

## EROSIONAL AND DEPOSITIONAL HISTORY OF THE ATLANTIC PASSIVE MARGIN AS RECORDED IN DETRITAL ZIRCON FISSION-TRACK AGES AND LITHIC DETRITUS IN ATLANTIC COASTAL PLAIN SEDIMENTS

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**ABSTRACT.** Comparison of fission-track (FT) ages of detrital zircons recovered from Atlantic Coastal Plain sediments to FT ages of zircons from bedrock in source terranes in the Appalachians provides a key to understanding the provenance of the sediments and, in turn, the erosional and depositional history of the Atlantic passive margin.

In Appalachian source terranes, the oldest zircon fission-track (ZFT) ages from bedrock in the western Appalachians (defined for this paper as the Appalachian Plateau, Valley and Ridge, and far western Blue Ridge) are notably older than the oldest ages from bedrock in the eastern Appalachians (Piedmont and main part of the Blue Ridge). The age difference is seen both in ZFT sample ages and in individual zircon grain ages and reflects differences in the thermotectonic history of the rocks. In the east, ZFT data indicate that the rocks cooled from temperatures high enough to partially or totally reset ZFT ages during the Paleozoic and (or) Mesozoic. The majority of the rocks are interpreted to have cooled through the ZFT closure temperature (~235 °C) at various times during the late Paleozoic Alleghanian orogeny. In contrast, most of the rocks sampled in the western Appalachians have never been heated to temperatures high enough to totally reset their ZFT ages. Reflecting their contrasting thermotectonic histories, nearly 80 percent of the sampled western rocks yield one or more zircon grains with very old FT ages, in excess of 800 Ma; zircon grains yielding FT ages this old have not been found in rocks in the Piedmont and main part of the Blue Ridge. The ZFT data suggest that the asymmetry of zircon ages of exposed bedrock in the eastern and western Appalachians was in evidence by no later than the Early Cretaceous and probably by the Late Triassic.

Detrital zircon suites from sands collected in the Atlantic Coastal Plain provide a record of detritus eroded from source terranes in the Appalachians during the Mesozoic and Cenozoic. In Virginia and Maryland, sands of Early Cretaceous through late early Oligocene age do not yield any old zircons comparable in age to the old zircons found in bedrock in the western Appalachians. Very old zircons yielding FT ages >800 Ma are only encountered in Coastal Plain sands of middle early Miocene and younger age.

Miocene and younger fluvial-deltaic deposits associated with the major mid-Atlantic Coastal Plain rivers that now head in the western Appalachians (the Hudson, Delaware, Susquehanna, Potomac, James, and Roanoke) contain abundant clasts of fossiliferous chert and quartzite and other distinctive rock types derived from Paleozoic rocks of the western Appalachians. These distinctive clasts have not been reported in older Coastal Plain sediments.

The ZFT and lithic detritus data indicate that the drainage divide for one or more east-flowing mid-Atlantic rivers migrated west into the western Appalachians, and the river(s) began transporting western Appalachian detritus to the Atlantic Coastal Plain, sometime between the late early Oligocene and middle early Miocene. By no later than late middle Miocene most if not all of the major rivers that now head west of the Blue Ridge were transporting western Appalachian detritus to the Coastal Plain. Prior to the drainage divide migrating into the western Appalachians, the ZFT data are consistent

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with the dominant source of Atlantic Coastal Plain sediments being detritus from the Piedmont and main part of the Blue Ridge, with possible input from distant volcanic sources.

The ZFT data suggest that the rapid increase in the rate of siliciclastic sediment accumulation in middle Atlantic margin offshore basins that peaked in the middle Miocene and produced almost 30 percent of the total volume of post-rift siliciclastic sediments in the offshore basins began in the early Miocene when Atlantic river(s) gained access to the relatively easily eroded Paleozoic sedimentary rocks of the western Appalachians.

Keywords: zircon fission-track ages, Atlantic passive margin, Atlantic drainage divide, provenance, Appalachian thermochronology

#### INTRODUCTION

The erosional history of the Appalachians has been discussed and debated for over a hundred years. Following formation of the ancestral Appalachians, culminating with the late Paleozoic Alleghanian orogeny, virtually all of the material eroded from the Appalachians is thought to have been carried to the west, into and beyond the Appalachian foreland basin. By the Jurassic, an inferred transcontinental paleoriver system carried detritus from headwaters in the central and southern Appalachians far to the west, north of the present-day Colorado Plateau. Westward drainage continues to the present, into the Gulf of Mexico (Pazzaglia and Brandon, 1996; Dickinson and Gehrels, 2003, 2009; Rahl and others, 2003).

Late Triassic-Early Jurassic continental rifting and the ultimate opening of the Atlantic led to eastward drainage from the Appalachians and transport of large volumes of sediment into the area of the present-day Atlantic Coastal Plain and offshore basins of the middle Atlantic margin (Judson, 1975; Poag and Sevon, 1989; Poag, 1992; Pazzaglia and Brandon, 1996). The offshore basins "... contain the detritus of no less than 7 km of rock, presumably eroded from the central and northern Appalachians ... " (Pazzaglia and Brandon, 1996, p. 256). The estimated volume of post-rift siliciclastic sediments of Middle Jurassic (Aalenian) and younger age in the offshore basins approaches  $1.5 \times 10^6 \text{ km}^3$  [Pazzaglia and Brandon, 1996; Gradstein and others (2012) time scale].

The rate of siliciclastic sediment accumulation in the offshore basins increased during at least four periods, with peaks in the Jurassic, Early Cretaceous, Late Cretaceous, and Miocene. The driving forces behind the increases in sediment flux are not well understood, particularly for the most recent large pulse that began in the Miocene and is responsible for almost 30 percent of the estimated total volume of siliciclastic sediments in the offshore basins (Pazzaglia and Brandon, 1996; Pazzaglia and Gardner, 2000).

In the Atlantic Coastal Plain, Lower Cretaceous and Miocene and younger fluvial-deltaic deposits correlate downdip with marine littoral and shelf deposits (Newell and Rader, 1982; Mixon and others, 1989; Pazzaglia, 1993; Pazzaglia and Gardner, 1993, 2000; Weems and Edwards, 2007; and others). Upper Cretaceous and Paleogene updip nonmarine deposits have been removed by pre-Miocene erosion.

The inner margin of the Atlantic Coastal Plain is typically marked by the boundary between the Cretaceous and younger fluvial to marine sediments of the Coastal Plain to the east and the generally high-grade metamorphic rocks of the Piedmont and rocks of the Mesozoic rift basins to the west. Locally, in the Fredericksburg, Virginia, area, Coastal Plain sediments are faulted against Piedmont rocks (Mixon and Newell, 1977), but generally the boundary is an unconformable erosional contact.

Local remnants of Coastal Plain sediments are preserved inland, on the Piedmont. Miocene surficial deposits generally are the oldest survivors (for example, Weems and Edwards, 2007), except for local outliers of middle Eocene marine sediments near

Raleigh, North Carolina (Cabe, ms, 1984) and Paleocene marine sediments near Warm Springs, Georgia (Reinhardt and others, 1984). Reworked dinoflagellates in middle Miocene sediments near Midlothian, Virginia, about 16 km west of the Piedmont-Coastal Plain boundary in the Richmond area, attest to the former presence of Upper Cretaceous and lower Eocene marine sediments on the eastern Piedmont of southern Virginia (Weems and others, 2012).

Major mid-Atlantic rivers cross the Piedmont-Coastal Plain boundary at the Fall Zone (Tidewater Fall Line of Weems, 1998), which marks the transition from hard rocks of the Piedmont to the softer substrate of the Coastal Plain. Fresh bedrock is exposed where rivers cross the Fall Zone, but generally the Piedmont uplands are underlain by deeply weathered, friable saprolite (Newell and others, 1980; Whittecar and others, 2015). Adjacent to large rivers, the Fall Zone is marked by assemblages of broad fluvial terraces and delta plains deposited at the abrupt change in gradient.

Detrital zircon suites and lithic detritus in the Coastal Plain sediments provide a record of material eroded from bedrock in the Appalachians and deposited in the Coastal Plain during the Mesozoic and Cenozoic. The main purpose of this paper is to determine the provenance of the sediments by comparing the FT age of detrital zircons in fluvial-deltaic to shallow marine Coastal Plain sediments of known stratigraphic age to the FT age of zircons in bedrock in the Appalachians. Interpretation of the FT data is supported by the lithic content of the fluvial-deltaic sediments associated with the major mid-Atlantic rivers that now head in the western Appalachians. Changes in provenance through time are in turn used to help reconstruct the erosional and depositional history of the Atlantic passive margin.

Beginning with Zimmermann and others (1975), numerous FT studies have been published on the Appalachians, but most contain only apatite FT data. Fission-track ages of zircon are typically more useful for provenance studies than apatite FT ages because zircon's higher track-retention temperatures make detrital zircons more likely to preserve provenance information (see "Fission-Track Analysis" below). Zircon FT data from the Appalachians include Lakatos and Miller (1983), Johnsson (1985, 1986), Roden and Miller (1991), Roden and Wintsch (1992), Kohn and others (1993), Roden and others (1993), Steckler and others (1993), Roden-Tice and Wintsch (2002), and Montario and Garver (2009). Comparison of the results from these studies suggests that ZFT ages from the eastern Appalachians (defined for this paper as the Piedmont and main part of the Blue Ridge) are generally younger than ZFT ages from the western Appalachians (far western Blue Ridge<sup>1</sup>, Valley and Ridge, and Appalachian Plateau). The present study expands the database of ZFT ages and then exploits the age difference between the eastern and western Appalachians, using not only sample ages as reported in most previous studies but also single-grain ages, to better define the provenance of Atlantic Coastal Plain sediments.

