

Decay of an old orogen: Inferences about Appalachian landscape evolution from low-temperature thermochronology

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ABSTRACT

The Appalachian Mountains (eastern United States) are the archetypal old, long-decaying orogen from which major theories for long-term landscape evolution have been derived. However, given the variability of relief and topographic correlation with geologic and tectonic history, it is difficult to describe the orogen as old and uniformly decaying. Long-term and short-term estimates suggest slow and steady erosion at ~20 m/m.y.; however, intermediate-time-scale data like sediment accumulation rates and river incision suggest unsteadiness, which we assess using apatite (U-Th)/He thermochronology. All cooling ages from the central Appalachian hinterland in Pennsylvania and New Jersey and from the rugged Blue Ridge Mountains of western North Carolina are pre-Cenozoic, which places an upper limit on the volume of sediment that could have been sourced from these regions in connection with the documented large accumulation of Miocene siliciclastics offshore. Interpreting the timing and processes governing landscape evolution in these regions was hindered by complex age relations between neighboring samples and considerable age dispersion within individual samples. Through experiments with physical abrasion using two representative samples from the Blue Ridge Mountains, we find that variable zonation of U and Th in conjunction with radiation damage–induced differences in helium diffusivity is the source of age dispersion. Abraded grains produced a strong correlation between age and effective uranium concentration (eU) that was not observed for untreated grains and is expected as a result of grain-specific accumulation of radiation damage during slow cool-

ing. Cooling histories derived from inverse modeling of the eU-age relationship of the abraded grains suggests that for a period of ~60 m.y. during the Late Cretaceous, valley floors were exhuming at nearly twice the rate of neighboring ridge tops, generating relief equivalent to the modern landscape. This result illustrates that at least portions of the modern landscape are not a direct erosional remnant of long-dead orogenic processes and suggests that significant modifications of the Appalachian landscape can occur within the framework of slow long-term average erosion rates.

INTRODUCTION—THE ENIGMA OF APPALACHIAN TOPOGRAPHY

Topography is a first-order signal and boundary condition in the geodynamics of orogens. However, compared to young or active settings, interpreting the processes that control the evolution of topography in old orogens can be more complex. The Appalachian Mountains (eastern United States) are a good example of this, where variations in mean elevation and relief have little memory of the processes that constructed the orogen in the Paleozoic or have dominated its erosion since that time (reviewed and modeled in Pazzaglia and Brandon, 1996). Along strike, relief in the Appalachians varies considerably, from 1500 m in the southern Appalachians to less than 200 m in Pennsylvania. Independent of the magnitude of relief, the location of highest elevations and relief varies in its relation to Paleozoic tectonic setting: the highest values in the southern Appalachians are developed in the Grenville-aged crystalline rocks of the Blue Ridge, compared to the topographic inversion seen in the central Appalachians, where elevations in the orogenic core have been reduced to sea level and the highest elevations occur in the foreland. Mesozoic rift basins, the youngest major tectonic feature in the region and bound by faults with kilometers of displacement, are

arrayed along the length of eastern North America, yet their boundaries are not defined by any significant change in local relief.

Appalachian landscapes are also enigmatic in their post-orogenic evolution, which is not consistent with simple erosional decay of an original orogenic welt. Data that can constrain this long evolution have nurtured the development of the leading long-term landscape evolution paradigms (e.g., Davis, 1889, 1899; Hack, 1960), but also commonly offer conflicting interpretations. For much of the Appalachians south of the glacial margin, low rates of erosion (~20 m/m.y.) are inferred from the slow cooling observed from low-temperature thermochronology (e.g., Blackmer et al., 1994; Boettcher and Milliken, 1994; Miller and Duddy, 1989; Naeser et al., 2004; Roden and Miller, 1989; Roden, 1991). These rates are perplexingly similar to shorter-term values obtained by methods using cosmogenic nuclides averaged over the past several tens of thousands of years (Pavich et al., 1985; Matmon et al., 2003; Hancock and Kirwan, 2007; Portenga and Bierman, 2011; Portenga et al., 2013). The conundrum here is that if the pace of landscape evolution is controlled by relief and slope (Ahnert, 1970), then erosion rates should decrease as a result of the progressive isostatic consumption of an orogenic root. This is especially true if the buoyancy of the crustal root can decrease through time (Fischer, 2002) and thickness of the modern crustal root is spatially variable across the region (Baker and Hawman, 2011; Hawman et al., 2012). Moreover, the low rates are observed over a wide range of localities with marked differences in topographic characteristics, and seem at odds with the observed variations in rock type, unsteady sediment deposition rates in margin shelf-slope basins (Pazzaglia and Brandon, 1996), and localized evidence for considerable, recent river incision, drainage rearrangement, and capture (Ward et al., 2005; Prince et al., 2011; Gallen et al., 2013). At a minimum, the integrated volume of post-early

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Miocene siliciclastics in the shelf-slope basins, if corrected for density and spread uniformly across the current contributing mid-Atlantic slope watersheds, indicated that at least 1 km of rock has been removed (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996). Such erosion in no obvious way fits with slow erosion at 20 m/m.y., simple post-orogenic decay of a late Paleozoic orogen, or relaxation following Mesozoic reactivation of Appalachian orogenic lithosphere by Atlantic rifting.

The observation of apparently steady exhumation rates over many time scales in the face of documented variations in surface and tectonic forcing raises interesting questions about the nature of exhumation processes at longer time scales. In this study we combine published and new apatite (U-Th)/He thermochronologic data with new methodologies that address problematic age dispersion found here and in other regions characterized by slow erosion rates (e.g., Belton et al., 2004; Spotila et al., 2004; Green et al., 2006; Fitzgerald et al., 2006; Danišik et al., 2008). We begin by reporting the general patterns of the data we collected and the large intra-sample age dispersion that we encountered. Next, we describe our detailed experiments involving two samples from the Blue Ridge Mountains of the southern Appalachians that were aimed at identifying and mitigating the source(s) of the age dispersion we observed. Finally, using these results we derive contrasting thermal histories from a novel approach to inverse modeling that takes advantage of the dispersion caused by radiation damage (Shuster et al., 2006; Flowers et al., 2009). From these models we demonstrate that despite wide age dispersion, careful sample and data treatment can allow apatite (U-Th)/He ages from slowly cooled regions to yield nuanced results that in our case provide new evidence for spatially variable long-term erosion rates and post-orogenic relief generation in the Appalachian landscape.

THE APPALACHIAN LANDSCAPE AND PREVIOUS WORK

The Modern Appalachian Landscape

The general bedrock geology and topographic characteristics of the central and southern Appalachians can be grouped into five physiographic provinces that are parallel to the strike of range (Fig. 1). Starting in the east, the Coastal Plain is flat, near sea level, and composed of Cretaceous to Quaternary clastic sediment shed off of the higher topography to the west. The Piedmont province is composed of Paleozoic metamorphic and igneous rocks that represent the core of the Paleozoic Appa-

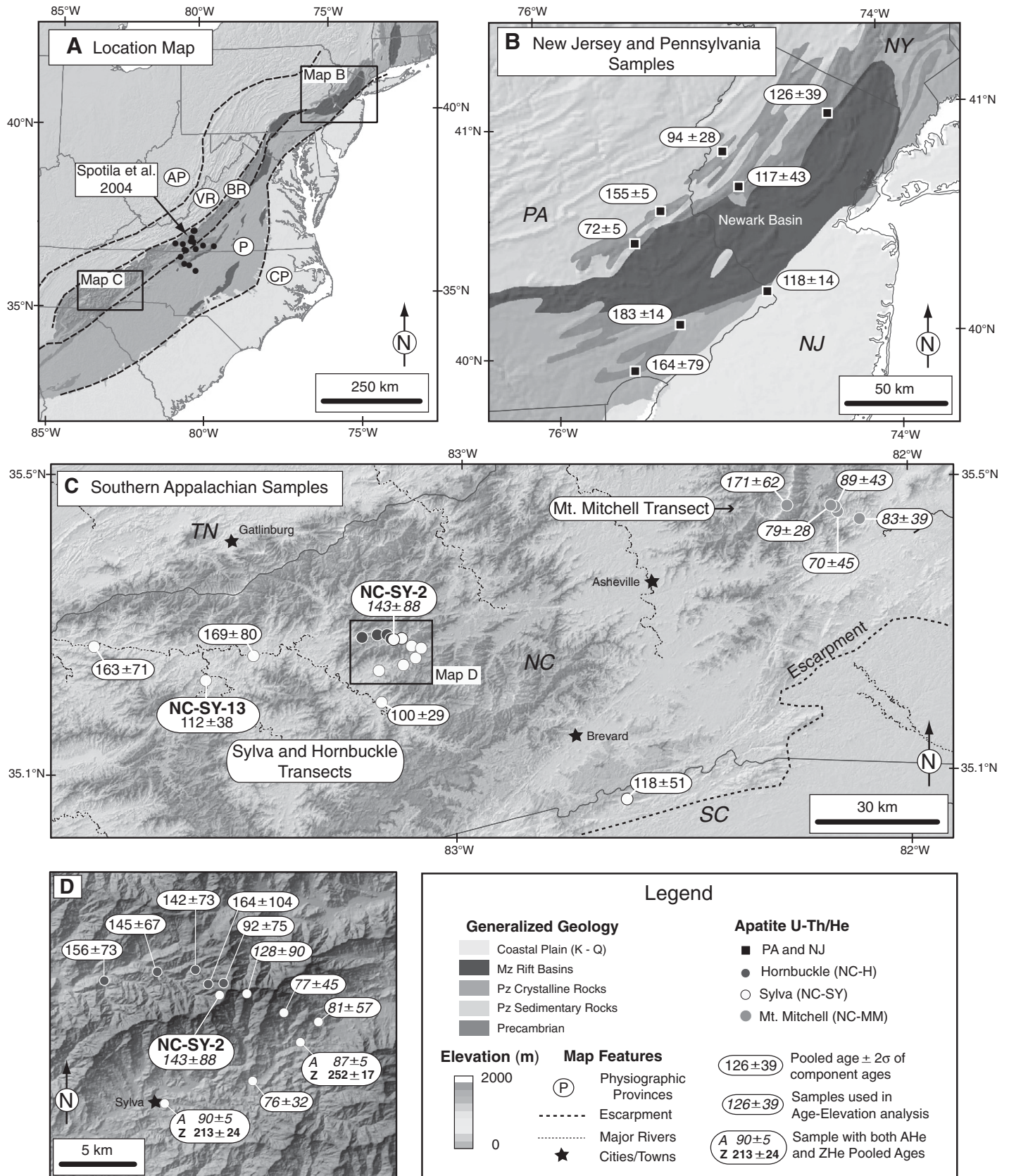
lachians, thought to have been Andean in scale (Slingerland and Furlong, 1989), but now characterized by very low relief and low elevation. The Blue Ridge escarpment, a seaward-facing topographic step of ~300–500 m height along its ~500 km length, in places coincident with the Grenville-Cambrian tectonic-stratigraphic units of the Blue Ridge, has been described as the remnants of a post-rift Great Escarpment (Spotila et al., 2004) where local stream capture continues to drive transient landscape response (Prince et al., 2011). The highest elevations and greatest relief south of the glacial boundary are found in the southern Blue Ridge province in the mountains of western North Carolina, which has recently been described as isostatically compensated for by a 45–55-km-thick crustal root (Hawman et al., 2012). Stepping further west, the Valley and Ridge province is composed of folded and thrust Paleozoic sedimentary rocks of the Appalachian foreland whereas the Appalachian Plateau furthest to the west is the undeformed part of the foreland. Elevation and relief in the Valley and Ridge and Appalachian Plateau vary considerably along strike, from subdued topography in Pennsylvania and the southern Appalachians to higher elevations and relief in the area of the New River of West Virginia. A record of post-rift erosion from this landscape is integrated by the siliciclastics of the offshore margin shelf-slope basins, including the Baltimore Canyon Trough (BCT) and Carolina Trough (CT) which contain up to 10 km of unsteady accumulation of Mesozoic and Cenozoic sediment (Pazzaglia and Brandon, 1996).

