CA3), where prior VR data were available, %R, (Ruppert et al., 2010) was entered directly into HeFTy using the Basin%R model of Nielsen et al. (2017). Reheating temperature constraints were left purposefully broad (25–220 °C) to allow for exploration by the model. All other sedimentary samples were from stratigraphic intervals without existing VR data, and temperature constraints of reheating were constructed using VR and CAI data from strata bounding the sampled rock unit, described in detail in Table S1 (footnote 1). Prior work constraining the timing of maximum thermal conditions is limited, and we applied a broad early to middle Permian (299–260 Ma) temporal constraint within the Valley and Ridge Province. The 299 Ma bound is specified by VR, CAI, and micro-inclusion thermometry data (Epstein et al., 1977; Evans, 2010; Repetski et al., 2014) that indicate the magnitude of burial exceeded the reconstructed stratigraphic thickness through the Carboniferous. The 260 Ma bound is conservatively drawn from late Permian synfolding paleomagnetic data suggesting that folding, which likely postdated maximum reheating temperatures, occurred in the range of ca. 280–260 Ma (Lewchuk et al., 2002; Cox et al., 2005; Elmore et al., 2006). Within the Appalachian Plateau Province, we required Permian maximum thermal conditions consistent with a burial model by Reed et al. (2005) and the presence of likely Permian rocks within western Maryland (Brezinski and Conkwright, 2013). As a comparison to t-T paths found using the above reheating constraints, Figure S8 displays thermal history outputs for models with significantly expanded reheating constraints.

Finally, we required cooling through boxes representing the upper bound of the AFT or AHe partial annealing and partial retention zones (120 °C and 80 °C), respectively, when existing dates were colocated with our ZHe samples (Roden, 1991; Reed et al., 2005). A lack of published technical data precludes integrating these samples directly into HeFTy. All models ended at surface thermal conditions of 20 °C.

Four known concerns with the ZRDAAM are relevant to the interpretation of our thermal model simulations. First, ZRDAAM does not account for anisotropic He diffusion in zircon, although this factor exerts a secondary control on He diffusion corresponding to ~10 °C differences in T (Anderson et al., 2020),
Figure 5. Inverse thermal history model outputs for 10 zircon (U-Th)/He (ZHe) samples using the zircon radiation damage accumulation and annealing model (Guenthner et al., 2013) implemented in HeFTy (Ketcham, 2005). Green lines indicate acceptable-fit time-temperature paths, purples lines represent good-fit paths, and the black line denotes the best-fit path. Thermal history paths are forced through blue boxes representing U-Pb crystallization dates, depositional ages, postdepositional reheating constraints, existing thermochronologic dates, and modern surficial temperatures. Date-effective uranium (eU) plots compare single-grain ZHe dates with the date-eU correlation predicted by the corresponding best-fit thermal history path. A full description of inverse model input parameters and sources of data is detailed in Table S1 (text footnote 1). AHe—apatite (U-Th)/He.
and we did not observe a strong correlation between date and aspect ratio within our data set (Fig. S2 [footnote 1]). Second, ZRDAAM likely overestimates the diffusivity of high-damage, high-eU grains, resulting in inverse t-T paths that may overestimate cooling or underestimate the temperature required to reset ZHe dates (Johnson et al., 2017). We were able to fit t-T paths to our highest eU grains and carefully interpreted model outputs. Third, ZRDAAM underestimates the amount of radiation damage required to cross the damage percolation threshold (Gautheron et al., 2020), thereby underestimating 4He diffusivity and returning thermal history paths that are hotter and/or heated for a longer duration than geologically required.

Fourth, ZRDAAM anneals radiation damage at temperatures lower than that reported by studies of experimental damage annealing (Ginster et al., 2019). To evaluate the impact of excessive damage annealing, we performed forward modeling comparing the radiation damage accumulated by a reheated zircon to that of a grain continually accumulating radiation damage at the surface (Fig. S5). The difference in alpha dose between these two thermal histories represents the amount of annealing predicted by ZRDAAM for the reheated grain. Within the Appalachian Plateau Province, geologically reasonable reheating at temperatures below 170 °C caused <5% difference in alpha dose, suggesting that excessive damage annealing has a negligible effect on the inverse thermal models (Fig. S5, blue paths). For the Valley and Ridge and Blue Ridge sample paths, reheating to 250 °C caused a 25% difference in alpha dose when compared to a surficially held sample (Fig. S5, green paths). An unknown portion of this 25% likely represents “true” annealing; however, any excessive annealing would reinforce our primary interpretation of fast Alleghanian exhumation. If grains in fact possess additional radiation damage, more rapid cooling through the ZHe PRZ would be required to yield the observed flat date-eU correlations.