#### FISSION-TRACK ANALYSIS

Fission tracks in minerals are damage zones in the crystal lattice resulting from the spontaneous fission of <sup>238</sup>U atoms present in trace amounts in the mineral. The number of spontaneous tracks in a mineral increases over time, and thus the age of a mineral can be calculated from the number of spontaneous tracks and amount of uranium it contains. However, when a mineral containing fission tracks is heated at sufficiently high temperatures, tracks progressively shorten (anneal) and ultimately disappear, resulting in a progressively younger (partially to totally reset) FT age.

<sup>1</sup> Refers to rocks west of the Gatlinburg fault in the Great Smoky Mountains National Park area in Tennessee (Southworth and others, 2012) and west of unnamed thrust fault(s) on the northwestern side of the Blue Ridge in the Shenandoah National Park region in northern Virginia (Gathright, 1976), which locally yield one or more zircon grains with >800 Ma FT ages.

Significant annealing occurs over a temperature range, referred to as the “partial annealing zone” (Naeser, 1979; Fitzgerald and others, 1995; Brandon and others, 1998). If a mineral is heated to high enough temperatures for a sufficiently long time, tracks are effectively totally annealed and the mineral yields a “zero” FT age. When the mineral cools, tracks again begin to accumulate, restarting the FT clock. Closure temperatures in zircon are a function of both the cooling rate and the total accumulated radiation damage (principally from  $\alpha$ -decay) in the zircon crystal. In natural  $\alpha$ -radiation-damaged zircon, effective closure temperatures are probably in the range of  $\sim 210$  to  $\sim 260$  °C for cooling rates of 1 to 100 °C/m.y., respectively (Brandon and others, 1998). For the present study, a mean value of  $235 \pm 25$  °C is adopted for the zircon FT closure temperature, and  $180 \pm 25$  °C and  $240 \pm 25$  °C are adopted for the approximate low- and high-temperature boundaries of the effective partial annealing zone (based on Brandon and others, 1998, fig. 6). Apatite, the other mineral routinely analyzed by the FT method, anneals over a lower temperature range (effective partial annealing zone =  $\sim 60$  to  $\sim 110$  °C; Fitzgerald and others, 1995).

The relatively high track retention temperatures of zircon typically make it more useful than apatite for determining the provenance of sediments. Fission-track analysis of detrital apatites has been widely used to determine the postdepositional low-temperature history of sediments and sedimentary basins related, for example, to burial and exhumation (C. W. Naeser, 1979; Gleadow and others, 1983; Green and others, 1989; N. D. Naeser and others, 1989). The downside is that the resetting of apatite ages at relatively low temperatures obscures provenance information. Zircon ages on the other hand are essentially unaffected by postdepositional annealing in sediments that have remained at temperatures  $< \sim 180$  °C. In such sediments, the FT ages of the individual detrital zircon grains provide information about the source rocks eroded to form the sediments. For example, within a detrital grain suite it may be possible to correlate individual age populations to probable source rocks to delineate sediment transport patterns in a basin. Changes in the zircon suite through time can be used to define input from different source areas, to reconstruct changes in sedimentation patterns, and to reconstruct the uplift and erosional history of the source rocks (McGoldrick and Gleadow, 1977; Zeitler and others, 1982, 1986; Hurford and others, 1984; Yim and others, 1985; Baldwin and others, 1986; N.D. Naeser and others, 1987, 1990; Cervený and others, 1988; N.D. Naeser, 1989; Hurford and Carter, 1991; Tagami and Dumitru, 1996; Garver and others, 1999, 2000; Bernet and others, 2001, 2004; Bernet and Spiegel, 2004; Montario and Garver, 2009; and others).

#### METHODS

In the present study, ZFT ages were determined using the external detector method (C.W. Naeser and McKee, 1970; N.D. Naeser and others, 1989) as follows. Zircon grains coarser than 74  $\mu\text{m}$  were separated from crushed samples using standard heavy-mineral separation techniques (N.D. Naeser and others, 1989, fig. 10.7). The zircon grains were then imbedded in FEP Teflon, polished, and etched in a molten flux of NaOH and KOH (Gleadow and others, 1976) for times between 16 and 69 hours at 207 to 220 °C to reveal spontaneous fission tracks in the grains. The easiest and most common way to determine uranium concentration for FT dating is to irradiate the zircons in a nuclear reactor with thermal neutrons, which creates a new set of fission tracks by inducing fission in  $^{235}\text{U}$  in the grains. Thus, after etching for spontaneous tracks, the grain mounts were covered with low-uranium-content-muscovite external detectors and irradiated at the U.S. Geological Survey Reactor in Denver, Colorado. National Institutes of Standards and Technology (NIST) standard glass SRM 962 (Carpenter and Reimer, 1974) was irradiated with the zircon grain mounts as a neutron dosimeter. The resulting induced track density, counted in the external detector, is a function of the uranium concentration in the zircon and the

neutron fluence the sample received during irradiation. Grain mounts and external detectors were counted at  $1250\times$  magnification using a  $100\times$  oil immersion lens.

The external detector method allows an age to be calculated for each individual zircon counted in a grain mount because it allows induced track density to be determined from the same grain, or same part of the grain in the case of zoned zircons (Appendix I), that was counted to determine spontaneous track density. Single-grain ages were calculated using the zeta calibration method (Hurford and Green, 1983) with a zeta value of 319.6, determined using standard glass NIST SRM 962 and the Fish Canyon Tuff, Tardree Rhyolite, and Buluk Tuff ZFT age standards (Hurford, 1990). For samples that pass the  $\chi^2$  test ( $P(\chi^2) \geq 5\%$ ) (Galbraith, 1981; Green and others, 1989), the Hurford and Green (1983) equation was also used to calculate sample ages, using the sum of all spontaneous and the sum of all induced tracks counted in the individual grains in the sample. Standard deviation was calculated by combining Poisson errors on the spontaneous and induced counts and on counts in the detector covering standard glass NIST SRM 962 (McGee and others, 1985). The “central age” (Galbraith and Laslett, 1993) is reported for samples that fail the  $\chi^2$  test.

N.D. Naeser and others (1987) showed that to use FT ages of detrital zircons effectively for provenance studies, it may be necessary to prepare more than one zircon grain mount for a given sample and etch each of the mounts for a different time. Generally the time required to properly etch fission tracks in zircon is inversely proportional to the total accumulated radiation damage, which is a function of the uranium concentration and the age of the grain. Grains with low radiation damage (typically the younger grains) require a longer etch time to fully develop tracks than grains with high radiation damage. Therefore, if a detrital suite is treated such that the older grains are properly etched, then the younger grains may be under-etched, leading to low track counts and erroneously young ages. Conversely, if the younger grains are properly etched, the older grains may be over-etched and more difficult or impossible to count. Therefore, in some detrital suites, a multiple-etch procedure may be needed to assure, to the extent possible, that all of the grains are properly etched and can be dated.

Ultimately, the multiple-etch method was not used in the present study because a test of four of the Coastal Plain samples showed that, for a given sample, the sample ages calculated from grains counted in the long- and short-etch mounts are statistically indistinguishable (at the 95% confidence level; Dalrymple and Lanphere, 1969) and the range of single-grain ages is very similar (table 1). As is typical in zircon populations (N.D. Naeser and others, 1987), many samples in this study, including those processed with multiple etches (table 1), contain grains that could not be dated for a variety of reasons (for example, the grains are too small or are metamict). Appendix I contains further discussion of the multiple-etch method and the FT dating of zircons, particularly very old, high-track-density grains.

#### ZIRCON FISSION-TRACK AGES

Zircon FT ages were determined on 137 samples as part of a FT study of the thermotectonic evolution of the central and southern Appalachians (N.D. Naeser and others, 1999, 2004, 2006; C.W. Naeser and others, 2001b, 2002b, 2004, 2005a, 2005b, 2006a, 2006b; Horton and others, 2002, 2005a; Kunk and others, 2004, 2005, 2006; Spotila and others, 2004; Southworth and others, 2006b, 2007, 2009b, 2010b, 2010c). The samples are from (1) outcrop and shallow core (<726 m depth) of Mesoproterozoic to Upper Triassic igneous, metamorphic, and sedimentary bedrock from the Appalachian Plateau, Valley and Ridge, Blue Ridge, and Piedmont in West Virginia, Maryland, Virginia, District of Columbia, Tennessee, North Carolina, and South Carolina; and (2) outcrop and shallow core (<411 m depth) of Lower Cretaceous to middle Miocene Atlantic Coastal Plain sands in Maryland and Virginia (fig. 1,

TABLE 1

Comparison of detrital zircon fission-track ages of selected Atlantic Coastal Plain samples, determined from short- and long-etch zircon grain mounts

Sample	Short etch <sup>1</sup>			Long etch <sup>2</sup>		
	Sample age (Ma) <sup>3</sup>	Range in single-grain ages (Ma) <sup>4</sup> (n)		Sample age (Ma) <sup>3</sup>	Range in single-grain ages (Ma) <sup>4</sup> (n)	
OG-3	217 ± 54	74-753	(30)	186 ± 90	50-694	(12)
OG-4	249 ± 31	120-474	(29)	265 ± 49	80-455	(16)
OG-5	238 ± 27	87-371	(30)	265 ± 56	110-365	(13)
OG-8	243 ± 33	114-497	(28)	259 ± 27	149-463	(29)

n, number of grains dated.

Sands recovered from the Oak Grove corehole, Virginia; locality and analytical data are in Appendix tables A2 and A3, respectively.

<sup>1</sup> Etched at 214 °C for 32 hours.

<sup>2</sup> Etched at 214 °C for 64 hours (OG-3, OG-5, OG-8) or 88 hours (OG-4).

<sup>3</sup> Central age ± 2 σ (see Appendix table A3).

<sup>4</sup> The range in single-grain ages reflects the Poissonian distribution (Harvey, 1969) of individual grain ages in single-age populations plus added dispersion from the spread in the ages of the source rocks for the detrital grains.

Appendix tables A1-A2). Analytical data are in Appendix table A3. The 1,563 individual zircon crystals dated in the 137 samples yielded ZFT ages ranging from 45 Ma to almost 3 Ga (fig. 2; table 2).