Low-Temperature Thermochronology

Fission-Track Dating

Extensive apatite fission-track (AFT) analysis from the Appalachian landscape provides a baseline for the pattern of long-term exhumation. AFT ages reflect cooling through 90–110 °C (Green et al., 1986; Carlson et al., 1999; Ketcham et al., 1999), which translates to ~4 km depth within the crust assuming a post-orogenic geothermal gradient of ~20 °C/km (summarized in Hulver, 1997). All AFT ages from throughout the Appalachian landscape are pre-Cenozoic, which places an upper limit on the extent of recent exhumation that can explain the observed pulse of Miocene sediment in offshore basins. Generally speaking, the oldest AFT ages in the Appalachian region are found in the sedimentary units of the Appalachian foreland now exposed in the Appalachian Plateau and the Valley and Ridge provinces of the central portion of the modern Appalachian Mountains, ranging from 100 to >200 Ma (Blackmer et al., 1994; Boettcher and Milliken, 1994; Miller and Duddy, 1989; Roden and Miller, 1989; Roden, 1991). AFT ages are youngest in northern New England (Roden-Tice and Tice, 2005; Roden-Tice et al., 2009) and the Adirondack region (Roden-Tice and Tice, 2005; Taylor and Fitzgerald, 2011) ranging from ca. 80 to 150 Ma, which are interpreted to be a result of thermal doming and incision caused by passage of that region over the Great Meteor hotspot during the early Cretaceous. In the southern Appalachians, Naeser et al. (2001) described a pattern of the oldest AFT ages from

Figure 1 (on following page). (A) Map showing the location of central and southern Appalachian study areas in the context of the bedrock geology and physiographic provinces of the Appalachian landscape of eastern North America. Physiographic provinces: AP—Appalachian Plateau; VR—Valley and Ridge; BR—Blue Ridge; P—Piedmont; CP—Coastal Plain. (B) Map showing the location and results of apatite (U-Th)/He (AHe) thermochronology in the central Appalachians surrounding the Mesozoic Newark rift basin, overlaid on a shaded-relief map colored with a digital elevation model (PA—Pennsylvania; NY—New York; NJ—New Jersey). Here, and for maps C and D, we report the pooled age and the 2 σ standard deviation of the component ages for each sample (see “Data Reduction in the Methods” section for explanation). (C) Shaded-relief map with bedrock geology showing the location and results of AHe and zircon (U-Th)/He (ZHe) thermochronology from the southern Appalachians of western North Carolina (TN—Tennessee; NC—North Carolina; SC—South Carolina). The location of samples NC-SY-2 and NC-SY-13 used for abrasion analysis and radiation damage modeling are indicated for reference. All of the samples were collected from the rugged topography of the Blue Ridge province to the northwest of the escarpment that separates the Blue Ridge from the Piedmont province. (D) Detailed shaded-relief map of the location and results from the Sylva (open circles) and Hornbuckle (filled circles) transects sampling east and west, respectively, from Waterrock Knob. Of note is the contrast in the age-elevation relationship of these two transects, where the Sylva samples show a positive correlation, but the Hornbuckle samples on the western side of the ridge show no correlation and much older ages at low elevation.



the Valley and Ridge (ca. 200 Ma), younger and more varied ages from the Blue Ridge (95–185 Ma), and intermediate ages from the Piedmont province (130–200 Ma). Samples from the high-relief region of the Blue Ridge in western North Carolina show an age-elevation relationship that suggests prolonged slow cooling at an average rate of 20 m/m.y. since the Jurassic (Naeser et al., 2004).

(U-Th)/He Dating

Previous application of apatite (U-Th)/He thermochronology (AHe) within the central and southern Appalachians is limited to a single study by Spotila et al. (2004). Using a combination of AHe and AFT data from the Piedmont and Blue Ridge physiographic provinces of Virginia, they found relatively old AHe ages with most ranging from 90 to 200 Ma. They observed the oldest ages from the high topography of the Blue Ridge province, the youngest at the base of the escarpment that separates the Blue Ridge from the Piedmont province, and ages increasing progressively southeast toward the center of the low-elevation and low-relief Piedmont. They interpreted this pattern to represent the slow and systematic northwestward retreat of a rift flank escarpment across the Piedmont province after it was generated during Mesozoic rifting, explaining both the existence and position of the modern topographic break and the distribution of ages they observed. For the purposes of comparing these data to those we report below, note that the AHe ages reported by Spotila et al. (2004) were determined on fairly large composites of many grains and for those samples where replicate aliquots were analyzed, age dispersion exceeding analytical uncertainty was common.

APATITE (U-Th)/He THERMOCHRONOLOGY

AHe thermochronology is based on the production of alpha particles (^4He) from the decay of U and Th (and to a minor degree Sm) and the thermally controlled retention of that helium within individual grains. The closure temperature (Dodson, 1973) of the AHe system is dependent upon the cooling rate through the zone of partial retention of helium (PRZ; ~35–90 °C) (Stockli et al., 2000; House et al., 2002; Flowers et al., 2009). At slow cooling rates, similar to those found in decaying orogens, helium diffusion in apatite can remain active at temperatures below 40 °C, and bulk closure for helium could be at temperatures as low as 50 °C (Shuster et al., 2006), which enables detection and quantification of small magnitudes of exhumation that are not possible

with higher-temperature thermochronologic systems. It has been shown that grain-specific characteristics of size (Farley, 2000) and effective uranium concentration (henceforth referred to as eU where $\text{eU} = [\text{U}] + 0.235 * [\text{Th}]$) (Shuster et al., 2006; Flowers et al., 2009) impact the closure temperature. Thus, as a result of slow cooling through the PRZ, different grains experiencing the same thermal history can produce different ages, raising the possibility that more detailed information about thermal history can be derived from a sample by analyzing single grains having different diffusion kinetics (e.g., Reiners and Farley, 2001; Flowers et al., 2007; Flowers, 2009). It is important to note that thermochronologic data measure temperature histories and need to be interpreted or modeled in order to represent exhumation rates through a temperature-for-depth transformation using a (typically assumed) geothermal gradient. For the southern Appalachians the modern geothermal gradient is ~15 °C/km (Nathenson and Guffanti, 1988). Presumably the gradient was higher immediately following the orogenies of the Paleozoic and Late Triassic rifting, and has been relaxing since. For comparisons of erosion rates using our results and modeling exercises we assume a constant geothermal gradient of 20 °C/km, which we feel is a plausible assumption for the long-term geothermal gradient for this post-orogenic region.

Sampling

With the goal of identifying the spatial and temporal variability of exhumation and perhaps a locality that gave young ages and might thus be a significant source of late Cenozoic sediment to the offshore basins, we examined two Appalachian regions that had not yet been subject to bedrock sampling for (U-Th)/He dating, the southern Blue Ridge Mountains in the southern Appalachians and a broader swath across the central Appalachians in southeastern Pennsylvania and New Jersey.

In the central Appalachians where relief is low, we used a reconnaissance approach to search for any regions that might give anomalously young ages. Samples were collected from outcrops of Precambrian crystalline rock surrounding the Mesozoic Newark rift basin. In the southern Appalachians, we focused sampling on two areas of high relief in the Blue Ridge province of western North Carolina. Samples were collected from Mount Mitchell, the highest point in the Appalachians, and from Water-rock Knob along the Blue Ridge Parkway in the Plott Balsams near the Great Smoky Mountains. We collected samples along simple vertical transects in the hopes that age-elevation rela-

tionships and the ages of the lowest-elevation samples might be informative about more recent landscape evolution. Sample locations are given in Table 1 and shown in Figure 1.

Methods

As we discuss below, our results are quite complex and we found slowly cooled bedrock apatites from the Appalachians to be analytically challenging. We expended considerable effort over a number of years in trying to understand the origin of this complexity, and as a result the analytical methods we used evolved during this time span. Technical details about analytical methods are given in the GSA Data Repository¹; in general these methods are similar to those used in most (U-Th)/He laboratories (e.g., Farley, 2002).

General Methods

Conventional mineral-separation procedures were used to extract apatite from bedrock samples from which grains were selected for AHe analysis using standard optical selection criteria (e.g., Farley, 2002; Ehlers and Farley, 2003) to be free of inclusions, fractures, and grain coatings, and when possible, euhedral. Apatites from these samples contained abundant mineral inclusions and grains were frequently picked under isopropyl alcohol or refractive oil to assist in identifying grains of suitable clarity for dating. Some analyses, particularly those made early in the project, used multiple grains per aliquot, up to as many as 20 or more, but many of our analyses were done on single grains (Table DR1 in the Data Repository [see footnote 1]). Alpha-loss (F_p) corrections (Farley et al., 1996) were calculated for each grain using two-dimensional measurements and then pooled for multi-grain aliquots. Selected grains were loaded into Pt or Nb micro-tube carriers for He, U, Th, and in later years, Sm analysis. Sample preparation and He analysis was conducted at the Noble Gas Geochronology Lab at Lehigh University. U, Th, and Sm analysis was conducted using inductively coupled plasma-mass spectrometry isotope dilution at Yale University and later the Arizona Radiogenic Helium Dating Lab at the University of Arizona. Additionally, for two samples from the southern Appalachians we analyzed several single-grain aliquots of zircon for (U-Th)/He ages using standard grain selection, helium extraction, and U and Th measurement (e.g., Reiners, 2005).

¹GSA Data Repository item 2013337, three figures and one table, is available at <http://www.geosociety.org/pubs/ft2013.htm> or by request to editing@geosociety.org.