Regional Interpretations

Within each physiographic province, we first interpret our data set using basic depositional constraints and zircon (U-Th)/He data systematics, including an analysis of date-eU correlations. Next, we obtain inverse model thermal model results, presented in Figures 5 and 6, to corroborate first-order interpretations and further constrain the timing and rates of burial and exhumation. Then, we summarize the along-transect description of trends in burial, Alleghanian exhumation. If grains in fact possess additional radiation damage, more rapid cooling through the ZHe PRZ would be required to yield the observed flat date-eU correlations.

Appalachian Plateau

All single-grain ZHe dates (11 grains) of the three sandstone samples from the Appalachian Plateau (CA1, CA2, CA3), west of the Allegheny structural front, predate Pennsylvania depositional ages (Fig. 4, blue circles), indicating that maximum postdepositional temperatures did not fully reset ZHe dates. This constraint suggests that postdepositional reheating did not significantly exceed 160 °C, the lower range of the ZHe PRZ, a result in good agreement with prior estimates of maximum thermal conditions using VR and micro-inclusion thermometry (Reed et al., 2005; Evans, 2010). This constraint imposes a ceiling on the magnitude of post-Pennsylvanian burial in the Appalachian Plateau originating from Alleghanian clastic input (Fig. 8C), and it likewise limits the magnitude of unroofing, as significant postburial exhumation would produce surficial exposures of rocks yielding ZHe dates fully reset by burial temperatures. A weak younging trend in single-grain ZHe dates toward the hinterland (samples CA1 to CA3) may indicate an eastward-increasing magnitude of partial resetting consistent with eastward-increasing post-Pennsylvanian burial depths and associated maximum thermal conditions.

Zircons within the Pennsylvania Appalachian Plateau likely experienced rapid predepositional Taconic or Acadian cooling. This is shown by flat to negative date-eU correlations for samples CA1, CA2, and CA3, indicating that...
samples cooled rapidly through disparate temperature sensitivities of individual zircon grains spanning the ZHe PRZ. Dates are broadly similar to early Paleozoic ZFT dates reported by Naeser et al. (2016), suggesting predepositional cooling from temperatures exceeding ~240 °C, which is the approximate effective $T_c$ of the ZFT thermochronometer (Yamada et al., 1995). Our single-grain ZHe dates are generally coeval with the timing of the Taconic and Acadian orogenies, suggesting that the Alleghanian orogeny drove erosion of Acadian or Taconic clastic wedges, which likely contained syntectonically cooled zircons, causing the westward transport and redeposition of these grains within Pennsylvanian strata. Alternatively, these predepositional cooling signatures could reflect the Alleghanian exhumation and erosion of Acadian and Taconic metamorphic core terranes that had previously cooled past the ZHe effective closure temperature.

Single-grain ZHe dates for sample CA4 (four grains; 376–233 Ma), an Upper Devonian sandstone from the easternmost Appalachian Plateau Province, span the depositional age, indicating partial resetting by postdepositional reheating. Partial resetting is consistent with a steep date-eU correlation (Fig. 3A), a result of the differential accumulation of radiation damage prior to reheating and a subsequent span in single-grain temperature sensitivities correlated to eU. Compared to ZHe dates not reset within Pennsylvanian rock units further west, partial resetting of this Devonian sandstone requires greater maximum thermal conditions. This was likely caused by a lower stratigraphic position, roughly 1 km below Pennsylvanian Pottsville Formation samples (CA1–CA3), as well as a greater depth of post-Pennsylvanian burial toward the east, consistent with a west-tapering sedimentary wedge in the Appalachian Plateau during adjacent Valley and Ridge deformation (Fig. 8C; Ruppert et al., 2010). The present exposure of this Devonian sample previously subject to deeper burial depths also suggests a greater magnitude of postdepositional exhumation toward the east. This partially reset ZHe sample cannot independently document the timing of this exhumation, however, because the date reflects the time-integrated sum of partially diffused predepositional relict helium and postdepositional accumulated helium.