#### *Appalachian Bedrock*

The contrast in ZFT ages from the eastern and western Appalachians suggested by the comparison of the results from previous studies is confirmed by our data (figs. 1 and 2, table 2, Appendix table A3). The oldest ZFT ages from the western Appalachians (far western Blue Ridge, Valley and Ridge, and Appalachian Plateau) are notably older than the oldest ages from the eastern Appalachians (Piedmont and main part of the Blue Ridge). This age difference is seen both in the sample ages and the zircon single-grain ages.

In the Piedmont and main part of the Blue Ridge and in comparable rocks to the northeast in New England (in the Hartford-Deerfield basins and adjacent basement rocks in Connecticut and Massachusetts), all of the dated samples (except C&O-21, discussed below) from this and previous studies, including the samples collected from rocks of Proterozoic age, yield Paleozoic or younger ZFT ages (Roden and Miller, 1991; Kohn and others, 1993; Steckler and others, 1993; Roden-Tice and Wintsch, 2002; Kunk and others, 2004, 2005; N.D. Naeser and others, 2004; C.W. Naeser and others, 2005b; table 2, Appendix tables A1-A3). With few exceptions (noted below), all of the ZFT ages are younger than the age of their host rocks.

The FT data have been interpreted as indicating that these rocks cooled from temperatures high enough to partially reset or, in most samples, totally reset the ZFT ages at various times during the Paleozoic and (or) Mesozoic. One possible exception is a structurally high Upper Cambrian sandstone sample from the Maryland Piedmont (Appendix tables A1, A3, sample C&O-21). Zircons from this sample yield a latest Neoproterozoic ( $579 \pm 56$  Ma) ZFT age, but it is possible that even these zircons were partially reset in the Paleozoic.

The majority of samples from the Piedmont and main part of the Blue Ridge dated in the present study yield late Paleozoic ZFT ages, interpreted as dating the cooling of the rocks through the zircon closure temperature ( $\sim 235$  °C) at various

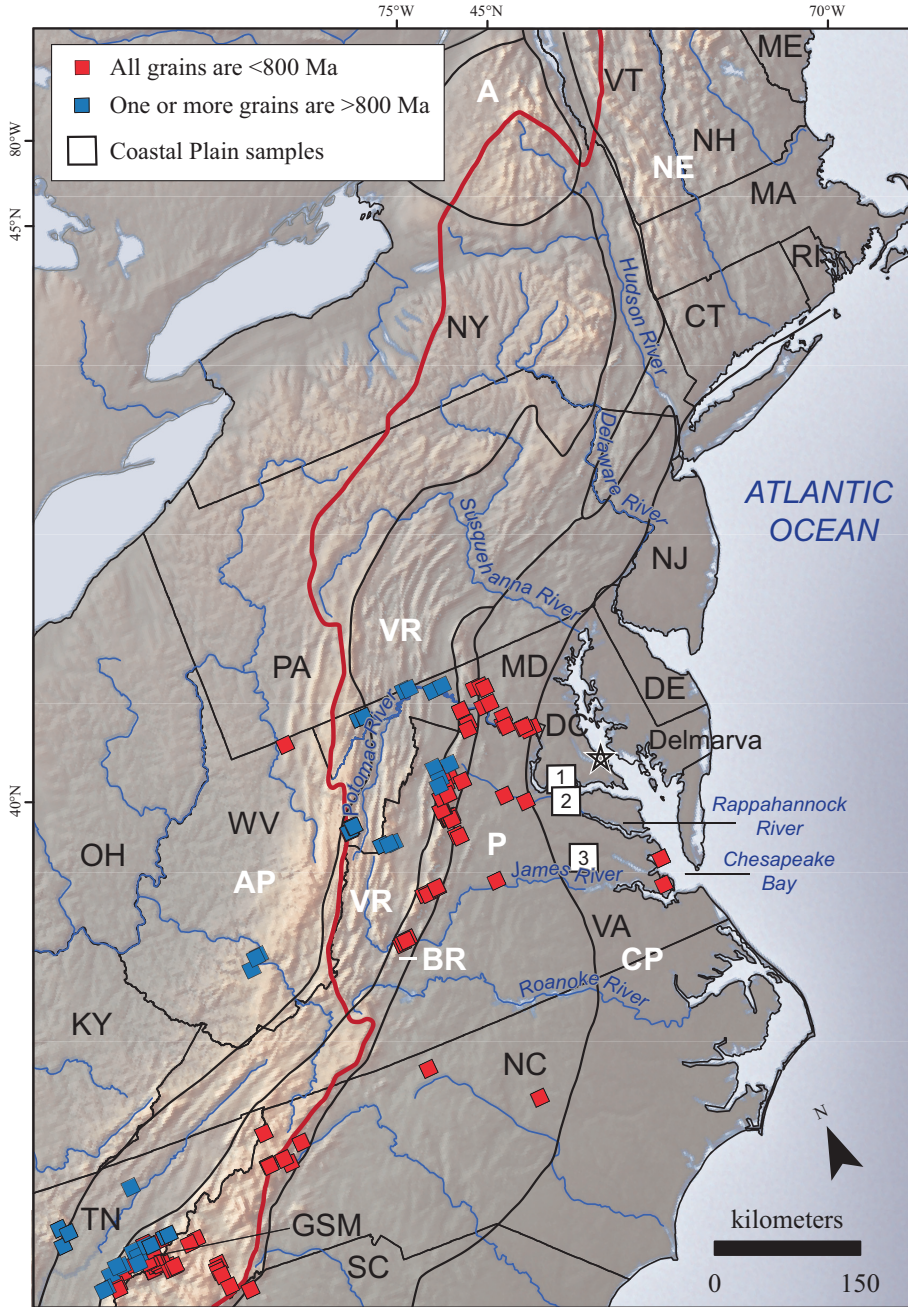


Fig. 1. Regional map of the Appalachians and Atlantic Coastal Plain showing location of bedrock samples in the central and southern Appalachians analyzed in the present study (Appendix tables A1, A2). Samples in which all of the dated zircon grains yield FT ages  $<800$  Ma are distinguished from samples yielding one or more zircon grains with FT ages  $>800$  Ma. Locations of Coastal Plain sand samples are shown for reference: 1, Popes Creek, Maryland (middle early Miocene Calvert Formation); 2, Oak Grove corehole, Virginia (Early Cretaceous Potomac Group—latest early-early middle Miocene Calvert Formation); 3, Tunstall, Virginia (late early Oligocene Old Church Formation). Bedrock samples plotted southeast of Coastal Plain locality 3 are from Piedmont rocks encountered beneath Coastal Plain sediments in USGS-NASA Langley and USGS Bayside #2 coreholes (Appendix table A2). “Far western Blue Ridge” as defined for

times during the late Paleozoic (Mississippian-Permian) Alleghanian orogeny (Kunk and others, 2004, 2005; N.D. Naeser and others, 2004). In the Blue Ridge, these late Paleozoic ages are interpreted as most likely reflecting rapid cooling of upper plate rocks associated with emplacement of Alleghanian thrust sheets, at times ranging from ~305 to ~280 Ma (N.D. Naeser and others, 2004).

Previous FT studies have found evidence that temperatures in several of the Late Triassic-Early Jurassic rift basins (including the Hartford-Deerfield, Newark, Taylorsville, and Richmond basins; Manspeizer and others, 1989, fig. 3) and in nearby crystalline basement rocks of the Piedmont were high enough in the Mesozoic to partially reset or, more commonly, totally reset most of the ZFT ages (Roden and Miller, 1991; Kohn and others, 1993; Steckler and others, 1993; Roden-Tice and Wintsch, 2002). These authors variously attribute the elevated Mesozoic temperatures to Late Triassic-Early Jurassic thermal events. The only rift-basin rocks sampled in the present study are from the northeastern Culpeper basin in Maryland (Poolesville Member of the Late Triassic Manassas Sandstone, samples C&O-9, C&O-11; Appendix tables A1, A3). Zircons from these samples yield late Paleozoic ZFT ages of  $263 \pm 40$  Ma and  $296 \pm 62$  Ma, respectively, typical of the ages found throughout much of the Piedmont and Blue Ridge.

In the previous study in the eastern Appalachians that reports ZFT single-grain-age data (Kohn and others, 1993), from the Newark basin and nearby rocks, the zircon grains all yield Permian or younger ages; almost all are Mesozoic. In the present study (figs. 1 and 2B, table 2, Appendix table A3), only a few of the individual zircon grains in eastern Appalachian samples yield pre-Paleozoic FT ages; none of the grain ages are  $>800$  Ma. The single-grain ages from the two samples of Late Triassic sandstone in the Culpeper basin are included on figure 2B and plotted separately on figure 3.

A very different pattern of ZFT ages emerges in the far western Blue Ridge, Valley and Ridge, and Alleghany Plateau. Locally the Neoproterozoic metasedimentary rocks in the northwestern foothills of the Great Smoky Mountains in Tennessee yield Paleozoic ZFT ages, interpreted as indicating that temperatures were high enough in the Paleozoic to reset the zircon ages. However, nearly two-thirds of our western Appalachian samples, collected from Mesoproterozoic granitoid and Neoproterozoic to late Paleozoic metasedimentary and sedimentary rocks, yield Proterozoic ZFT ages. On the western edge of the Blue Ridge in Tennessee and northern Virginia (near the boundary with the Valley and Ridge) and throughout the Valley and Ridge and Appalachian Plateau, the samples, which are all from Neoproterozoic to late Paleozoic sedimentary rocks, yield ZFT ages that are equal to or older than their depositional age (Appendix tables A1 and A3). Preservation of these old ZFT ages indicates that these rocks have never been heated to temperatures above the zircon closure temperature (~235 °C). Some of the zircons may in fact have undergone little, if any, postdepositional annealing.