TABLE 1. APATITE AND ZIRCON (U-Th)/He DATA FOR POOLED AGES FROM THE CENTRAL AND SOUTHERN APPALACHIANS

Sample	Age (pooled) (Ma)	Uncertainty* ± 2σ (Ma)	Analytical scatter† 2σ (Ma)	eU (pooled) (ppm)	Analyses (used / total)	Elevation (m)	Latitude (DD)	Longitude (DD)
Apatite:								
Central Appalachians								
APL-BUTL-00	126.1	3.5	39	105	4 / 4	126	41.0000	74.3333
APL-CHFD-00	164.1	5.1	79	7	6 / 7	48	39.8708	75.5958
APL-JJ-99	93.8	1.9	28	93	4 / 4	122	40.8583	74.9833
APL-LBCL-00	71.9	1.1	5	235	4 / 4	153	40.4583	75.5500
APL-MORR-00	117.5	3.7	14	37	3 / 3	6	40.2000	74.7708
APL-SCDM-00	183.2	7.4	14	26	4 / 4	15	40.0708	75.3083
APL-SMT-99	155.4	6.5	5	79	3 / 3	229	40.6000	75.3833
APL-VSP-00	116.9	3.7	43	81	3 / 3	183	40.6917	74.9000
Mount Mitchell transect								
NC-MM-4a	82.8	1.2	39	11	7 / 7	443	35.7351	82.1026
NC-MM-6	69.7	1.2	45	2	4 / 4	688	35.7512	82.1527
NC-MM-7	88.7	2.9	43	2	3 / 5	794	35.7623	82.1578
NC-MM-9	79.6	1.5	28	3	3 / 5	1044	35.7653	82.1675
NC-MM-16	170.9	7.0	62	8	4 / 4	2034	35.7644	82.2647
Sylva transect								
NC-SY-2AB	142.7	4.5	88	7	5 / 5	1780	35.4605	83.1441
NC-SY-3	127.7	3.9	90	12	4 / 4	1686	35.4610	83.1274
NC-SY-5	76.9	1.6	45	10	3 / 4	1419	35.4493	83.1044
NC-SY-7	81.3	1.2	57	6	7 / 8	1092	35.4437	83.0833
NC-SY-8	86.8	2.0	5	7	3 / 3	932	35.4632	83.0982
NC-SY-9	75.5	1.1	32	4	6 / 6	808	35.4075	83.1236
NC-SY-10	89.8	1.9	16	10	4 / 4	695	35.3937	83.1780
NC-SY-11	100.2	2.0	29	19	3 / 4	634	35.3224	83.1719
NC-SY-12	169.1	7.7	80	11	3 / 4	520	35.4271	83.4584
NC SY 13	112.4	1.9	38	13	10 / 10	530	35.3722	83.5650
NC-SY-14	162.5	4.8	71	18	7 / 7	402	35.4469	83.8148
Hornbuckle transect								
H4	92.1	1.5	51	10	7 / 7	1659	35.4678	83.1416
H8	164.0	4.4	75	17	8 / 8	1400	35.4672	83.1512
H9	141.6	3.3	104	14	8 / 8	1227	35.4758	83.1592
H11	144.5	4.0	73	4	6 / 7	933	35.4747	83.1824
H12	155.6	4.4	67	18	7 / 8	757	35.4693	83.2152
CH01	118.2	2.7	73	11	6 / 7	961	35.1059	82.6240
Total:					160 / 177			
Zircon:								
NC-SY-8	252.4	20.4	17	320	2 / 2	932	35.4632	83.0982
NC-SY-10	212.7	14.5	24	250	2 / 2	695	35.3937	83.1780

Note: eU—effective uranium concentration; DD—decimal degrees.

*Uncertainties in ages are 2σ (Ma); based on propagation of long-term analytical uncertainties in ^4He , U, and Th, and 1% uncertainty in alpha-loss (F_T) factor. For pooled ages, lowered uncertainties reflect propagation of component uncertainties through averaging.

†Analytical scatter is a simple 2σ standard deviation of measured ages, given as a measure of scatter in the component analyses for the pooled age.

Data Reduction

Uncertainties on the ages reported for individual analyses are based on a blanket 2.9% error (1σ) derived from Monte Carlo simulation that propagated uncertainties in the lab's long-term reproducibility of the Durango apatite standard, typical uncertainties in U and Th measurements, and a 1% error in the F_T alpha-correction factor. We feel this is the best measure of overall precision for those analyses made earlier in the history of our laboratory. For purposes of general discussion about our conventional results, we choose to report pooled ages (Vermeesch, 2008) as the best representation of the age of our samples. A pooled age is calculated by summing the He, U, Th, and Sm measured for all aliquots (single or multi-grain) from an individual sample and using these values to compute the age for the sample; it is analogous to putting all of the apatite grains in a single aliquot. This choice is justified by the fact that the component analyses for each sample involved both single- and multi-grain analyses,

and due to the wide intra-sample age dispersion we encountered the pooled ages are the simplest means to compare between samples and with the results of Spotila et al. (2004), who analyzed multi-grain aliquots exclusively. For pooled ages, the uncertainty represents the propagated uncertainty of the individual component ages. Because it is based only on the fairly good analytical precision, the pooled-age uncertainty will be quite low, so as a qualitative indicator for the actual dispersion between multiple aliquots of a single sample that contributed to the pooled ages, we also report the 2σ standard deviation of the component ages.

Results

Figure 1 and Table 1 summarize the results using pooled ages for 30 samples from the central and southern Appalachians. Individual component ages (from more than 170 aliquots) and analytical data can be found in Table DR1 in the GSA Data Repository (see footnote 1).

Data Quality and Dispersion

In the form of pooled ages, our results are relatively consistent, as can be seen in Figure 1. However, more locally among some adjacent samples, and especially internally within samples for which we analyzed a number of aliquots, the age dispersion can be very large, certainly greater than that predicted from analytical uncertainties (Table 1; Table DR1 [see footnote 1]). For example, 10 single- and multi-grain aliquots from sample NC-SY-13 produced a range of F_T -corrected ages from 75 to 131 Ma, where the pooled analytical uncertainty (2σ) was 1.9 m.y., but the 2σ standard deviation of the component ages was 38.2 m.y. In addition to wide dispersion, some aliquots produced old ages or ages that were clearly erroneous (e.g., >1 Ga) or fell into a more perplexing range of 200–350 Ma while distinctly separated from the range of other aliquots from the same sample. We used the pooled zircon (U-Th)/He ages from the southern Appalachians (Fig. 1D) as an upper limit for acceptable AHe ages due to

the considerable difference in the closure temperature of the two minerals (~160–200 °C for zircon versus ~50–80 °C for apatite [Reiners et al., 2004; Flowers et al., 2009, respectively]). Thus any aliquot with an AHe age of greater than 250 Ma was excluded from the pooled age calculation, and the number of total aliquots analyzed relative to those used in calculating the pooled age for each sample is indicated in Table 1.

Central Appalachians

Pooled ages from this region range widely between 70 and 185 Ma, with no direct indication of Cenozoic cooling related to significant exhumation from this region (Becker, 2001). Relief is low in this landscape and ages do not display any meaningful relationship with elevation. Ages tend to be younger on the western, footwall side of the Newark rift basin and oldest to the southeast, with all ages post-dating extensional deformation. These results are consistent with AFT ages from sedimentary units within the northern portion of the Newark basin that range from 129 to 196 Ma (Roden and Miller, 1991). Because of the difference in the closure temperatures between the two systems, long-term exhumation rate estimates are essentially equivalent for the sedimentary units filling the basin and the Proterozoic crystalline rocks that were deformed to accommodate it. This result is interesting both in the context of lithologic controls on long-term erosion rate and for the longevity of preexisting topography on the landscape and its role in influencing the modern landscape.

Southern Appalachians

Pooled AHe ages from this portion of the southern Appalachians are also relatively old, ranging from 70 to 171 Ma. For two samples analyzed for zircon (U-Th)/He, pooled ages are 212 and 252 Ma, compared to pooled AHe ages from the same samples of 90 and 87 Ma, respectively. These ages are generally consistent with available zircon and AFT data available for the Blue Ridge area of western North Carolina where zircon fission-track ages are ca. 280 Ma and unvarying with elevation and AFT ages range from 90 to 165 Ma and systematically increase with greater elevation (Naeser et al., 2004). Unlike the AFT data, our apatite pooled ages from the rugged topography of the Blue Ridge province show complex relationships with elevation and landscape position, such that neither is a universal predictor of the age observed. For the Mount Mitchell and Sylva transects, pooled ages are oldest at the highest elevations and then decrease toward the valleys, showing a change in slope of the age-

elevation relationship from slow exhumation to fast exhumation around 80–100 Ma that is similar to that observed for an exhumed PRZ (Fig. 2). However, the Hornbuckle transect, which steeply descends the opposite side of the ridge from the Sylva transect, shows no correlation between age and elevation (Fig. 1) with all pooled ages being quite old (ca. 150 Ma). Similarly, all three transects locally display a trend of younger to the southeast, older to the northwest, but this trend does not appear to be influenced by position relative to the Blue Ridge escarpment as was described by Spotila et al. (2004) for samples further to the north (Fig. 2). Given the complexity of the pooled ages and the wide intra-sample age dispersion we observed, these results motivated our detailed experiments described below.

ADDRESSING AGE DISPERSION

Similar to this study, others using AHe thermochronology in regions characterized by slow cooling have reported problems with age dispersion (e.g., Belton et al., 2004; Spotila et al., 2004; Green et al., 2006; Fitzgerald et al., 2006; Danišik et al., 2008), where different grains from the same sample produce a range of ages that far exceeds the analytical uncertainty of the measurements of parent and daughter isotopes. The sources of age dispersion in AHe thermochronology fall into three categories: (1) internal and external impurities, (2) assumptions of U, Th, and Sm homogeneity, and (3) grain-specific variations in helium diffusion kinetics. The first two categories add noise to the data set and interfere with the interpretation of the low-temperature thermal history the sample experienced. In contrast, the third category is an inherent aspect of the technique and adds resolution to the thermal history derived if the effect of kinetic differences can be isolated from the influence from the first two categories. Grain-specific kinetic differences are rooted in variations in grain size (Farley, 2000) and radiation damage (Shuster et al., 2006), and can result in a range of grain-specific closure temperatures that produce multiple data points to constrain the time-temperature history the sample experienced. Figure 3 shows the eU-age relationship for all 120 aliquots from the southern Appalachians that are components of the pooled ages presented. Two general patterns emerge from this data set, one displaying the expected positive correlation between age and increasing radiation damage (resulting from greater eU concentrations) for samples that have experienced slow cooling, the other showing ages ranging widely from less than 100 Ma to above 200 Ma with low concentrations of eU. The averaging inher-

ent in the analysis of multi-grain aliquots could distort the bulk relationship between age and radiation damage of several grains of different size and eU concentration. However, the single grains show the same patterns and suggest that the dispersion we observe in this data set is likely a combination of several different factors acting in concert. In order to try and isolate the effect of the “useful” dispersion from kinetic differences, we conducted several experiments aimed at mitigating the dispersion caused by impurities and assumptions of U, Th, and Sm homogeneity. For a more thorough discussion of possible sources of age dispersion in AHe thermochronology, the reader is directed to previous reviews by Farley (2002), Ehlers and Farley (2003), Fitzgerald et al. (2006), and a recent update to these by Flowers and Kelley (2011).

Constraining Internal and External Impurities

Because of the energetic decay of U and Th, He can be implanted into an apatite grain from neighboring U- and Th-bearing minerals or pore fluids, which in isolated cases has been shown to generate anomalously old ages in low-eU apatites (Spiegel et al., 2009). Given our observation of generally low-eU apatites with wide age dispersion, we dated additional single-grain aliquots of untreated and physically abraded apatite grains from NC-SY-2 (ridge top sample) and NC-SY-13 (valley bottom sample) in an attempt to constrain age dispersion sourced from external impurities by removing the portion of the grain that is subject to implantation. Grains were abraded with several milligrams of aluminum oxide abrasive media in an air abrasion cell similar to the design of Krogh (1982) and grain-size reduction was documented through digital imagery. Grains were abraded until more than 25 μm was removed from all sides of the grain to remove the entire portion of the grain that could be affected by helium ejection due to energetic decay or helium implantation from external sources. Abraded apatite grains were loaded individually in Nb micro-tubes and analyzed for He, U, Th, and Sm as per the untreated grains. Ages derived from abraded grains are not F_T corrected because of the removal of the portion of the grain that is subject to alpha particle ejection.