Good-fit HeFly inverse thermal model paths for Pennsylvanian Appalachian Plateau ZHe dates integrated with prior regional VR data (Fig. 5; CA1, CA2, CA3) exhibit fast predepositional cooling and require a reheating temperature...
not exceeding ~160 °C, corroborating the above interpretations derived from date-eU correlations and depositional constraints. Good-fit model t-T paths display a short cooling pulse immediately following maximum postdepositional temperatures, a feature that likely satisfies maximum thermal conditions required by VR data without a prolonged duration of heating that would reset ZHe dates. This pulse of cooling could represent a small quantity of exhumation toward the end of the Alleghanian orogeny and is in agreement with a thermal reconstruction by Evans (1995). However, the cooling signal within our models is fairly weak and could alternatively have been caused by known flaws of the ZRDAAM.

HeFTy inverse t-T paths for Devonian sample CA4 show isothermal holding at temperatures within the ZHe PRZ (Fig. 5), consistent with a prolonged duration of partial resetting at thermal conditions hotter than those experienced by Pennsylvanian samples further west.

Valley and Ridge

All single-grain ZHe dates (13 grains) for Silurian and Ordovician strata in the Valley and Ridge Province postdate depositional ages (Fig. 4; CA5, CA6, CA8, CA10), suggesting postdepositional reheating in excess of 190–200 °C, which is the upper range of the ZHe PRZ. Compared to non-reset ZHe dates in Appalachian Plateau Pennsylvanian strata, complete resetting of Valley and Ridge samples resulted from structurally lower positions below the Devonian Acadian-related clastic wedge, as well as greater quantities of postdepositional overburden during overthrusting and/or clastic input related to the North Mountain thrust sheet (Fig. 8B). Moreover, compared to non-reset ZHe dates of Pennsylvanian strata in the Appalachian Plateau Province, the modern exposure of Ordovician and Silurian strata previously subjected to greater burial suggests a greater magnitude of postdepositional exhumation toward the east.
Single-grain ZHe dates coeval with Alleghanian orogenic growth, in concert with flat date-eU correlations (Fig. 3B), suggest rapid syn-Alleghanian cooling of the Valley and Ridge Province. Flat date-eU correlations developed as grains quickly cooled through the ZHe PRZ, yielding a similar date across a span in single-grain temperature sensitivities. No clear trend exists among ZHe dates along strike, across strike, and at deeper stratigraphic levels (Fig. 2). Collectively, these cooling signatures indicate rapid Alleghanian exhumation of the Valley and Ridge coincident with the west-trending development of surficial folds and underlying duplexes during the middle Permian (Fig. 8). These data suggest maximum thermal conditions were achieved in the early to middle Permian, and that sedimentation and/or thrust loading of the Valley and Ridge ceased by the middle to late Permian and was supplanted by rapid erosion of presumably elevated terrain (Slingerland and Furlong, 1989). This result is consistent with syndeformational paleomagnetic fold data suggesting middle to late Permian folding within the central Appalachian Valley and Ridge Province (Stamatakos et al., 1996; Cox et al., 2005; Elmore et al., 2006). Single-grain dates from Silurian sandstone sample CA6 are notably older (336–298 Ma) than prior estimates for the initiation of cooling within the western Valley and Ridge Province, suggesting that it may retain partial quantities of predepositional helium.

HeFTy inverse thermal model paths for Valley and Ridge samples are consistent with the above interpretations and further refine the timing, duration, and magnitude of the Alleghanian cooling signal (Figs. 5 and 6, blue paths). Good-fit paths for samples CA6, CA9, and CA10 require cooling to have initiated by 270 Ma, a constraint that overlaps with the syndeformation paleomagnetic fold test data within the western Valley and Ridge spanning from 280 to 260 Ma. Together, these data suggest that the Wills Mountain anticline and underlying duplex in the region likely formed by 280–270 Ma and were actively exhuming by 270 Ma, coincident with regional west-directed shortening and formation of the Long Ridge anticline to the east (Fig. 8C; Evans, 2010). The elevated topography of the Wills Mountain anticline and adjacent structures shed sediment westward on the Appalachian Plateau, suggesting maximum burial of the plateau occurred after 270 Ma. Moreover, folds in the easternmost Appalachian Province, including the Elkins Valley anticline to the west, also likely formed after 270 Ma as a result of overburden-induced increases in pore-fluid pressure (Evans, 2010). Sample CA9, located 100 km southwest of the study transect within the St. Clair thrust sheet, displays a steeper date-eU correlation consistent with slower rates of cooling. This may reflect along-strike spatial variability in Alleghanian exhumation rates, or, alternatively, it could be due to zircon grains that were only partially reset by burial temperatures.