In previous studies in the western Appalachians, zircon ages from a Late Devonian sandstone in New York and Ordovician bentonites in Alabama, Tennessee, Kentucky, and New York are interpreted as being only partially reset (Lakatos and Miller, 1983;

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Fig. 1 (continued). this paper refers to the areas on the west side of the Blue Ridge province in northern Virginia and in the Great Smoky Mountains area in Tennessee where locally the rocks yield one or more zircon grains with  $>800$  Ma FT ages. Atlantic rivers discussed in the text are labeled. Boundaries of physiographic provinces (A, Adirondack; AP, Appalachian Plateau; BR, Blue Ridge; CP, Coastal Plain; NE, New England; P, Piedmont; VR, Valley and Ridge) and the location of the modern drainage divide (red line) separating Atlantic drainage to the east-southeast from drainage to the west and north modified from Hack (1989) and Gunnell and Harbor (2010). GSM, Great Smoky Mountains. State names designated by U.S. Postal Service abbreviations. Star, location of Calvert Cliffs section discussed in the text.

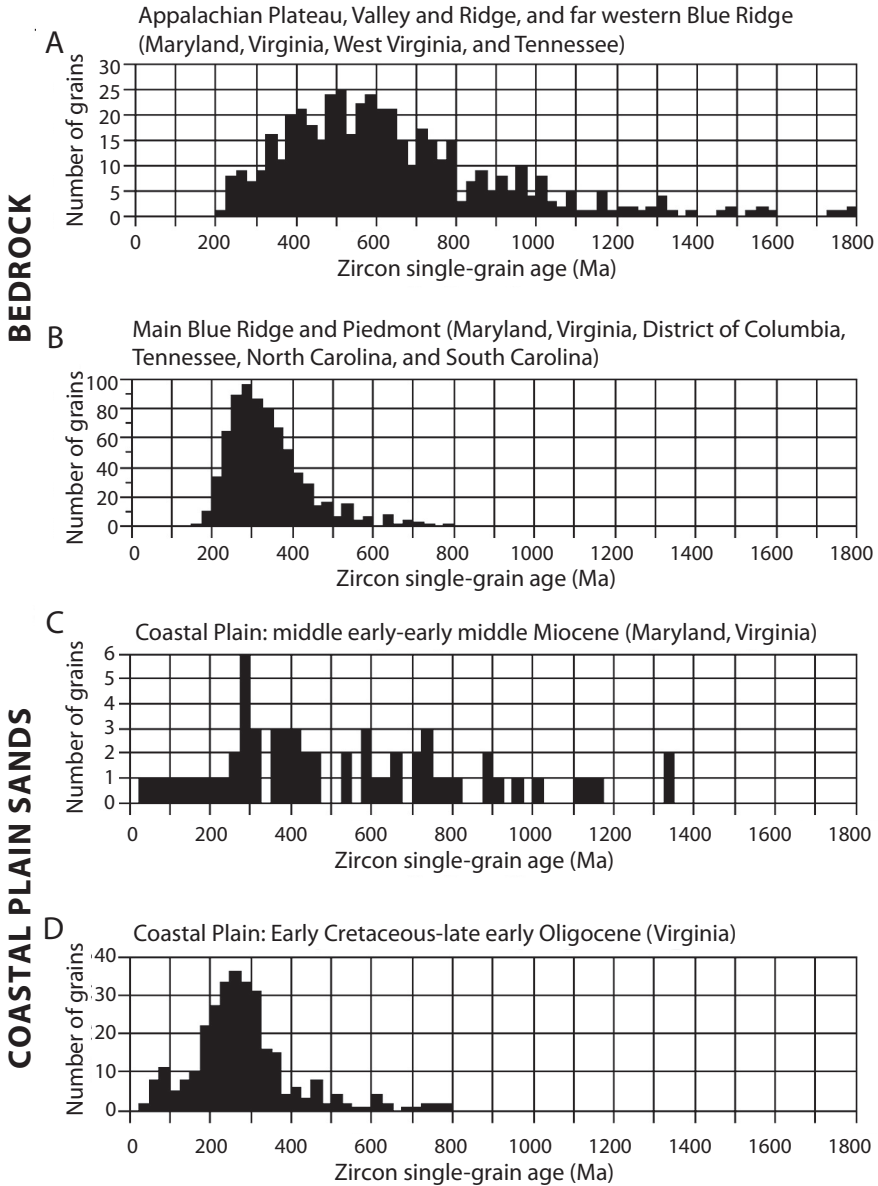


Fig. 2. Histograms showing the distribution of zircon single-grain FT ages from bedrock in (A) the western Appalachians (Appalachian Plateau, Valley and Ridge, and far western Blue Ridge) and (B) eastern Appalachians (Piedmont and main part of the Blue Ridge) and from Atlantic Coastal Plain sands of (C) middle early to early middle Miocene age (Calvert Formation; fig. 1, localities 1, 2) and (D) Early Cretaceous to late early Oligocene age (Early Cretaceous Potomac Group, early-middle Paleocene Aquia Formation, early Eocene Nanjemoy Formation, late early Oligocene Old Church Formation; fig. 1, localities 2, 3) in Virginia and Maryland. For ease of plotting, the four oldest single-grain ages in (A) (1860, 1931, 2283, and 2960 Ma) have been omitted. (B) includes the data from Poolesville Member of the Late Triassic Manassas Sandstone in the Culpeper basin (samples C&O-9 and C&O-11) plotted on fig. 3. Stratigraphic ages of samples from the Calvert and Old Church Formations are discussed in the text. Sample localities are plotted on fig. 1 and detailed in Appendix tables A1 and A2.

TABLE 2

Summary of zircon fission-track ages from the Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain determined in the present study

Province <sup>1</sup>	Stratigraphic age of samples	Approximate range of ZFT ages (Ma)	
		Sample ages (n) <sup>2</sup>	Single-grain ages (n) <sup>2</sup>
Appalachian Plateau + Valley and Ridge + far western Blue Ridge	Mesoproterozoic-Paleozoic	350-950 (46)	220-2960 (476)
Main Blue Ridge + Piedmont	Mesoproterozoic-Mesozoic	240-580 (81)	165-785 (725)
Coastal Plain	Miocene	345-390 (2)	45-1340 (60)
	Cretaceous-early Oligocene	175-280 (8)	45-795 (302)

Locality and analytical data are in Appendix tables A1-A3.

<sup>1</sup> "Far western Blue Ridge" refers to rocks west of Gatlinburg fault in the Great Smoky Mountains National Park region (Southworth and others, 2012) and west of unnamed thrust fault(s) on the northwestern side of the Blue Ridge in the Shenandoah National Park region (Gathright, 1976), which locally yield one or more zircon grains with >800 Ma fission-track ages.

<sup>2</sup> For sample ages, n is number of samples dated; for single-grain ages, n is number of grains dated.

Johnsson, 1985, 1986; Roden and others, 1993; Montario and Garver, 2009). Early Paleozoic sandstones from the flanks of the Adirondack Mountains in New York yield detrital zircon populations with FT ages older than the depositional ages of the rocks,

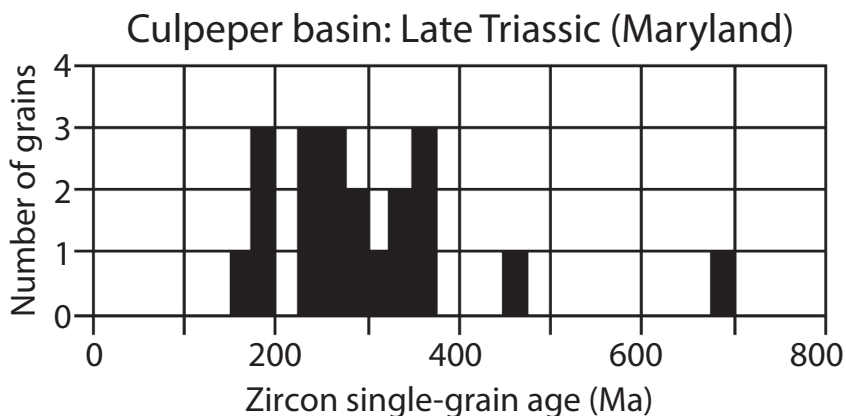


Fig. 3. Histogram showing distribution of zircon single-grain FT ages in the two samples collected from the Poolsville Member of the Late Triassic Manassas Sandstone, northeastern Culpeper basin, Maryland (Appendix table A1, samples C&O-9 and C&O-11).

indicating no significant postdepositional resetting of the zircon ages (Montario and Garver, 2009).

In contrast to rocks in the eastern Appalachians, where none of the zircon grains in our samples yield ages >800 Ma, nearly 80 percent of our western Appalachian samples yield one or more zircon grains with ZFT ages in excess of 800 Ma (figs. 1 and 2A, table 2, Appendix table A3). The percentage of >800 Ma grains in these samples is as high as 70 percent of the total zircon population. In areas where the rocks are interpreted to have undergone little or no postdepositional annealing, the Neoproterozoic-late Paleozoic sedimentary rocks yield detrital zircon grains with FT ages as old as ~3 Ga. Similarly, zircons from the early Paleozoic sandstones in the Adirondack Mountains area dated by Montario and Garver (2009) yield a population of detrital zircons with ZFT ages >800 Ma, with single-grain ages as old as 2.1 Ga.

#### *Atlantic Coastal Plain Sediments in Virginia and Maryland*

*Sample location and stratigraphic age.*—Coastal Plain samples analyzed in this study were collected in Virginia and Maryland, from fluvial-deltaic Lower Cretaceous and shallow marine Paleogene and Neogene sands (fig. 1, localities 1-3). Outcrop samples are from the Popes Creek Sand Member of the Miocene Calvert Formation, collected on the east bank of the Potomac River south of Popes Creek, Maryland (locality 1), and the Oligocene Old Church Formation, collected near Tunstall, Virginia (locality 3) (Appendix table A1). Eight subsurface samples, ranging in age from Early Cretaceous to Miocene, were recovered from the Oak Grove corehole, a stratigraphic test hole located southeast of Fredericksburg, Virginia, that penetrated 420.6 m of Coastal Plain sediments (locality 2) (Gibson and others, 1980; Reinhardt and others, 1980a, 1980b) (Appendix table A2).