U- and Th-bearing mineral inclusions are often cited as a potential source for age dispersion (Farley, 2002; Ehlers and Farley, 2003; Fitzgerald et al., 2006; Vermeesch et al., 2007) because they implant all of their helium into the host grain, but are not dissolved using the standard nitric acid dissolution protocol, and therefore produce too-old ages because of the

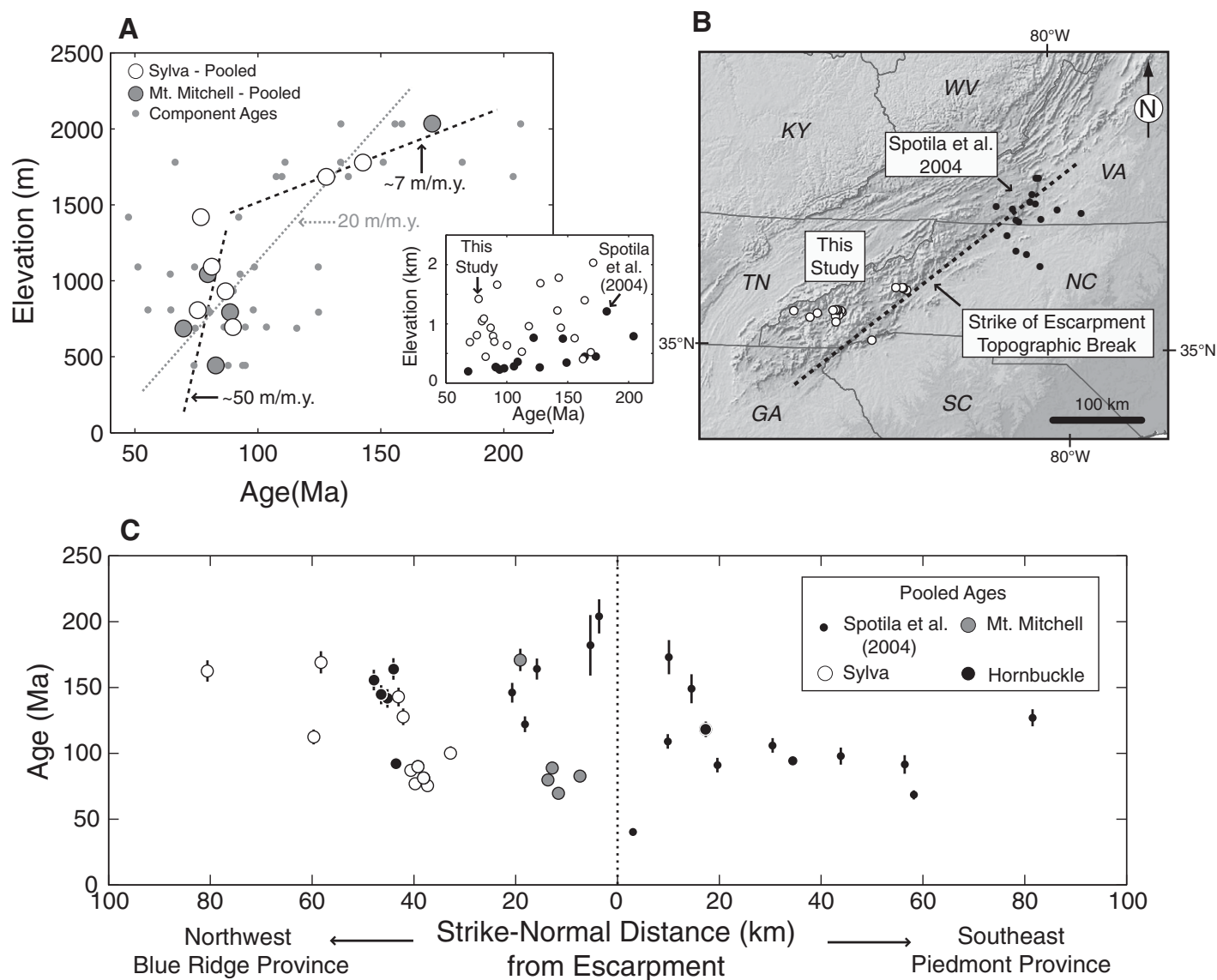


Figure 2. Results of pooled apatite (U-Th)/He (AHe) ages from the southern Appalachians and the data from Spotila et al. (2004) plotted against elevation and landscape position. (A) Inset plot of age-elevation relationship for all AHe samples from the southern Appalachians (open circles from this study, filled circles from Spotila et al. [2004]) and selected samples from the Sylva and Mount Mitchell transects (large circles) with their component ages showing the intra-sample dispersion (small gray circles) on the main plot. These plots collectively illustrate that potentially intriguing information about exhumation rate unsteadiness may be stored in the cooling history of these rocks; however, the regional data set suggests significant complexity. (B) Shaded-relief map of the southern Appalachian region showing the location of the samples relative to the strike of the escarpment topographic break, used in C. GA—Georgia, KY—Kentucky, NC—North Carolina, SC—South Carolina, TN—Tennessee, VA—Virginia, WV—West Virginia. (C) Plot of pooled age versus strike-normal distance from the escarpment topographic break (black dashed line in B) that separates the Piedmont from the Blue Ridge physiographic province. Error bars illustrate the 2σ analytical uncertainty of the pooled age, not the dispersion of the component ages. Of note is that locally our samples show a pattern of younger samples to the southeast and older ages to the northwest similar to that observed by Spotila et al. (2004); however, this trend shows no correlation with distance from the escarpment for our samples.

“parentless” helium. Due to the tendency of apatites from this region to contain both large (up to 25 μm) and small (1–5 μm) mineral inclusions, we selected 14 inclusion-bearing grains from NC-SY-13 of suitable morphology and analyzed half using the standard nitric

acid dissolution protocol and half with the more rigorous hot hydrofluoric acid (HF) dissolution protocol for digesting zircons (Reiners, 2005) in order to fully digest the grain and its inclusions. In addition, five inclusion-free grains that were representative of those used for untreated

and abraded aliquots were also digested using hot HF to test for the presence of impurities that could not be detected using optical grain selection techniques. For this experiment with inclusions, samples were loaded individually in Nb micro-tubes and He, U, Th, and Sm analyses

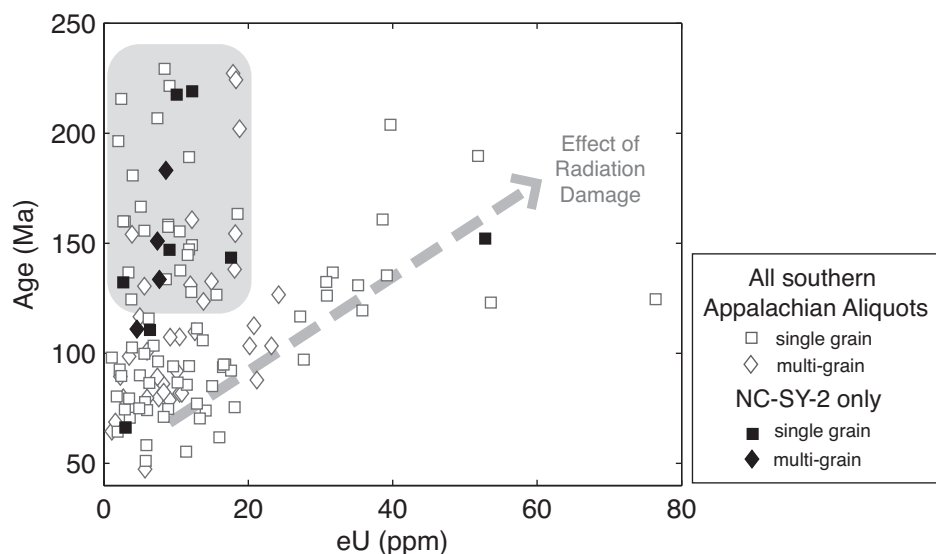


Figure 3. Relationship between radiation damage (inferred through effective uranium concentration [eU]) and apatite (U-Th)/He (AHe) age for the component aliquots that compose the southern Appalachian pooled ages with aliquots from one sample (NC-SY-2) highlighted in black. The gray dashed line illustrates the expected correlation between increasing eU and AHe age for samples that have experienced slow cooling. The gray shaded region indicates samples where eU is generally low and the observed age dispersion significantly exceeds what is attributable to grain-specific concentrations of radiation damage.

were all conducted at the Arizona Radiogenic Helium Dating Lab at the University of Arizona. For all apatites analyzed to address age dispersion, analytical uncertainty is calculated by propagating the uncertainty for each He, U, Th, Sm measurement with a 1% uncertainty on the F_T correction (where applied).

Results of Abrasion and Inclusion Experiments

Abrasion Results

Physically abraded grains from both samples displayed nearly the same wide range of ages as untreated aliquots (Fig. 4 and Table 2); however, abraded grains were observed to have a much wider range of eU concentrations than their untreated counterparts. For NC-SY-13, abraded grain ages ranged from 75 to 154 Ma with eU concentrations from 6 to 162 ppm compared to untreated single grain aliquots that ranged from 75.0 to 154.4 Ma and 5–28 ppm. Similarly, for NC-SY-2, abraded grain ages ranged from 47.6 to 185.0 Ma with eU concentrations of 6–140 ppm with untreated single grain aliquots ranging from 66.3 to 219.1 Ma and 3–53 ppm. Interestingly, for physically abraded grains, age was positively correlated with eU for both samples, a relationship that is predicted through the accumulation of radiation damage during slow cooling (Shuster et al., 2006; Flowers et al., 2009),

but was not observed in the untreated aliquots (Fig. 4) or the majority of aliquots that comprised the pooled ages (Fig. 3).

Inclusion Results

For sample NC-SY-13, neither the presence of inclusions nor the protocol used for dissolving apatite grains was found to impact the observed age dispersion (Fig. 4 and Table 3). Ages of inclusion-bearing grains that received the standard nitric acid dissolution protocol ranged from 80 to 130 Ma versus 98–132 Ma for grains digested with the more rigorous hot HF dissolution protocol. Five inclusion-free grains digested using hot HF that are representative of the grains selected for all non-inclusion-bearing analyses ranged from 76 to 111 Ma. Regardless of the presence of inclusions or the dissolution protocol, ages from this experiment displayed no correlation to grain size or eU (Fig. 4).

Sources of Age Dispersion

The analysis of physically abraded grains from NC-SY-2 and NC-SY-13 produced three key observations that explain the dispersion observed for untreated grains. First, if implanted He from external sources was the source of the age dispersion, then ages of abraded grains should be younger than untreated grains. This was not observed in either sample and suggests that

implanted helium from external sources was not a major factor contributing to the observed age dispersion (Fig. 4). Second, unlike the untreated grains that tended to have low eU concentrations, the physically abraded grains spanned a wide range of eU concentrations with maximum concentrations nearly threefold greater than the maximum of the untreated grains (Fig. 4). This can only occur if at least some grains from these samples are zoned, with U- and Th-rich cores relative to low-concentration rims, because if all grains had homogeneous distributions of U and Th there would be no difference between the eU distribution of abraded and untreated grains. This assertion is corroborated by maps of eU concentration for three grains from NC-SY-13 that show varying degrees of core enrichment ranging from strongly zoned with 16:1 core enrichment to patchy zonation patterns with nearly equivalent eU concentration from core to rim (Figure DR1 [see footnote 1]). Spotila et al. (2004) also reported observing core-enriched zonation patterns in the distribution of fission tracks for some, but not all, of their samples from metamorphic apatites from the Blue Ridge Mountains further to the north.