Within Valley and Ridge samples CA6, CA9, and CA10, all good-fit model paths require cooling to at least 140 °C by 250 Ma, and best-fit model paths tend to display even greater amounts of cooling by the end of the Permian (Fig. 5). Together with Cretaceous AFT (Tc = ~80–120 °C) dates in the Valley and Ridge Province and easternmost Appalachian Plateau Province (Rodon, 1991), our thermal models suggest an ~100 m.y. period of relatively stable thermal conditions from the end of the Permian to the beginning of the Cretaceous, coeval with the initiation of rifting (Fig. 6). Stable thermal conditions during this interval argue against significant rift-associated cooling or reheating within the Valley and Ridge Province, and indicate that the decay of Alleghanian topography within the Valley and Ridge may have largely ceased by the end of the Permian.

**Blue Ridge**

Sample CA7 from the Cambrian Chilhowee Group of the western Blue Ridge Province yielded reset single-grain ZHe dates that are generally contemporaneous with the late stages of the Alleghanian orogeny. Similar to foreland basin samples from the Valley and Ridge Province, the fully reset grains from the Blue Ridge capture a synorogenic exhumation signature as foreland basin and underlying passive-margin sedimentary rocks were uplifted and exhumed. A parabolic to negatively trending date-eU correlation, maintained up to eU values of 1838 ppm, with presumably high damage (Figs. 3C and 5), suggests significant, rapid cooling through the ZHe PRZ during the late Permian. Structural reconstructions of the central Appalachians indicate that the activation of the Blue Ridge thrust likely preceded the activation of the North Mountain thrust and other thrusts to the west (Fig. 8A), suggesting that cooling may have initiated in the Blue Ridge prior to that in the Valley and Ridge (Evans, 1989). However, we did not observe any significant difference between Valley and Ridge and Blue Ridge ZHe dates, indicating at minimum that both were rapidly exhuming in the late Permian. However, it is possible that, within the Blue Ridge Province, an earlier cooling signal exists at temperatures exceeding the upper bound of the ZHe PRZ (~200 °C).

Good-fit HeFTy inverse model paths for Blue Ridge sample CA7 feature a rapid cooling pulse during the late Permian (Fig. 5). Good-fit t-T paths do not precisely constrain the timing of cooling initiation, but they do require cooling below 125 °C by 200 Ma. However, the ZRDAAM tends to overestimate the diffusivity of high-damage zircons, which may force t-T paths to overestimate the magnitude of cooling within this sample.

**Piedmont**

A quartzofeldspathic schist from the interior of the Piedmont Province yielded single-grain ZHe dates ranging from 186 to 121 Ma, i.e., significantly younger than single-grain dates of 288–217 Ma from the Blue Ridge Province sampled ~80 km to the west. A flat, slightly negative date-eU correlation (Fig. 3C, purple circles) suggests rapid Jurassic cooling after the initiation of rifting, which is further shown within the inverse thermal model t-T paths (Fig. 5). This cooling may have been caused by two linked mechanisms. First, rift-induced lithospheric thinning and asthenospheric edge convection may have driven rift-flank uplift and subsequent exhumation inboard of the rift margin during and immediately after rifting (ca. 200–150 Ma), as illustrated by the presence of “great escarpments” along rift shoulders (Steckler, 1985; Buch, 1986; Spotila et al., 1996; Basler et al., 2006).
2004). Second, the relaxation of an elevated geothermal gradient, estimated at 55–60 °C/km during rifting further north in the Newark Basin (Kohn et al., 1993), may also have contributed to the cooling signal. Rapid rift-induced cooling is supported by fully reset Jurassic ZFT and titanite FT dates within Mesozoic rift basins along the length of the North American rift margin (Kohn et al., 1993; Steckler et al., 1993). These data also correlate to a pulse of postrift offshore sedimentation in the Baltimore Canyon Trough (Pazzaglia and Brandon, 1996) as well as an accelerated postrift cooling signal observed in low-temperature AFT data sets (Roden, 1991; Roden et al., 1993; Shorten and Fitzgerald, 2021).

Orogen-Perpendicular Burial and Exhumation Trends

Burial Trends within the Appalachian Foreland

The eastward increase in maximum burial temperatures, from <160 °C in the Pennsylvanian Appalachian Plateau to 150–180 °C in the eastern Devonian Appalachian Plateau and to >190 °C in the Valley and Ridge and Blue Ridge Provinces (Fig. 7), is broadly consistent with prior maximum thermal estimates (e.g., Epstein et al., 1977; Reed et al., 2005; Evans, 2010; Ruppert et al., 2010; East et al., 2012). Our model-output maximum postdepositional temperatures within the Pennsylvanian Appalachian Plateau, however, are 15–25 °C hotter than previous estimates. This discrepancy is likely a function of the basin%R model of Nielsen et al. (2017), which at low VR values yields warmer maximum thermal estimates than those derived from the Easy%R model of Sweeney and Burnham (1990).