The time of deposition of three of the sampled sands, two from the Calvert Formation and one from the Old Church Formation, is particularly critical in interpreting the detrital ZFT ages in the Coastal Plain sands.

Dinoflagellates from Calvert Formation sample OG-1 recovered from the Oak Grove corehole (fig. 1, locality 2) place this part of the Calvert Formation in dinocyst Zone DN4 (de Verteuil and Norris, 1996; de Verteuil, 1997), recalibrated to ~16.5 to ~15.0 Ma, or latest early to early middle Miocene (latest Burdigalian to early Langhian) time, on the Gradstein and others (2012) time scale (fig. 4). The top of DN4 is recalibrated to Gradstein and others (2012) using a correlation based on polarity chrons (fig. 4). The base of DN4 (base of *L. truncatum modicum*) is taken from Louwey and others (2008).

The Popes Creek Sand Member (Gibson, 1983) of the Calvert Formation exposed on the east bank of the Potomac River ~1.5 km south of Popes Creek, Maryland, was placed in dinocyst Zone DN2 by de Verteuil and Norris (1996, fig. 8). Their locality TML 1705 is within a few hundred meters of the locality where our sample CP-1 was collected (fig. 1, locality 1), and their lowest sample (S5+2) represents approximately the same stratigraphic level (in the basal few meters of the section). The presence of *E. insigne* in sample S5+2 (de Verteuil and Norris, 1996, table 2) places this part of the Popes Creek Sand Member in the upper part of Zone DN2 (DN2b/2c; de Verteuil, 1997), recalibrated to ~19.6 to ~18.7 Ma, or middle early Miocene (early Burdigalian), on the Gradstein and others (2012) time scale, using a correlation based on polarity chrons (fig. 4).

The age of the Old Church Formation (fig. 1, locality 3; Appendix table A1, sample OC) has been determined from Sr-isotope ages and nannoplankton assemblages (Weems and others, 2006). Mollusk shells collected from the formation at locality 3 (fig. 1) yield  $^{87}\text{Sr}/^{86}\text{Sr}$  ages ranging between 29.5 and 28.8 Ma, with an average of 29.3 Ma, indicating a late Rupelian (late early Oligocene) age for the formation [Gradstein and others (2012) time scale]. The formation yields an NP24

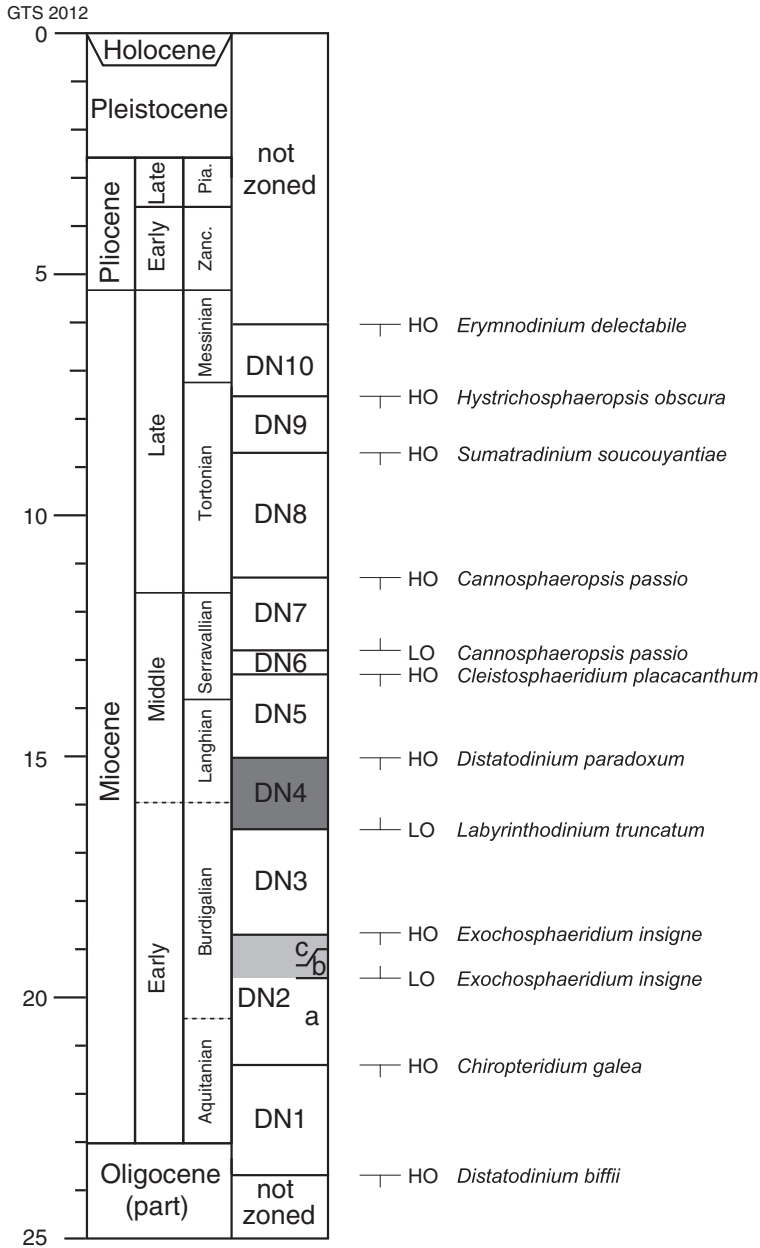


Fig. 4. Time of deposition of Calvert Formation samples OG-1 from the Oak Grove corehole in Virginia (upper shaded band) and CP-1 collected from the Popes Creek Sand Member of the Calvert Formation near Popes Creek, Maryland (lower band), based on their dinoflagellate cyst content as related to the age of dinoflagellate cyst zones DN1–DN10 of the uppermost Oligocene-Miocene of the U.S. Atlantic margin (de Verteuil and Norris, 1996; de Verteuil, 1997). The ages of the dinocyst zones are recalibrated to the Gradstein and others (2012) time scale (GTS 2012) using the correlation of polarity chrons to dinocyst zones and the age of the chrons in Hilgen and others (2012, table 29.3), with the following exception. The base of DN4 (base of *L. truncatum modicum*) is taken from Louwe and others (2008). The presence of *L. truncatum* and *D. paradoxum* in sample OG-1 assigns this part of the Calvert Formation to dinocyst Zone DN4, indicating a time of deposition of ~16.5 to ~15.0 Ma. Sample CP-1 is assigned to the upper part of Zone DN2 (see text), indicating a time of deposition of ~19.6 to ~18.7 Ma. HO, highest occurrence. LO, lowest occurrence. Pia., Piacenzian. Zanc., Zanclean.

nannoplankton assemblage. The NP24 zone spans the late Rupelian-early Chattian (Vandenbergh and others, 2012), consistent with the late Rupelian age indicated by the Sr-isotope ages.

*Zircon single-grain ages.*—Histograms showing the FT ages determined for individual detrital zircons from the Atlantic Coastal Plain sands collected in Virginia and Maryland (fig. 1) are shown on figures 2C and 2D.

Several lines of evidence indicate that the Coastal Plain sands sampled for this study have not been heated to temperatures high enough to affect the FT ages of the detrital zircons, namely:

(1) In any given sample, the ZFT age is older than the depositional age of the sediment, indicating that the sediments have never been heated to temperatures high enough ( $> \sim 240$  °C) to totally anneal zircon.

(2) The present-day temperature of even the most deeply buried and stratigraphically oldest sample [OG-9, collected from the Lower Cretaceous “lower” Potomac Group (Reinhardt and others, 1980a) at a depth of  $\sim 410$  m below surface in the Oak Grove corehole] is only about 25 °C<sup>2</sup>, well below the temperature ( $\sim 180$  °C) required for even the onset of effective track annealing in zircon (Brandon and others, 1998).

(3) Finally, the FT ages determined for apatites from the Oak Grove corehole indicate that maximum paleotemperatures in the sediments have remained below  $\sim 110$  °C (the temperature at which apatite is effectively totally annealed; Fitzgerald and others, 1995). Specifically, five samples from the corehole yielded datable apatite, including three of the samples that yielded zircon (OG-3, OG-8, OG-9) (Appendix table A4). All five samples, including the deepest sample in the corehole (OG-9), yield apatite FT ages older than the depositional age of the sediments.

Because postdepositional temperatures have remained well below the onset of effective annealing of fission tracks in zircon, the FT ages of individual detrital zircon grains still provide information about the source rocks eroded to form the sediments and thus provide a key to determining the provenance of Coastal Plain sediments.

The range of zircon single-grain FT ages in the older, Early Cretaceous through late early Oligocene (“lower” Potomac Group through Old Church Formation) part of the Coastal Plain section (fig. 2D) is generally very similar to the range of ages in the Piedmont and main part of the Blue Ridge (fig. 2B). Most important to the present study is the lack of old zircons in the pre-Miocene sands. None of the Early Cretaceous-late early Oligocene samples yield detrital zircons with FT ages  $> 800$  Ma.

In marked contrast to the pre-Miocene Coastal Plain sands, both of the Miocene samples (OG-1 and CP-1), collected from the Calvert Formation, contain detrital zircon grains with FT ages in excess of 800 Ma (fig. 2C).

One anomaly that stands out in comparing the detrital zircon single-grain FT ages in the Coastal Plain (figs. 2C and 2D) to those in Appalachian bedrock (figs. 2A and 2B) is the presence of a number of detrital zircons yielding ZFT ages  $< 150$  Ma old in the Coastal Plain sands. None of the zircons dated in the bedrock samples yielded FT ages this young. The provenance of these young grains is discussed below (see “Discussion”).