Core-enriched zonation impacts AHe age determinations in two ways. The first involves correcting for alpha ejection and the second is related to radiation damage and how the age is interpreted relative to the bulk eU concentration of the grain. Because zonation patterns of individual grains are not known prior to analysis following standard AHe protocols (e.g., Farley, 2002), it is assumed that eU is homogeneously distributed and ages are F_T corrected for alpha ejection. The low-eU rim of a core-enriched grain will lose less He to ejection than a grain of the same dimensions with a homogeneous distribution of eU, thus the F_T correction will overcorrect for the actual He loss the zoned grain experienced and cause the resulting F_T -corrected age to be too old (Farley et al., 1996); however, for all but the most severely zoned grains, modeling and observation suggests the impact of this effect is modest, typically less than 10% (Farley et al., 1996; Ault and Flowers, 2012).

More importantly for this study, core-enriched zonation will also impact the interpretation of ages in relation to radiation damage because eU is measured as a bulk concentration for a single grain, which may not accurately represent the effects of spatially varying radiation damage (and He retentivity). For a hypothetical core-enriched grain cooling through the PRZ at Appalachian rates, the low-volume high-eU core will accumulate radiation damage more quickly, and as a result retain He more effectively, than the high-volume low-eU rim that will dilute the bulk eU concentration of the

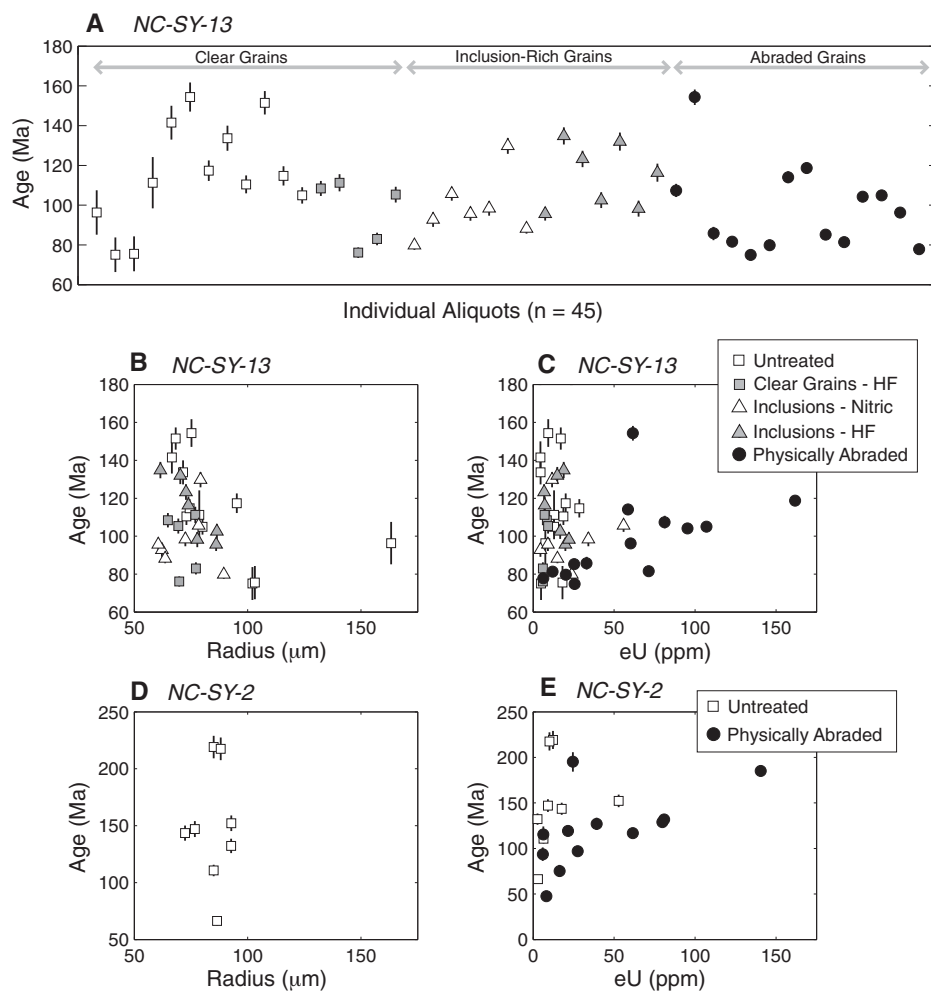


Figure 4. Results of inclusion and abrasion experiments. (A) Plot of ages derived from 45 single-grain aliquots with different treatments from sample NC-SY-13; each symbol represents a single aliquot. Squares represent clear grains appropriate for apatite (U-Th)/He analysis, triangles represent grains with inclusions, and circles represent physically abraded grains. Light gray shading of squares and triangles indicates aliquots that received the more rigorous hot hydrofluoric acid (HF) dissolution protocol to fully digest inclusions. (B and D) Plots showing the lack of correlation between grain size (radius of a sphere of equivalent alpha loss [F_T]) and age for all untreated aliquots for samples NC-SY-13 (B) and NC-SY-2 (D). (C and E) Plots showing the lack of correlation between effective uranium concentration (eU) and age for all unabraded aliquots and the strong positive correlation that is uncovered by physical abrasion for samples NC-SY-13 (C) and NC-SY-2 (E). For all plots, error bars represent the 2σ propagated uncertainty of He, U, Th, and Sm measurement and the F_T correction (where appropriate); where error bars are not visible, the analytical uncertainty is less than the size of the symbol.

grain. In this situation, the age of the hypothetical grain will appear too old for its relatively low bulk eU concentration when compared to that predicted by plausible cooling rates using the Radiation Damage Accumulation and Annealing Model (RDAAM) (Flowers et al., 2009). The severity of core enrichment will dictate the magnitude of offset between the observed age and that predicted by the RDAAM for the bulk

eU concentration. This effect helps explain the third key observation of our analysis of abraded grains, that untreated grains produced a wide range of ages with generally low eU concentrations and no correlation between eU and age. Whereas given the evidence of slow cooling for the region (Naeser et al., 2004), abraded grains from the same sample produce the expected result of a positive eU-age correlation over a

considerably wider range of eU concentrations (Fig. 4). Taken together, the observations from our experiments with inclusions and abrasion suggest that the age dispersion observed from untreated grains is a product of the combined effect of radiation damage and variable zonation of U, Th, and Sm. Although abrasion is a blunt means to decipher the nuances of grain-specific zonation patterns and their impact on eU-age correlations, our results suggest that to a first order, this technique is permissible.

RADIATION DAMAGE MODELING

Because the variation of He diffusion kinetics caused by radiation damage results in grain-specific closure temperatures (Shuster et al., 2006; Flowers et al., 2009), for samples that span a wide range of eU concentrations, ages will become more dispersed as the cooling rate slows down. The 20 m/m.y. long-term average exhumation rate observed for the southern Blue Ridge from AFT analysis (Naeser et al., 2004) makes a prediction of the age and magnitude of age dispersion that we should observe for the abraded data sets if both of our samples experienced this cooling history. We used the kinetic model HeFTy (Ketchum, 2005) and the RDAAM (Flowers et al., 2009) to forward model AHe ages for a wide range of eU concentrations. To isolate the effect of radiation damage we used the following parameters to control the forward model: a grain radius of 80 μm , a modern surface temperature of 10 $^{\circ}\text{C}$, and a monotonic cooling rate of 0.4 $^{\circ}\text{C}/\text{m.y.}$, which is representative of steady, slow exhumation at 20 m/m.y. assuming a stable geothermal gradient of 20 $^{\circ}\text{C}/\text{km}$. When compared to the abraded data sets (Fig. 5), we find that the ridge top sample (NC-SY-2) generally fits the prediction of slow and steady exhumation at a rate of 20 m/m.y., but the ages observed for the valley bottom sample (NC-SY-13) are both younger and less dispersed than those predicted by slow and steady exhumation.

Inverse Modeling Using Abraded Grains

To more fully explore the cooling history information stored in the eU-age relationship from our physically abraded data sets, we used an inverse modeling approach to find the thermal history that best fits the observations of each abraded data set, again using HeFTy and the RDAAM. Because these samples are complex and we analyzed nearly double the number of abraded grains for each than could be input into a single HeFTy model, we chose to model the eU-age trend of each sample by fitting an exponential regression through the observed