Spatial and temporal trends in maximum thermal conditions reflect differential burial based on stratigraphic level, proximity to the orogenic front, and structural history, presented visually in Figure 8. Within the Valley and Ridge Province, maximum thermal conditions may have been regulated by the early to mid-Permian emplacement of the North Mountain thrust sheet, which either thickened the section that includes footwall rocks of the easternmost Valley and Ridge Province or served as the source of sediments shed to the west (Fig. 8B; Evans, 2010). Footwall samples closer to the ramp of the North Mountain thrust or at lower stratigraphic levels in the footwall consequently achieved hotter maximum thermal conditions. In the Appalachian Plateau Province, maximum thermal conditions display a similar westward-decreasing trend consistent with a west-tapering sedimentary wedge. However, maximum thermal conditions in the Appalachian Plateau were likely achieved in the late Permian, after the Valley and Ridge Province, and coeval with the erosion and westward deposition of material from the Alleghany highlands (Fig. 8C).

Alleghanian Exhumation in the Foreland

ZHe data interpreted in the context of prior thermochronology provide evidence that the magnitude and rates of Alleghanian exhumation were greatest in the east (Fig. 6). Within the Blue Ridge and Valley and Ridge Provinces, ZHe data constrain rapid Permian cooling initiating before 270 Ma, and cooling to at least 140 °C by 250 Ma from maximum temperatures exceeding 190 °C. We interpret this rapid cooling pulse to represent rapid syntectonic exhumation of the actively deforming fold-and-thrust belt.

By contrast, Pennsylvanian Appalachian Plateau samples located west of the Allegheny structural front exhibit ZHe dates that limit maximum thermal conditions during burial to less than 160 °C, which likely occurred after 270 Ma (Fig. 8C). When compared to early to mid-Mesozoic AFT dates (246–171 Ma; Roden, 1991) within the region, this constraint both limits the total quantity of Alleghanian exhumation and suggests moderate-to-slow postorogenic rates of cooling. Our inverse thermal models did identify a potential Alleghanian cooling pulse within Pennsylvanian samples (CA1, CA2, and CA3), which may represent limited synorogenic exhumation within the Appalachian Plateau. However, this feature is poorly constrained and may alternatively be an artifact of the modeling approach.

Using average good-fit t-7 paths, spatial patterns of maximum postdepositional thermal conditions, average Alleghanian cooling rates, and the total magnitude of Alleghanian cooling are visualized in Figure 7. Consistent with above interpretations, this map indicates that the magnitude and average rates of Alleghanian cooling increase toward the east, which thus indicates surficial exposures of older, more thermally mature rocks in the eastern Valley and Ridge Province.

Postorogenic Rift-Shoulder Exhumation

Piedmont Province sample CA8 records a rapid postrift cooling event at ca. 150 Ma, which we attribute to rift-flank exhumation and the postrift relaxation of the geothermal gradient. Acceptable-fit thermal model paths constrain cooling rates of 2.3–3.4 °C/m.y. between 200 and 120 Ma, which are in good agreement with previously reported zircon and titanite fission-track studies of the Piedmont Province (Kohn et al., 1993; Kunk et al., 2005) and correlate to a documented pulse of offshore sedimentation (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996).

By contrast, our ZHe dates within the Appalachian Plateau, Valley and Ridge, and Blue Ridge Provinces, interpreted in the context of prior thermochronology, indicate stable synrift thermal conditions. Thermal models for samples CA7 and CA9 within the Blue Ridge and Valley and Ridge Provinces (Fig. 5), respectively, both require cooling beneath 140 °C by 250 Ma, a temperature just above the ~120 °C effective closure temperature of the AFT thermochronometer. Within the Valley and Ridge Province, AFT dates are generally 150 Ma or younger (Roden, 1991), suggesting that averaged Triassic cooling rates in the foreland were less than 0.25 °C/m.y. Remarkably stable postorogenic, synrift thermal conditions indicate that rift-induced cooling was concentrated outboard of the foreland within Piedmont terranes. This eastward decrease in syn- and postrift exhumation is further supported by Mesozoic, fully reset
AFT dates within the Appalachian Plateau and Valley and Ridge Provinces that young toward the hinterland (Roden, 1991). Reed et al. (2005) also detailed a similarly slow postorogenic early Mesozoic cooling rate of 0.5 °C/m.y further basinward within the Appalachian Plateau Province.