#### LITHIC DETRITUS

Studies of the provenance of lithic detritus in the Coastal Plain sediments help interpret the ZFT data. The mineralogy and lithology of pre-Miocene fluvial-deltaic and marginal marine-marine deposits in the Coastal Plain are distinctive. The

<sup>2</sup> Assuming a 20 to 25 °C/km geothermal gradient (Hulver, ms, 1997) and a mean annual surface temperature of  $\sim 13$  °C (Fredericksburg NP weather station, www.worldclimate.com, June 13, 2005) in the Oak Grove area.

mineralogy and lithology of Cretaceous arkoses are interpreted as indicating a provenance in nearby Piedmont and Blue Ridge rocks (Reinhardt and others, 1980a). Large clasts are commonly vein quartz, unfossiliferous quartzite, metarhyolite, and other silica-rich metamorphic rocks that survived deep saprolite weathering of the Piedmont. Succeeding glauconite-, phosphate-, and carbonate-rich, siliciclastic-starved Paleocene, Eocene, and lower Oligocene marine sediments on the Atlantic margin give way to the siliciclastic marine and fluvial-deltaic sediments that dominate the mid-Atlantic margin in the Miocene and Pliocene, as observed both in outcrop and in onshore and offshore wells. Data from the limited Oligocene marine deposits suggest that the transition to siliciclastic sediments began in the late Oligocene ( Chattian) (Reinhardt and others, 1980a, 1980b; Haq and others, 1987; Poag and Sevon, 1989; Miller, 1997).

From New Jersey south to the Virginia-North Carolina border, Miocene and younger fluvial-deltaic Coastal Plain deposits associated with rivers that now head west of the Blue Ridge are distinctive because the lithologies include abundant Paleozoic chert and fossiliferous quartzite pebbles, cobbles, and boulders derived from erosion of Paleozoic carbonates and quartzites on the west side of the Blue Ridge and in the Valley and Ridge (for example, Schlee, 1957; Hack, 1965; Rader and Biggs, 1976; Weems, 1986, 1990; Rader and others, 1996; Southworth and others, 2009a; Whittecar and others, 2015). Much of the chert in the Miocene and younger Coastal Plain deposits is gray, black, or white with recognizable Paleozoic corals, brachiopods, bryozoans, and other fossil fauna (for example, Schlee, 1957; Weems, 1986). Another distinctive suite of clasts of chert pebbles, cobbles, and boulders that are massive, generally brown or ochre-stained with leached rinds and opaline fracture fillings indicate that an extensive deeply weathered regolith has long blanketed the Paleozoic carbonate sequences exposed in the Valley and Ridge. Large volumes of these deposits exist at present in the Valley and Ridge and indicate a long continuum of weathering processes and residual deposits across the Appalachians, analogous in mode and time of formation to the saprolite cover on the metamorphic rocks of the Piedmont and Blue Ridge.

In contrast, pre-Miocene deposits in the Coastal Plain are generally devoid of the distinctive fossiliferous rock clasts that characterize the Miocene and younger deposits. Paleozoic cherts and quartzites either are not present or are so rare that they are generally not reported. Also, the high-level Miocene terrace deposits that rest on the Piedmont along the Rappahannock River (fig. 1), which has not breached the Blue Ridge, contain no Paleozoic chert clasts. Clasts in these deposits are from Piedmont and eastern Blue Ridge rocks (Whittecar and others, 2015).

#### *Geographic Distribution and Age of Neogene Fluvial-Deltaic Gravels with Western Appalachian Clasts*

Neogene fluvial-deltaic Coastal Plain gravels containing abundant Paleozoic chert and other distinctive Paleozoic rock types derived from the west side of the Blue Ridge and from the Valley and Ridge are associated with all of the major mid-Atlantic rivers that now originate in the western Appalachians, from the Hudson River south to the Roanoke River (fig. 1). Direct dating and correlation of fluvial-deltaic gravels in the Coastal Plain has long been hindered by the typical lack of biostratigraphic and other datable material in the deposits. Consequently, assigned ages commonly rely in large part on various proposed correlations to the downdip marine section, including (from oldest) the early-middle Miocene Calvert Formation, late middle Miocene Choptank Formation, late Miocene St. Marys and Eastover Formations, Pliocene Yorktown Formation, and their equivalents (Pazzaglia, 1993; Edwards and others, 2005, 2010; Weems and Edwards, 2007; Weems and Lewis, 2007; Weems and others, 2009, 2012).

Across the Coastal Plain in central and southern New Jersey and in the northern to central core of the Delmarva Peninsula, fluvial-deltaic late middle Miocene and younger gravels dominantly associated with the ancestral Hudson-Delaware River are unconformable on older Neogene, Paleogene, and Cretaceous deposits. The fluvial sands and gravels of the Bridgeton and Pensauken Formations include large boulders and are deeply weathered and leached. The deposits are arkosic and include many rock types, weathered feldspars, and micas. Rock types include distinctive black, gray, and white Paleozoic chert pebbles and cobbles and resistant Paleozoic quartzite derived from Valley and Ridge rocks of upstate New York, northern New Jersey, and northeastern Pennsylvania, as well as locally derived clasts of red beds of the Mesozoic basins (Owens and Minard, 1979; Pazzaglia, 1993; Owens and others, 1998; Newell and others, 2000).

The age of the Pensauken and Bridgeton Formations has been debated by a number of authors (Owens and Minard, 1979; Pazzaglia, 1993). They are interpreted as late Miocene or older (Bridgeton) and late Miocene (Pensauken) by Owens and Minard (1979) and middle to late Miocene (Bridgeton) and late Miocene(?) to Pliocene(?) (Pensauken) by Newell and others (2000). Pazzaglia (1993) suggests late Miocene (Bridgeton) to Pliocene(?) early Pleistocene (Pensauken) ages for the formations, based mainly on petrographic lithostratigraphic correlation to the downdip marine section. Stanford and others (2002) interpret the time of deposition of the Pensauken to be within the interval between ~4 and ~2 Ma (Pliocene-early Pleistocene; Gradstein and others, 2012; Pillans and Gibbard, 2012), based on pollen and other evidence from the Pensauken and overlying till.

The older Cohansey Formation is made up of a complex interfingering of nonmarine and marine sediments (Owens and others, 1998). Dominantly fluvial gravels in the Cohansey, including gravels referred to as a separate unit, the Beacon Hill Gravels, by Owens and Minard (1979) but considered a facies of the Cohansey by Newell and others (2000), contain Paleozoic chert and quartzites, locally in large concentrations, transported from the Valley and Ridge, likely by the ancestral Hudson(?) Delaware River system (Owens and Minard, 1979; Stanford and others, 2002). Biostratigraphic and Sr-isotope dating indicate a late middle-early late Miocene (Serravallian-early Tortonian) age for the Cohansey, coinciding at least in part to the time of deposition of the marine Choptank Formation [Owens and Minard, 1979; Pazzaglia, 1993; Owens and others, 1998; Newell and others, 2000; Weems and Edwards, 2007; Gradstein and others (2012) time scale].

The ancestral Hudson-Delaware River drainages have had a complex and at times apparently interrelated history (Owens and Minard, 1979; Stanford and others, 2002; Braun and others, 2003). Most if not all of the Pensauken Formation is attributed to the ancestral Delaware River (Owens and Minard, 1979), but the relative contribution of the Delaware to the older deposits is unclear. The oldest deposits with western Appalachian clasts directly attributable to the Delaware may be younger than late middle Miocene.

In contrast to the Cohansey, Pensauken, Bridgeton, and younger formations, Paleozoic chert and other distinctive western-Appalachian-sourced rock clasts are notably lacking in the early Miocene to late middle Miocene (Aquitainian-Serravallian) marine Kirkwood Formation and in older, Paleogene and Cretaceous fluvial to marginal marine-marine sediments (for example, Owens and others, 1998; Newell and others, 2000).

The modern valley of the Susquehanna River is a bedrock gorge that does not appear to have large fluvial deposits analogous to those associated with the ancestral Hudson and Delaware Rivers. However, old high-level terrace deposits occur on the lower Susquehanna upstream from the Fall Zone and are correlated to remnants of the

main phase (“members 2 and 3”) of the fluvial Bryn Mawr Formation that occur near the mouth of the river, resting on the Piedmont and Cretaceous Coastal Plain deposits. Both the high-level terrace deposits and the correlative Bryn Mawr contain Valley and Ridge-derived clasts, including sandstone, siltstone, quartzite, and chert. Fossil *Favosites* corals found in the Bryn Mawr are from Silurian limestones in the Valley and Ridge (Pazzaglia, 1993; Pazzaglia and Gardner, 1993, 2000; F. J. Pazzaglia, personal communication, 2010). Pazzaglia (1993) and Pazzaglia and Gardner (1993) suggest that the time of deposition of the main phase of the Bryn Mawr most likely ranges from early to late Miocene, based primarily on petrographic lithostratigraphic correlations along the Fall Zone and downdip into the marine section. Isolated remnants of older fluvial deposits (“member 1” of the Bryn Mawr) that unconformably underlie members 2 and 3 are correlated to the early Miocene part of the Calvert Formation or to the Oligocene Old Church Formation (Pazzaglia, 1993; Pazzaglia and Gardner, 1993). The lithic-clast content of these older deposits has not been determined (F. J. Pazzaglia, personal communication, 2010).

Across the upland of the southern Maryland Coastal Plain, fluvial gravels, referred to collectively as the gravels of the “upland deposits” by Hack (1955) and Schlee (1957) and including gravels mapped as the “Brandywine formation” by Hack (1955) and others, are thick, extensive, and rich in Paleozoic chert and other rock clasts transported from west of the Blue Ridge by the ancestral Potomac River. They rest unconformably on Miocene and Paleogene marine sediments. To the west, unnamed ancestral Potomac River weathered gravel deposits with distinctive western Appalachian clasts cap the highest Piedmont hills around the National Cathedral in Washington, D.C., and in the Tysons Corner area of northern Virginia and extend at grade up the Potomac River valley. They overlie the early Miocene Fairhaven Member of the marine Calvert Formation and older Coastal Plain sediments and Piedmont rocks (Darton, 1951; Hack, 1955; Schlee, 1957; Fleming and others, 1994; Drake and Froelich, 1997; Weems and Edwards, 2007; Whittecar and others, 2015; S. Southworth, personal communication).