TABLE 2. (U-Th)/He DATA FOR UNTREATED AND PHYSICALLY ABRADED GRAINS FROM SAMPLES NC-SY-2 AND NC-SY-13

Sample	Radius* (μm)	^4He (mol)	U (mol)	Th (mol)	Sm (mol)	eU† (ppm)	$F_T^\S$	Raw age (Ma)	Corrected age (Ma)	$\pm 2\sigma^\#$ (Ma)	Th/U
Sample SY-2—ridge top											
<i>Untreated</i>											
NC-SY-2AB (2)	86.5	1.50E-14	1.97E-13	4.63E-14	9.84E-14	3.0	0.84	55.58	66.33	3.85	0.23
SY2-1	85.0	4.31E-14	3.40E-13	7.66E-14	8.82E-13	6.4	0.84	92.71	110.67	5.10	7.90
SY2-2	92.7	2.09E-14	1.27E-13	6.60E-14	1.69E-12	2.7	0.85	112.37	132.23	6.29	6.07
SY2-3	92.8	4.89E-13	2.76E-12	6.27E-13	6.47E-12	52.8	0.85	129.50	152.17	6.89	5.64
SY2-4	85.0	1.21E-13	4.76E-13	1.12E-13	3.08E-12	12.25	0.84	183.46	219.09	9.91	3.94
SY2-5	76.7	6.65E-14	4.14E-13	3.91E-14	1.73E-12	9.1	0.82	120.67	147.07	6.98	6.22
SY2-6	72.4	8.32E-14	5.30E-13	8.49E-14	1.89E-12	17.6	0.81	116.14	143.52	6.65	6.38
SY2-8	88.1	1.86E-13	7.40E-13	1.48E-13	1.98E-12	10.1	0.84	183.41	217.52	9.97	3.98
<i>Physically abraded**</i>											
sy2-pa01	NA	2.90E-15	2.61E-14	1.53E-14	2.27E-13	16.25	NA	75.31	75.31	6.62	9.01
sy2-pa02	NA	1.91E-14	1.42E-13	4.33E-14	7.14E-13	27.6	NA	96.86	96.86	5.52	7.43
sy2-pa03	NA	2.42E-15	3.62E-14	1.28E-14	4.46E-13	8.1	NA	47.55	47.55	3.92	14.97
sy2-pa04	NA	3.49E-14	2.05E-13	2.93E-14	9.23E-13	39.2	NA	127.05	127.05	6.68	5.86
sy2-pa05	NA	4.36E-14	1.60E-13	4.73E-14	3.73E-13	24.5	NA	195.03	195.03	10.67	3.67
sy2-pa06	NA	1.32E-13	8.40E-13	5.87E-14	2.21E-12	21.65	NA	119.34	119.34	3.81	6.35
sy2-pa07	NA	7.51E-15	4.82E-14	7.67E-15	5.09E-13	6.25	NA	115.19	115.19	9.01	6.41
sy2-pa08	NA	3.51E-13	1.41E-12	2.05E-13	2.22E-12	140.45	NA	184.96	184.96	4.57	4.01
sy2-pa09	NA	1.75E-13	9.91E-13	1.38E-13	2.26E-12	80.95	NA	131.78	131.78	3.86	5.66
sy2-pa10	NA	5.55E-14	3.56E-13	4.41E-14	1.22E-12	61.6	NA	116.78	116.78	5.16	6.41
sy2-pa11	NA	8.75E-14	4.99E-13	9.77E-14	1.87E-12	79.75	NA	128.89	128.89	4.97	5.71
sy2-pa12	NA	6.18E-15	4.95E-14	5.80E-15	1.11E-13	5.95	NA	93.72	93.72	7.39	8.02
Sample SY-13—valley bottom											
<i>Untreated</i>											
NC SY 13 400(1)	163.3	4.02E-13	3.43E-12	3.23E-13	NA	7.5	0.92	88.22	96.31	11.17	0.09
NC-SY-13 2	102.1	5.36E-14	6.06E-13	1.11E-13	7.76E-13	4.9	0.87	64.90	75.03	8.70	0.18
NC-SY-13 3	103.2	1.18E-13	1.27E-12	4.97E-13	1.17E-12	18.1	0.87	65.31	75.51	8.76	0.39
NC-SY-13 1	78.7	8.89E-14	6.95E-13	1.85E-13	9.92E-13	12.9	0.83	91.79	111.26	12.91	0.27
SY13-1	66.6	1.60E-14	8.69E-14	9.94E-14	1.69E-12	4.5	0.79	111.27	141.51	8.50	5.42
SY13-2	75.2	5.49E-14	3.15E-13	8.11E-14	2.17E-12	9.3	0.82	125.94	154.38	7.31	5.74
SY13-3	95.2	1.96E-13	1.30E-12	8.65E-13	1.40E-11	20.1	0.85	100.11	117.38	5.16	6.64
SY13-4	71.5	1.96E-14	1.18E-13	9.36E-14	1.98E-12	4.6	0.80	107.32	133.67	6.33	6.01
SY13-5	73.0	7.19E-14	4.47E-13	7.64E-13	5.42E-12	18.7	0.80	88.48	110.42	4.50	6.23
SY13-6	68.3	7.18E-14	2.71E-13	8.26E-13	6.68E-12	17.1	0.78	118.59	151.50	5.86	3.78
SY13-7	74.4	1.21E-13	7.83E-13	9.75E-13	6.69E-12	28.5	0.81	92.61	114.72	4.84	6.45
SY13-8	80.1	6.08E-14	3.21E-13	9.69E-13	7.26E-12	12.9	0.81	85.50	104.92	4.13	5.28
<i>Physically abraded</i>											
PA-SY13-1	NA	5.78E-14	3.17E-13	4.18E-13	2.76E-12	81.3	NA	107.43	107.43	3.30	5.49
PA-SY13-2	NA	8.94E-14	2.04E-13	1.04E-12	5.20E-12	61.55	NA	154.28	154.28	3.91	2.28
PA-SY13-3	NA	2.65E-14	2.34E-13	1.66E-14	1.50E-12	33	NA	85.75	85.75	3.35	8.84
PA-SY13-4	NA	2.42E-14	1.78E-13	2.23E-13	4.04E-13	71.3	NA	81.64	81.64	2.53	7.35
PA-SY13-5	NA	9.64E-15	7.47E-14	1.06E-13	7.42E-13	25.45	NA	74.89	74.89	2.62	7.75
PA-SY13-6	NA	1.12E-14	9.31E-14	5.89E-14	2.91E-12	20.3	NA	79.77	79.77	2.80	8.30
PA-SY13-7	NA	5.12E-14	1.73E-13	7.46E-13	3.45E-12	58.7	NA	114.08	114.08	2.97	3.37
PA-SY13-8	NA	2.31E-13	1.11E-12	1.69E-12	3.26E-12	161.85	NA	118.69	118.69	3.46	4.81
PA-SY13-9	NA	2.07E-14	1.33E-13	2.36E-13	1.26E-12	25.4	NA	85.24	85.24	2.60	6.41
PA-SY13-10	NA	3.21E-15	2.15E-14	3.62E-14	8.85E-13	12.05	NA	81.34	81.34	4.48	6.71
PA-SY13-11	NA	9.07E-14	6.16E-13	2.29E-13	5.01E-12	95.25	NA	104.15	104.15	3.52	6.80
PA-SY13-12	NA	8.48E-14	5.61E-13	2.58E-13	4.84E-12	106.9	NA	105.02	105.02	3.69	6.61
PA-SY13-13	NA	3.21E-14	2.37E-13	8.56E-14	1.52E-12	60.15	NA	96.30	96.30	3.32	7.38
PA-SY13-14	NA	4.09E-15	3.72E-14	1.24E-14	8.60E-13	6.15	NA	77.83	77.83	4.09	9.09

Note: NA—not applied.

*Radius— F_T -equivalent spherical radius of the grain (Ketcham et al., 2011); not applicable to abraded grains.

†eU—effective uranium = $[U] + 0.235[Th]$.

‡ F_T —alpha-loss correction factor from Monte Carlo simulation; not applicable to abraded grains.

$\pm 2\sigma$ —analytical uncertainty from propagated error of He, U, Th, and Sm analyses along with F_T and blank measurements.

**U, Th, Sm analyzed at Caltech; all other Appalachian aliquots analyzed at University of Arizona.

eU-age data. Our rationale for this decision stems largely from the fact that although abrasion improved the interpretability of our data, it is likely that for some grains the problem of eU dilution or enrichment due to zonation persists after abrasion. Because we did not measure the zonation pattern of each grain prior to analysis, and therefore do not know how to correct individual data points, we assume eU homogeneity for the abraded grains and use

the averaging of the whole data set to smooth over individual outliers as is typical for standard AHe analysis (e.g., Farley, 2002). We chose to use an exponential regression because the relationship between the concentration of radiation damage and age is nonlinear and the exponential fit afforded the best compromise between simplicity and accurately fitting the results of RDAAM-predicted eU-age relationships for a range of slow cooling rates (see Figure DR2

[see footnote 1]). To populate the model with data points that represent the eU-age trend, we used discrete eU-age points along the regression and the 68.3% C.I. (confidence interval) bounds (representative of 1σ) of the regression for the age uncertainty as input for the inverse models of each sample (Fig. 4). The location of points along the regression were chosen to capture both the range of eU concentrations observed and the eU concentrations where the observed data were

TABLE 3. (U-Th)/He DATA FOR THE INCLUSION EXPERIMENT USING SINGLE GRAINS FROM SAMPLE NC-SY-13

Sample	Radius* (μm)	^4He (mol)	U (mol)	Th (mol)	Sm (mol)	eU† (ppm)	F_T ‡	Raw age (Ma)	Corrected age (Ma)	$\pm 2\sigma^\S$ (Ma)	Th/U
Nitric acid dissolution—apatite protocol											
<i>Inclusion-bearing grains</i>											
SY13-Li7	89.5	1.57E-13	1.41E-12	1.69E-12	1.28E-12	23.9	0.837	66.9	79.9	2.4	1.20
SY13-Li5	62.2	1.12E-14	9.54E-14	1.05E-13	1.91E-13	4.5	0.775	71.9	92.8	3.7	1.10
SY13-Li3	78.4	3.52E-13	2.69E-12	1.84E-12	1.15E-12	55.8	0.821	86.8	105.7	3.4	0.69
SY13-Li1	60.6	2.24E-14	2.03E-13	1.20E-13	5.71E-13	9.1	0.771	73.8	95.7	3.5	0.59
SY13-Si5	72.5	1.67E-13	1.56E-12	1.72E-13	8.93E-13	34.1	0.814	80.1	98.4	3.7	0.11
SY13-Si3	79.2	8.67E-14	4.92E-13	5.72E-13	9.93E-13	11.7	0.817	106.1	129.8	4.0	1.16
SY13-Si1	63.6	3.24E-14	1.68E-13	8.85E-13	6.58E-13	15.0	0.758	66.9	88.2	2.5	5.28
Hot hydrofluoric acid dissolution—zircon protocol											
<i>Inclusion-bearing grains</i>											
SY13-Li8	86.1	1.57E-13	1.47E-12	1.08E-13	—	19.9	0.842	80.5	95.6	3.4	0.07
SY13-Li6	61.5	6.02E-14	2.94E-13	6.83E-13	—	18.9	0.762	102.7	134.8	4.3	2.33
SY13-Li4	72.8	3.84E-14	2.09E-13	3.90E-13	—	6.8	0.804	99.1	123.3	4.1	1.87
SY13-Li2	86.4	1.40E-13	1.21E-12	2.08E-13	—	16.7	0.839	86.0	102.5	4.0	0.17
SY13-Si6	70.3	7.39E-14	3.53E-13	8.29E-13	—	14.9	0.792	104.6	132.0	4.5	2.35
SY13-Si4	77.8	1.14E-13	9.92E-13	4.36E-13	—	22.1	0.817	80.2	98.2	4.0	0.44
SY13-Si2	73.9	3.68E-14	2.69E-13	1.37E-13	—	7.1	0.807	94.0	116.4	4.6	0.51
<i>Clear grains</i>											
SY13-N5	64.8	2.93E-14	2.14E-13	2.22E-13	—	8.5	0.784	85.0	108.4	3.8	1.04
SY13-N4	76.9	3.95E-14	3.21E-13	5.69E-14	—	7.0	0.816	90.8	111.2	4.3	0.18
SY13-N3	69.8	1.81E-14	2.11E-13	7.33E-14	—	6.0	0.801	61.0	76.1	2.7	0.35
SY13-N2	77.2	2.63E-14	2.80E-13	7.60E-14	—	6.0	0.818	67.9	83.0	3.2	0.27
SY13-N1	69.4	3.66E-14	3.18E-13	7.43E-14	—	9.2	0.799	84.1	105.3	4.0	0.23

Note: U, Th, Sm analyzed at Caltech; all other Appalachian aliquots analyzed at University of Arizona.

*Radius— F_T -equivalent spherical radius of the grain (Ketcham et al., 2011).

†eU—effective uranium = $[U] + 0.235[Th]$.

‡ F_T —alpha-loss correction factor from Monte Carlo simulation.

§ $\pm 2\sigma$ —analytical uncertainty from propagated error of He, U, Th, and Sm analyses along with F_T and blank measurements.

most densely clustered. While these simplifying choices fall short of a true representation of the complexity of the individual grains the eU-age trends are trying to model, we feel that they are the most defensible and the ramifications of these choices are small with respect to the differences observed between the two samples.

We applied no constraints to random t - T paths generated by HeFTy other than their starting and ending positions. The starting constraint required paths to begin between 140 and 170 °C at 230–250 Ma, which was based on regional zircon (U-Th)/He ages acquired as part of this study, and paths were required to end at the present time at 10 °C, which was chosen as an average temperature for the region during the late Cenozoic. For NC-SY-13 (valley bottom sample) we generated 100,000 random t - T paths, with the model finding 828 “acceptable” and 288 “good” statistically significant fits to the input data from the exponential regression. For NC-SY-2 (ridge top sample), the greater uncertainty of the exponential regression resulted in the model finding more statistically significant fits in fewer iterations. To fairly compare the results between the samples, we chose to run the inversion for NC-SY-2 until 300 “good” fits were found to match the results of NC-SY-13; this required ~18,000 iterations and generated 752 “acceptable” fits in the process (Fig. 5). In HeFTy, the statistical significance of a path is determined by applying a goodness-of-fit

test to the predicted age for each of the seven input eU-age pairs and is described in detail in Ketcham (2005). We direct the interested reader to the Data Repository (specifically Fig. DR3 [see footnote 1]) for further discussion of the specific model conditions used here.