Blue Ridge sample CA7, yielding single-grain dates of 298–217 Ma, is distanced only ~60 km from sample CA8, which yielded single-grain dates of 186–121 Ma. This difference in cooling dates within the Blue Ridge Province was previously noted in a ZFT study by Naeser et al. (2016), who exploited it as a tracer of provenance for coastal plain sediments. Our more detailed thermal models suggest that Jurassic extension accommodated by lower-crustal thinning and upper-crustal normal faulting resulted in localized exhumation in the western portion of the Piedmont Province. Although speculative, several upper-crustal structures located along the eastern margin of the Blue Ridge and within the Piedmont Province may have accommodated Triassic–Jurassic rifting and exhumation of sample CA8. Such structures could include the Mountain Run fault zone along the western margin of the Blue Ridge Province, or the Lakeside-Spotsylvania fault zone and the Brookneal fault zone–Shores mélange zone within the Piedmont Province (Gates et al., 1986; Gates, 1987; Evans and Milici, 1994; Bailey et al., 2004). Detailed field-based structural studies along these candidate structures and higher-resolution ZHe data across the Blue Ridge and Piedmont Provinces are needed to evaluate these hypotheses.

The spatial patterns of exhumation within our ZHe data set conform to a tectonic model of orogen development and subsequent rifting (Fig. 8). Within the Appalachian fold-and-thrust belt, rates and total quantities of exhumation increase toward the hinterland (Fig. 8), where the magnitude and duration of deformation and crustal thickening were greatest. Rapid syntectonic rates of exhumation are collocated with orogen-scale Alleghanian surface folds and underlying thrust duplexes, suggesting that significant paleotopography and relief were maintained in the deformed foreland (Fig. 8C). As topography decayed following the cessation of convergent tectonism, a protracted period of relatively stable thermal conditions existed within the foreland. The onset of Atlantic rifting drove cooling along the outer rift margin, likely as a result of rift-flank uplift and exhumation, and the eventual relaxation of an elevated geothermal gradient. However, relatively stable thermal conditions persisted within the foreland during Atlantic rifting to the east, suggesting that the thermal imprint of rifting did not penetrate significantly into the east.

CONCLUSIONS

We report ZHe data for nine detrital samples and one crystalline sample from an orogen-perpendicular transect across the Appalachian Plateau, Valley and Ridge, Piedmont, and Blue Ridge physiographic provinces of the central Appalachian Mountains. Inverse thermal modeling of these data exploiting the effect of radiation damage on ³He diffusivity, along with prior geochronologic and thermal constraints, supports the following conclusions:

(1) Within the Appalachian Plateau Province, detrital ZHe dates were not reset by the latest episode of burial and instead record rapid predepositional cooling coeval with the Taconic and Acadian orogenies, thereby suggesting provenance from either pre-Carboniferous foreland basin strata or exhumed pre-Alleghanian terranes.

(2) Within the Valley and Ridge and Blue Ridge Provinces, fully reset ZHe dates are contemporaneous with the Alleghanian orogeny and display flat date-eU correlations. This result is consistent with rapid Alleghanian exhumation initiating prior to 270 Ma, the magnitude and rates of which increase toward the east.

(3) Within the Valley and Ridge Province, existing AFT dates are generally >100 m.y. younger than our ZHe dates, reflecting a prolonged period of relatively stable post-Alleghanian thermal conditions from ca. 250 to 145 Ma.

(4) Within the Piedmont Province, single-grain ZHe dates range from 186 to 121 Ma and exhibit a flat date-eU correlation, suggesting rapid cooling during Mesozoic rifting, which was likely driven by rift-flank uplift and lessening of the geothermal gradient.

(5) There is an ~100 m.y. difference in ZHe dates between samples collected from the adjacent Blue Ridge and Piedmont Provinces (~60 km horizontal distance). This result is consistent with rift-induced uplift of the Piedmont accommodated along existing structural discontinuities between the two provinces.

(6) Detrital ZHe dates that are not reset or are partially or fully reset by burial document pre-, syn-, and postorogenic exhumation signals and demonstrate the ability of ZHe dating to reconstruct higher-temperature thermal histories of fold-and-thrust development within orogens that experience a significant duration and magnitude of postorogenic decay.

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