Early workers generally assigned a Pliocene or Pliocene(?) age to the upland gravels on the Maryland Coastal Plain (summarized by Hack, 1955, and Schlee, 1957). Hack (1955, p. 37) concluded that deposition may have begun as early as the Miocene and extended into the Pleistocene, with deposits at higher elevations generally being older than those inset at lower elevations. The flora described by McCarden and others (1990) in a clay lens in the upland gravels demonstrates that the second-oldest sand and gravel lobe in the upland gravels southeast of Washington, D.C., is no older than late Miocene. However, if these clay deposits lie unconformably beneath their overlying gravels, as suggested by dewatering and weathering of the clays, then the overlying gravels could be considerably younger than late Miocene. More recent regional correlation indicates that the bulk of the high-level interfluvial gravels range from Pliocene (marine Yorktown Formation-equivalent) age in the northwestern part of the southern Maryland Coastal Plain to post-Yorktown, Pleistocene age to the southeast (R. E. Weems, personal communication). The oldest upland gravels are laterally equivalent to the high-level ancestral Potomac River gravels on the Piedmont, interpreted to be of late middle Miocene (upper Choptank-equivalent) age (Weems and Edwards, 2007).

Detailed study of the upland gravels deposited by the ancestral Potomac River on the Maryland Coastal Plain and on the Piedmont in the District of Columbia and northern Virginia identified clasts from a number of specific sources in the western Appalachians (Schlee, 1957). Identifiable brachiopods, corals, and bryozoans tie many of the chert pebbles to Lower Devonian rocks in the Valley and Ridge. Distinctive texture identifies other clasts as chert pebbles of the Beekmantown Formation (Ordo-

vician). Quartzite pebbles with fossil Devonian brachiopod impressions were probably derived from the Lower Devonian Oriskany Sandstone. Distinctive *Skolithos*-bearing quartzite clasts identified in the high-level ancestral Potomac gravels extending up the Potomac River valley are derived from Early Cambrian rocks that only occur on the western side of the Blue Ridge (Hack, 1965; Rader and others, 1996; S. Southworth, personal communication).

Western Appalachian clasts have generally not been reported in older Coastal Plain sediments in southern Maryland and on the Piedmont in the District of Columbia and northern Virginia (Darton, 1951; Hack, 1955; Fleming and others, 1994; Drake and Froelich, 1997). An exception is in the middle Miocene part of the marine Calvert Formation (beds 12, 13, 14 of Shattuck, 1904) exposed in the Calvert Cliffs on the western shore of Chesapeake Bay (fig. 1), where Vogt and Parrish (2012) report clasts with a western Appalachian provenance. These sediments also contain clasts of Piedmont rocks that Vogt and Parrish (2012) identify as Port Deposit gneiss from the Susquehanna River drainage.

In the eastern Piedmont in central and southern Virginia and along the inner edge of the Coastal Plain, fluvial terrace deposits correlate with Miocene and Pliocene marginal marine and marine deposits that overlie the Fall Zone (Wentworth, 1930; Newell and Rader, 1982; Weems, 1986; Mixon and others, 1989, 2000; Weems and Edwards, 2007). The high-level fluvial Midlothian gravels along the James River upstream from Richmond contain abundant *Skolithos*-bearing quartzite clasts, derived from early Paleozoic rocks that occur west of the Blue Ridge in central Virginia (Weems, 1986, 1990, 1998; Evans, 1998). These old gravels are thought to be remnants of once more extensive fluvial-deltaic deposits that correlate down-dip to the late middle Miocene (Serravalian) marine sediments of the upper Choptank Formation (Weems and Edwards, 2007; Weems and others, 2012). Downriver in Richmond, a 14-cm-long quartzite cobble with abundant *Skolithos* tubes, found by R. E. Weems in the basal part of the late Miocene marine Eastover Formation overlying the Choptank Formation (Weems, 1990), was likely reworked from the upstream gravels.

To the south, Roanoke River delta deposits of Pliocene (Yorktown Formation-equivalent) age contain significant quantities of western Appalachian-derived clasts (Newell and Rader, 1982; Whittecar and others, 2015). Whittecar and others (2015) regard these as the oldest Roanoke River deposits. Weems and Edwards (2007) interpret remnants of *Skolithos*-bearing gravels that occur along the Roanoke River (Weems and Lewis, 2007; Weems and others, 2009) as probable late middle Miocene, upper Choptank-equivalent age.

Older stratigraphic units along the inner edge of the Virginia Coastal Plain generally contain no recognizable western Appalachian clasts. South of the Roanoke River, coastward draining rivers head on the Blue Ridge escarpment or in the Piedmont. Resistant rock clasts stored in high terrace deposits consist predominantly of vein quartz from Piedmont metamorphic rocks and granitic intrusives; no chert, *Skolithos*-bearing quartzite, or other western-sourced material has been reported (Weems and Lewis, 2007; Weems and others, 2009; W. L. Newell, personal communication).

#### DISCUSSION

Very old zircon grains, yielding FT ages  $>800$  Ma, are found in nearly 80 percent of our bedrock samples from the western Appalachians, extending from Maryland south to Tennessee (figs. 1 and 2A). They have also been reported in lower Paleozoic sediments flanking the Adirondack Mountains in northern New York (Montario and Garver, 2009). In contrast, zircon grains this old have not been found in bedrock samples from the eastern Appalachians (figs. 1, 2B, and 3; Kohn and others, 1993). Their absence in the eastern Appalachians is not surprising given the thermotectonic history of the bedrocks. The ZFT data from this and previous studies indicate that

throughout most of the eastern Appalachians, zircons in rocks presently at the surface were partially reset or, in most samples, totally reset at various times in the Paleozoic and (or) Mesozoic. In contrast, the ZFT data indicate that throughout most of the western Appalachians, rocks presently at the surface have never been heated to temperatures high enough to totally reset their ZFT ages; in some rocks, the zircons may have undergone little if any postdepositional annealing.

Detrital zircons recovered from sediments in the Atlantic Coastal Plain provide a record of detritus eroded from the Appalachians during the Mesozoic and Cenozoic. In Coastal Plain sands sampled in Virginia and Maryland, Early Cretaceous fluvial-deltaic sands and Tertiary shallow marine sands as young as late early Oligocene do not yield any detrital zircon grains with FT ages  $>800$  Ma (fig. 2D). Detrital zircons with FT ages older than 800 Ma first appear in sands of the middle early Miocene Popes Creek Sand Member of the Calvert Formation, deposited  $\sim 19$  Ma (figs. 2C and 4). Based on our data, the only known source for zircon grains yielding these old FT ages in the present-day watershed of the Atlantic Coastal Plain is rocks in the western Appalachians. The absence of  $>800$  Ma zircons in the older part of the Coastal Plain section suggests that detritus eroded from the western Appalachians did not reach the Coastal Plain until sometime between the late early Oligocene and middle early Miocene (between deposition of the Old Church Formation and the Popes Creek Sand Member of the Calvert Formation).

Our interpretation of the ZFT data is that sometime during that interval, the drainage divide for one or more mid-Atlantic rivers migrated west into the western Appalachians, allowing detritus from the western Appalachians to flood eastward and be deposited in the Atlantic Coastal Plain. Prior to that, and as early as the time of deposition of the "lower" Potomac Group during the Early Cretaceous, the ZFT data indicate that Coastal Plain sediments were likely derived mainly from rocks in the eastern Appalachians, with possible minor input from distant volcanic sources (see below). Drainage from the western Appalachians during this time is interpreted to have been directed entirely to the west.

The presence of western Appalachian zircon grains in Coastal Plain sediments in the Miocene is consistent with the clast content of the fluvial-deltaic sediments deposited in the Piedmont and Coastal Plain by the major mid-Atlantic rivers that now head in the western Appalachians. Specifically, abundant clasts of fossiliferous Paleozoic chert and quartzite and other distinctive rock types derived from rocks on the west side of the Blue Ridge and in the Valley and Ridge are found in Miocene and younger fluvial-deltaic gravels associated with the Hudson, Delaware, Susquehanna, Potomac, James, and Roanoke Rivers (fig. 1).

The Miocene fluvial-deltaic gravels containing western Appalachian clasts are the oldest preserved Tertiary fluvial-deltaic sediments associated with these rivers. The time of deposition of the gravels has been interpreted mainly by downdip correlation to the marine section. For most of the rivers, the age of the oldest preserved gravels is interpreted to be late middle Miocene (Serravallian) (Choptank Formation-equivalent) (or possibly younger in the case of the Delaware River). An exception is the Susquehanna River where remnants of older, early Miocene gravels with western Appalachian clasts are preserved, based on correlation of high-level terrace deposits and the oldest part of the main phase of the Bryn Mawr Formation with the early part of the marine Calvert Formation (Pazzaglia, 1993; Pazzaglia and Gardner, 1993). The clast data suggest, therefore, that by no later than late middle Miocene the drainage divide of all of the major mid-Atlantic rivers (with the possible exception of the Delaware) that now head in the western Appalachians had migrated into the western Appalachians and the rivers were transporting western Appalachian detritus to the

Coastal Plain. At least one of the rivers, the Susquehanna, had migrated west into the western Appalachians by the early Miocene.

It is possible that one or more of the other rivers had similarly reached the western Appalachians by the early Miocene, but the potentially corroborating evidence in the form of associated fluvial-deltaic sediments of early Miocene age, and the clast content of such sediments, is missing. A thick section of Miocene siliciclastic sediments was deposited offshore prior to the late middle Miocene (Pazzaglia and Brandon, 1996, fig. 5a, table 1), but if fluvial-deltaic sediments of this age were deposited along Coastal Plain rivers other than the Susquehanna, they were evidently quickly removed by erosion (Weems and Edwards, 2007). The oldest preserved fluvial gravels associated with these rivers typically rest on older Miocene and Paleogene marginal marine-marine sediments and Cretaceous fluvial-deltaic sediments lacking western Appalachian clasts or on Piedmont rocks.