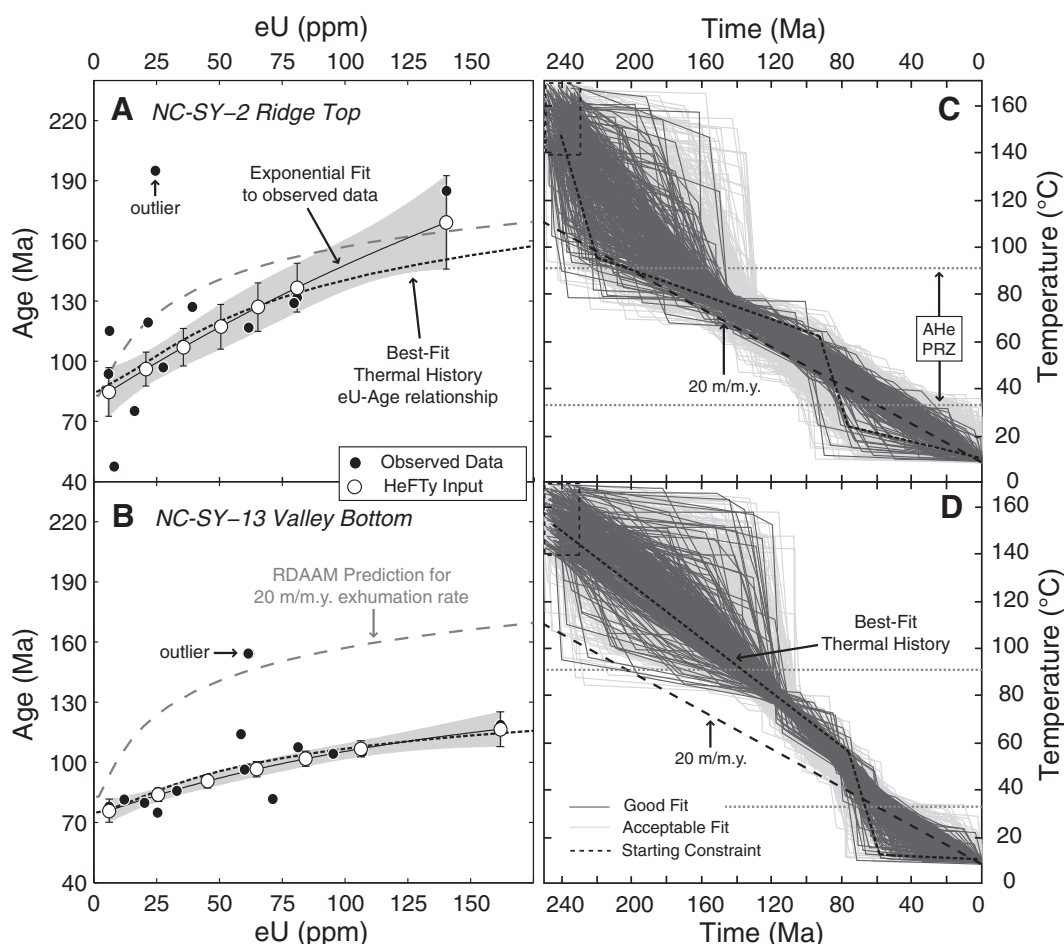
Inverse Model Results

The results of inverse modeling of the eU-age relationship from abraded grains illustrate the enhanced resolution of the thermal history that is stored in the age dispersion resulting from radiation damage. Figure 5 compares the results of the inverse models to the thermal history predicted by the regional long-term average exhumation rate of 20 m/m.y., and Figure 6 compares the “good” t - T paths from each sample. For this discussion we use the term PRZ to refer to the generalized partial retention zone for AHe thermochronometry spanning ~35–90 °C and not grain-specific PRZs resulting from differences in the concentration of radiation damage. We show the single best-fit thermal history result for both samples on Figure 5 as a means to assess the fairly good ability of the inverse model to fit the input eU-age pairs from the exponential regressions. It is provocative that the best fits for both samples suggest unsteady, pulsed cooling histories; however, because these are model fits to the eU-age trend of each sample, we choose to concentrate on the trends of

the good fits revealed by the inverse model and not a specific path.

For NC-SY-2, the inverse model suggests relatively rapid cooling from the zircon (U-Th)/He window to the upper part of the apatite PRZ by ca. 170 Ma and then steady slow cooling in line with the 20 m/m.y. exhumation rate. The coalescing of the “good” fit t - T paths is constrained by the need for quick cooling to fit an age of 170 Ma with an eU concentration of 140 ppm, but then slow cooling through the apatite PRZ to build the wide range of the eU-age relationship observed. For NC-SY-13, the model does not constrain the high-temperature cooling history prior to 120 Ma; however, at that point the statistically significant t - T paths become narrowly restricted and suggest more rapid cooling at an exhumation rate of 35 m/m.y., nearly double that predicted by the 20 m/m.y. long-term average exhumation rate. The tight clustering of “good” fits from 120 to 80 Ma is representative of the portion of the thermal history that is constrained by the input eU-age data from the exponential regression. For both models, below ~45 °C the RDAAM has reached or exceeded its limit to constrain the very low-temperature thermal history, which is manifest in the fanning out of the good fits below these thresholds. It is important to note that our assumption of a stable geothermal gradient of 20 °C/km, from which we infer exhumation rates, is corroborated by our inverse model results. At 120 Ma the ridge

Figure 5. Cooling histories derived from inverse modeling of physically abraded grains from samples NC-SY-2 and NC-SY-13 using the HeFTy kinetic model and the Radiation Damage Accumulation and Annealing Model (RDAAM). (See “Radiation Damage Modeling” section.) (A and B) Plots showing the observed effective uranium concentration (eU)–age data for the physically abraded grains from both samples (black circles), and exponential regressions (thin black lines) and 68.3% confidence intervals (light gray shading) fit to the observed data. The open circles and error bars lying along the exponential regressions indicate the eU–age data input into the HeFTy inverse models. The eU–age relationship predicted by the RDAAM for an exhumation rate of 20 m/m.y. (assuming a geothermal gradient of 20 °C/km) is shown by the dashed lines. (C and D) Results from inverse modeling showing time–temperature (*t*–*T*) paths yielding acceptable fits (light gray) and good fits (dark gray) to the input eU–age data points from the exponential regressions. The dashed box indicates the starting constraint for the *t*–*T* paths and a 20 m/m.y. exhumation rate is indicated by the dashed black line. The best-fit *t*–*T* path for each model (tight dashed line) is indicated with the results and plotted on the eU–age input plots. The partial retention zone (PRZ) is indicated to illustrate the temperature range where He diffusion transitions from fully open- to fully closed-system behavior and indicates where variations in eU between individual aliquots can influence the shape of the *t*–*T* paths that produce acceptable and good fits for each sample.



top sample (NC-SY-2) is modeled to be in the middle of the PRZ at ~60 °C, whereas the valley bottom sample (NC-SY-13) is just entering the PRZ at ~85 °C, a difference of 25 °C for samples that are vertically separated by 1.2 km. Taken together, these results illustrate that while the long-term average rate of exhumation has been slow, there is evidence that erosion of this portion of the Blue Ridge Mountains has not been uniformly steady.

DISCUSSION—INTERPRETING APPALACHIAN LANDSCAPE EVOLUTION

From Pooled AHe Ages

Despite the considerable dispersion we observed, the pooled ages represent a coarse but useful estimate for time of cooling through low

temperatures, and our ages are comparable to other results obtained from AHe and AFT dating in the Appalachians. However, we argue that the specifics of the pace and variability of the cooling history as they relate to the geomorphic evolution of the modern landscape and the observed unsteadiness of offshore sediment deposition (Pazzaglia and Brandon, 1996) are beyond the sensitivity of this data set. Most significantly, based on these pooled ages (and the data from Spotila et al., 2004), at any locality we studied in the central and southern Appalachians there is no evidence for significant Cenozoic erosionally induced cooling sufficient to be recorded as a Cenozoic cooling age (e.g., cooling of tens of degrees, equivalent to kilometer-scale exhumation as a result of erosional unroofing). This finding places an upper limit on the amount of material that can be sourced from the Appalachian landscape in connection to the large pulse

of sediment deposited offshore during the Miocene (Pazzaglia and Brandon, 1996), suggesting that any denudation related to this depositional event was regional in scale.

The small and complex data set from the central Appalachians is a good example of the lack of sensitivity of the pooled ages and raises more questions than it answers. Broadly speaking the AFT ages from within the Newark basin (Roden and Miller, 1991) and our pooled ages from the Paleozoic and Precambrian crystalline rocks surrounding it record a similar slow cooling history suggestive of a long-term exhumation rate of ~20 m/m.y. There is a trend toward older ages to the southeast near the coastal plain and younger ages to the northwest in the hills of the Reading Prong; however, on both sides of this trend there are significant contrasts in age between neighboring samples (Fig. 1). Possible explanations for the pattern of the pooled ages could be

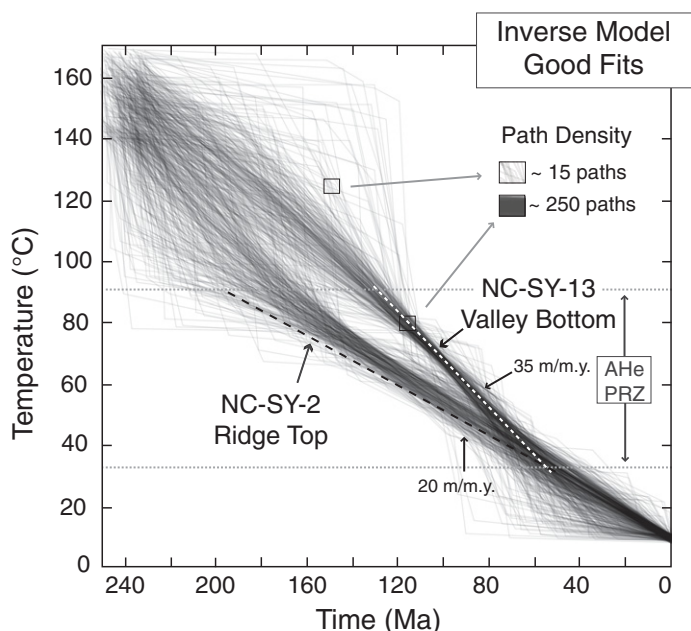


Figure 6. Comparison of the results of inverse modeling for samples NC-SY-2 and NC-SY-13 showing only the time-temperature (t - T) paths that produced statistically good fits to the input data from the exponential regressions. The paths are displayed with 90% transparent lines, thus the darker color indicates where the random t - T paths overlap. The path density examples show the number of paths that pass through an ~ 5 m.y. by 5 °C window to produce the color saturation observed. The dark saturation within the partial retention zone (PRZ) for both samples illustrate how the good fits follow dominantly linear and narrowly restricted cooling paths (approximated by the dashed lines) that suggest that the different positions in the landscape represented by the two samples experienced different erosion rates. The ~ 20 °C offset between the samples prior to 120 Ma corroborates our assumption of the assumed geothermal gradient of 20 °C/km because the samples are vertically offset by 1.2 km. AHe—apatite (U-Th)/He.

related to the progressive westward migration of the drainage divide after rifting and filling of the Newark basin, greater exhumation of material from the footwall side of the basin-forming normal fault, or dispersion caused by one or more of the sources seen in the samples from the southern Appalachians and therefore unrelated to the geomorphic history of the region. The low resolution of the sampling and the averaging of long-term erosion rate estimates derived from individual points along a cooling history preclude us from drawing meaningful conclusions about the processes controlling landscape evolution in this region.

The pooled age-elevation data in the southern Appalachians also do not provide evidence for Cenozoic cooling, nor are they particularly informative about the nature of the cooling history. In the Blue Ridge Mountains we find older ages at high elevations and also to the far west of

our study area, which generally agrees with the patterns from AFT (Naeser et al., 2001, 2004) and AHe (Spotila et al., 2004), but our attempts to derive more detail using age-elevation relationships uncovered strong contrasts in cooling ages over very short distances between the Sylva and Hornbuckle transects from Waterrock Knob (Figs. 1 and 2). Here we used a relatively dense sampling strategy to combat age dispersion arising from problems associated with the warping of shallow isotherms and transient topography; however, we uncovered a complex data set reflective of the influence of grain-specific characteristics, which we found had a strong impact on our measured ages. We feel that these two suites of samples are emblematic of the reality of using the standard protocols for bulk (U-Th)/He thermochronology analysis in the Appalachians specifically, and slowly eroding landscapes in general.

Simple thermal models run using Pecube (Braun, 2003) and rules of thumb (e.g., Reiners and Brandon, 2006) suggest that topography having the wavelength observed in the southern Appalachians will most likely have an isotherm structure that is sub-parallel to it, meaning that age-elevation data from surface samples will not be able to sample the true isotherm-normal age-elevation relationship. The only exception to this would be if the entire landscape were carved recently such that the paleo-isotherm structure was not in equilibrium with the current topography. Whereas there is evidence for localized disequilibrium in the modern Appalachian landscape (e.g., Ward et al., 2005; Prince et al., 2011; Gallen et al., 2013), the magnitude of incision in these locations falls well short of the 1–1.5-km-scale relief in the modern Blue Ridge Mountains. Furthermore, incision of this magnitude would require recent erosion at rates inconsistent with cosmogenic measurements (Pavich et al., 1985; Matmon et al., 2003; Hancock and Kirwan, 2007; Portenga and Bierman, 2011). The only slim signature in the age-elevation data takes the form of the few old ages seen at highest elevations; these could be interpreted as representative of an older, very slow-cooling regime, with the younger low-elevation ages, however dispersed, representing a period of accelerated cooling that exhumed the fringe of a fossil partial-retention zone. Given the low number of old ages and the overall dispersion, it does not seem advisable to press this line of reasoning.

A curious result from the combined data set of our pooled ages and Spotila et al. (2004) is the common occurrence of a minimum age of ca. 70 Ma at different elevations throughout the central and southern Appalachians. While there are a number of potential sources of dispersion that make ages older, it is difficult to systematically make ages younger (save for a pervasive rim-enriched zonation pattern which was not observed by either study), making these young ages difficult to ignore. A possible interpretation of these young ages is that a widespread exhumation event around 70 Ma rapidly cooled a significant amount of material, such that the widely dispersed ages we observe are from samples that sat in the PRZ for a long time and the young ages are from material that resided below the PRZ and then rapidly exhumed through it to set the minimum age. By contrast, linear cooling at the Appalachian background erosion rate of 20 m/m.y. in conjunction with radiation damage predicts a spectrum of ages that is similar to that observed and where the minimum ages are ca. 70 Ma for grains with the lowest eU concentrations (Fig. 5). This juxtaposition highlights limitations of the pooled age data set where only

the age is considered without constraining the possible sources of age dispersion, both useful and otherwise. The abraded data sets show the enhanced resolution of the thermal history that is stored within the age dispersion and gives no evidence for significant exhumation around 70 Ma (Fig. 5). As a result we suggest caution when interpreting our pooled ages and encourage future studies in slowly eroding regions to characterize the sources of age dispersion within their data sets thoroughly.

From Radiation Damage Modeling

The major contribution of our work in the Appalachian landscape has been to illustrate that although the long-term average erosion rate has been slow, the spatial variability of erosion rates through time suggests that landscape evolution has not been uniformly steady. Our models suggest that while the ridge top of Waterrock Knob could best be described as steadily eroding at 20 m/m.y. since 170 Ma, the modern river valleys draining this high terrain experienced a protracted period of erosion at nearly twice that rate starting at or before 120 Ma. The differential erosion rates between the summit ridges and valley bottoms persist until ca. 60 Ma when the thermal histories converge at ~40 °C and the rocks that are now at the surface were at a depth of 1–1.5 km in the crust. Despite the fact that the rates are slow, differential erosion of the landscape as suggested by our inverse models argues for nearly 1 km of relief generation during the Cretaceous, a time with no obvious tectonic process acting on the landscape in the Blue Ridge Mountains. We are not suggesting that over this 60 m.y. period valley bottoms were eroding steadily at 15 m/m.y. faster than the summit ridges and that the growth of relief was linear with respect to time. Rather we suspect the erosion rates we model reflect the averaging of impulsive waves of valley incision, which could be related to the fluvial response to changes in climate, drainage reorganization, and divide migration, or perhaps indicative of epeirogenic surface uplift and propagation of knickpoints related to dynamic mantle processes (Moucha et al., 2008). Whatever the cause, the processes that sustained the differential exhumation rates in this region had to be long-lived to produce the thermal histories suggested by our inverse models.

Returning to the question of how the modern topography reflects the post-orogenic evolution of the Appalachian landscape, using a novel method we have made progress on a longstanding conundrum about measured rates versus geologically inferred processes. The similarity of long-term average erosion rates suggests

that roughly the same magnitude of material has been exhumed from the flat terrain of the Piedmont province and the rugged mountains of the southern Appalachians. However, lost within these long-term averages is the question of when and how these very different landscapes were generated. Our work in the Blue Ridge Mountains illustrates that rugged modern topography need not be an erosional remnant of a once-greater orogenic landscape. Rather, it appears that significant relief can be generated in “old” landscapes in the absence of contractional or extensional tectonic regimes. With this in mind the longevity of topography on the landscape remains an open question, but to assume that any topography must be genetically linked to prior periods of major tectonic activity is also problematic. Recent work by Galen et al. (2013) using geomorphic characteristics of drainage basins suggests that the Blue Ridge region of western North Carolina has experienced a more recent period of relief generation during the Neogene, the timing of which they suggest favors epeirogenic uplift as the driver rather than late Cenozoic climate change. Taken together, the emerging picture is one where the rugged modern topography of the southern Blue Ridge Mountains is the product of multiple pulses of rejuvenation, the timing and nature of which we are just beginning to understand. In both cases, greater spatial resolution of the timing and magnitude of exhumation and incision is necessary to understand the process or processes that are responsible.

Finally, the recognition of multiple phases of topographic rejuvenation within the Appalachian landscape potentially help to explain the unsteady rate of sedimentation observed in offshore basins along the Atlantic margin (Poag and Sevon, 1989). Modeling of the volume of material necessary to generate the pulses of rapid sediment deposition has led to the conclusion that epeirogenic uplift and erosion of a large portion or portions of the source region was required (Pazzaglia and Brandon, 1996). Previously this uplift and erosion has been difficult to explain in the context of slow and steady long-term and short-term erosion rates found throughout the Appalachian region and supported by our pooled ages. However, the period of relief generation we infer for the Blue Ridge Mountains from our inverse models spans several pulses of high sediment flux in the Cretaceous. Our data set is insensitive to the large Miocene pulse because the magnitude of exhumation from ca. 60 Ma to present has been too small to leave a thermal signature that could be detected using (U-Th)/He thermochronology, but the results of Galen et al. (2013) suggest a similar coupling in time of relief generation and

high sediment deposition rates. To be clear, we are not implying that the large amount of sediment deposited during these repeated offshore pulses of rapid sedimentation was derived exclusively from the Blue Ridge Mountains of North Carolina. In fact, it is likely this area contributed little if any sediment to the basins in the Atlantic because most of the region currently drains to the Gulf of Mexico and presumably has been draining to the west since prior to rifting in the Triassic. Rather, we suggest that the emerging history of unsteady exhumation of the Blue Ridge Mountains is evidence of the repeated rejuvenation of a much larger area which has been proposed to explain the offshore sedimentary record (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996).

CONCLUSIONS

We analyzed over 250 apatite (U-Th)/He cooling ages determined on bedrock samples from the central and southern Appalachians of eastern North America collected in an attempt to quantify the spatial and temporal variability of exhumation of the Appalachian landscape. We found considerable age dispersion that was uncorrelated to known causes, which was emblematic of previous studies using apatite (U-Th)/He thermochronology in regions with slow long-term erosion rates (Belton et al., 2004; Spotila et al., 2004; Green et al., 2006; Fitzgerald et al., 2006; Danišák et al., 2008). We addressed age dispersion for all samples using pooled ages (Vermeesch, 2008) as a means of comparing samples composed of sometimes widely dispersed single-grain aliquots. Age-elevation and spatial relations using these pooled ages generally reflect slow and steady exhumation, but the specifics of how and when the modern landscape gained its character is beyond the sensitivity of this data set.

Through experiments with grain abrasion and more rigorous dissolution protocols, we find that the dispersion we observed is rooted in variable and sometimes severe zonation of U and Th, which affects both the correction for alpha particle ejection (the F_T correction) and the relationship between radiation damage (eU) and cooling age. Unlike the untreated grains, ages derived from abraded grains were strongly correlated with eU, as would be expected for slowly eroding regions given that the closure temperature of an individual grain is an evolving function of the accumulation of radiation damage and the cooling rate (Shuster et al., 2006; Flowers et al., 2009). Exploiting the eU-age relationship of the abraded grains provides much higher resolution of the low-temperature cooling history than the pooled ages. Inverse

modeling of two samples from the southern Blue Ridge Mountains reveals a period of nearly 60 m.y. during the late Cretaceous when present-day valley floors were exhuming at almost twice the rate of the modern ridge tops. Despite the fact that the rates are slow, ~20 m/m.y. for the ridge tops compared to ~35 m/m.y. for the valley floors, differential exhumation over this period resulted in the generation of relief that is comparable in magnitude to that observed in the modern landscape.

The recognition of significant post-orogenic rejuvenation of the landscape is a step toward unraveling the enigma of Appalachian topography. Along-strike variability of relief and topographic correlation to bedrock geology and tectonic history are easier to explain given that the diversity of modern topography need not be a direct erosional remnant of a common orogenic past. The pulses of comparatively rapid sediment deposition offshore during the Cretaceous (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996) are contemporaneous with relief generation in the southern Appalachians, and there is new evidence linking the timing of renewed incision in the region with the anomalous pulse of sediment deposited in the Miocene (Galen et al., 2013). The coupling of onshore and offshore processes suggests that unsteadiness in the sedimentary record is related to unsteadiness in the landscape, which was hypothesized previously (Poag and Sevon, 1989; Pazzaglia and Brandon, 1996), but not detectable with existing long-term and short-term erosion rate estimates from the Appalachian landscape. Finally, it is these paradoxes that have made the Appalachians difficult to explain in the context of an old and uniformly decaying landscape, but it is also from them that we stand to learn the most about what drives the continued evolution of this and other decay-phase landscapes.

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