The Susquehanna is therefore the only river that, based on the lithic clasts in its associated fluvial-deltaic sediments, can be shown to have been transporting western Appalachian detritus to the Coastal Plain in the early Miocene, at about the same time that  $>800$  Ma zircons first appear in our Coastal Plain samples—in the shallow marine sands of the middle early Miocene Popes Creek Sand Member of the Calvert Formation in the southern Maryland Coastal Plain (fig. 1, locality 1). The Susquehanna River as the potential source for the  $>800$  Ma zircons in our samples is supported by Vogt and Parrish's (2012) interpretation that detritus from the Susquehanna was reaching the southern Maryland Coastal Plain in the early middle Miocene, based on the presence of clasts of Piedmont rocks identified as Port Deposit gneiss from the Susquehanna River drainage in Calvert Formation beds exposed in the Calvert Cliffs on Chesapeake Bay (fig. 1). Vogt and Parrish (2012) also identify western Appalachian clasts in these beds. The Calvert Cliffs section is about 44 km east-northeast of our locality 1. The clasts studied by Vogt and Parrish (2012) are from beds 12 (oldest), 13, and 14 (Shattuck, 1904) of the Calvert Formation, which correlate to dinoflagellate zone DN 5 (de Verteuil and Norris, 1996, fig. 4). Beds 12 and 13 correlate to the lower part of DN 5 (DN 5a of McCarthy and others, 2013), indicating that they were deposited in the early middle Miocene (Langhian), not long after deposition of the younger of our Calvert Formation samples with  $>800$  Ma zircons (sample OG-1; fig. 1, locality 2; fig. 4).

This does not necessarily exclude other rivers such as the Potomac and Hudson as potential sources for the western Appalachian zircons in our Calvert Formation samples. Logically, the ancestral Potomac River would seem to be a likely source of the old zircons in both samples. Locality 1 is on the east bank of the present-day Potomac River, and both localities are close to the late middle Miocene-Pleistocene course of the river, as defined by the ancestral Potomac River upland gravels. The Hudson River is known to contain a significant population of zircons yielding FT ages  $>800$  Ma in the area of its present-day headwaters in the Adirondack Mountains (Montario and Garver, 2009). Unfortunately, again, because no early Miocene fluvial-deltaic sediments can be directly tied into either the Potomac or the Hudson Rivers, a key piece of evidence is missing for determining if these rivers were indeed transporting detritus from the western Appalachians by the time the  $>800$  Ma zircons first appear in our Coastal Plain samples.

A remaining question is the source of zircon grains yielding FT ages  $<150$  Ma that are found in the Coastal Plain samples (figs. 2C and 2D) but not in our bedrock samples (figs. 2A and 2B). These grains first appear in the Early Cretaceous Potomac Group sands sampled in OG-8 (Appendix table A-2) and are found in all stratigraphically younger samples. They are typically only  $\sim 5$  to 10 percent of the zircons in any given sample, but approach 30 percent in samples OG-3 and OG-10 (collected from

Paleocene and Eocene sands), reflecting a significant increase in the number of 50 to 100 Ma zircons in those two samples (see below). The youngest zircon grain in a given sample is generally younger in successively younger stratigraphic horizons: the youngest zircon grain in the Early Cretaceous sands sampled in OG-8 is ~115 Ma, whereas the youngest zircons in the Tertiary sands are ~45 to 50 Ma.

Several possible sources can be identified for the oldest of these detrital zircons, yielding FT ages between ~100 and ~150 Ma. Probably the most likely based on their proximity to our sample sites is rocks in the Late Triassic-Early Jurassic rift basins and the nearby crystalline basement of the Piedmont. Roden and Miller (1991), Kohn and others (1993), Steckler and others (1993), and Roden-Tice and Wintsch (2002) demonstrated that zircons in most of these rocks were partially to totally reset in the Mesozoic. Kohn and others (1993) (the only study that reports the single-grain ZFT ages) report zircon grains as young as ~100 to 150 Ma in the affected basement rocks in the Newark basin area. None of our bedrock samples were collected in the areas where the previous studies found evidence for Mesozoic resetting, which could explain the absence of 100 to 150 Ma zircons in our Piedmont-main Blue Ridge age spectrum (fig. 2B). Another possible source of 100 to 150 Ma zircons is rocks of the New England-Quebec volcanic province (McHone and Butler, 1984; Foland and others, 1986; Eby, 1987; Lyons and others, 1997), either from erosion of rocks in the source area or from the primary or reworked air-fall tephra that may have been associated with the Lower Cretaceous silicic pyroclastic rocks that occur in the province in, for example, New Hampshire (Lyons and others, 1997).

Detrital zircons yielding FT ages between ~50 and 100 Ma (figs. 2C and 2D) are found in OG-5 (Early Cretaceous "upper" Potomac Group) and all younger Coastal Plain samples (with the younger zircons in this age range occurring only in the younger, post-Cretaceous samples). They are generally <~5 percent of the zircon population, except in samples OG-3 and OG-10, where the percentage peaks at ~20 percent. A likely source for zircons of this age has not been identified in the Appalachian region. Looking farther afield, the ages of the zircon grains suggest a possible source in the fallout from the numerous air-fall tephra eruptions that were taking place during this time in both the Cordillera of the Western United States and in the Gulf Coast region. In the Cordillera, Late Cretaceous marked a major period of explosive volcanism that peaked at ~95 Ma and ~75 Ma, as evidenced by abundant air-fall tephra beds, mostly preserved as bentonites, in Upper Cretaceous sedimentary rocks in the Western Interior (Christiansen and others, 1994). The widespread tephra beds are interpreted to be the product of plinian eruptions of silicic magma, associated with emplacement of ignimbrites and caldera collapse (Christiansen and others, 1994). Ash from such eruptions can be dispersed far beyond the limits of the recognizable air-fall tephra beds, which can extend hundreds to thousands of kilometers from their source vents (Fisher and Schmincke, 1984).

In the Gulf Coast region, numerous bentonites, interpreted to be air-fall tephra from volcanic centers in Gulf Coast area, have been identified in Upper Cretaceous-Tertiary rocks from Texas to at least as far east as Alabama (Ross, 1955). A Gulf Coast origin has also been suggested (Ross, 1955) for a thin bentonite identified in Upper Cretaceous marine sands on the New Jersey Coastal Plain (Stephenson, 1936).

In addition to the age of the tephra, another factor in assessing the likelihood that air-fall eruptions supplied the ~50 to 100 Ma zircons found in the Atlantic Coastal Plain sands is the grain size of the zircons: namely are the zircons in the Coastal Plain sands too large to have been transported from eruptive centers as far away as the Cordilleran and Gulf Coast? The zircons dated in this study are  $\geq 74 \mu\text{m}$  (very fine sand size or larger). Studies of decreasing maximum grain size with increasing distance from source in air-fall tephra from the large 75,000-yr BP Toba eruption in Sumatra

(Ninkovich and others, 1978; Fisher and Schmincke, 1984) and the  $0.639 \pm 0.002$  Ma Lava Creek B eruption in Yellowstone National Park (Izett, 1987; Lanphere and others, 2002) show that particles (specifically zircon crystals in the case of the Lava Creek B ash bed) as large as 125 to 150  $\mu\text{m}$  are present 2,000 to 2,500 km or more away from the source vents. Comparable eruptions would put the 50 to 100 Ma zircons in the Atlantic Coastal Plain area within reasonable range of the Gulf Coast and possibly at least some of the eruptive centers in the Cordillera.

One or two of the detrital zircons in four of our samples yield ZFT ages close to the depositional age of their host sediments. This suggests that, if in fact the zircons were derived from air-fall tephra, the tephra eruptions were essentially contemporaneous with deposition of the sediments. More commonly, the 50 to 100 Ma zircons are older than the depositional age of their host sediments, suggesting the zircons were reworked from primary tephra-fall sites in the Coastal Plain drainage area. This is a common fate of air-fall tephra, which frequently undergo some degree of reworking, in both terrestrial and shallow marine environments (Christiansen and others, 1994).

The youngest ( $\sim 45$ – $50$  Ma) detrital zircons are in the Tertiary sands. Volcanism occurred in western Virginia and eastern West Virginia in the Eocene, at  $\sim 47$  to 48 Ma (Southworth and others, 1993; Mazza and others, 2014). Tso and others (2004) suggest that pyroclastic eruptions were part of this volcanism, but the resulting ejecta may have been too localized to account for the zircons found in pre-Miocene Tertiary sands on the Atlantic Coastal Plain.

In summary, the ZFT and lithic clast data taken together indicate that by the middle early Miocene ( $\sim 19$  Ma), the drainage divide for one or more rivers, probably including the Susquehanna and possibly the Potomac and (or) Hudson, had migrated into the western Appalachians, allowing the rivers to transport western Appalachian detritus to the Coastal Plain for the first time since at least as early as the Early Cretaceous. Early Cretaceous through the late early Oligocene Coastal Plain sediments were derived primarily from rocks in the main part of the Blue Ridge and Piedmont with possible input from distant volcanic centers.

The ZFT data indicate major changes in drainage patterns and in erosion and deposition on the Atlantic passive margin that have implications for the evolution of the modern Appalachians:

(1) In the northern and central part of the study area, the modern drainage divide that separates Atlantic drainage from drainage to the north and west lies in the Adirondack Mountains of northern New York, the Appalachian Plateau, and far western Valley and Ridge, within the western Appalachians where rocks yield zircon grains with  $>800$  Ma FT ages (fig. 1; Montario and Garver, 2009). In southern Virginia, the divide crosses the Valley and Ridge into the Blue Ridge. South of the Roanoke River, east-flowing Atlantic rivers originate on the Blue Ridge escarpment or in the Piedmont, east of rocks containing  $>800$  Ma zircons; rivers draining most of the Blue Ridge and the Valley and Ridge and Appalachian Plateau, such as the New River and Tennessee River, flow to the west and ultimately into the Gulf of Mexico.

The ZFT data indicate that prior to the late early Oligocene-middle early Miocene the drainage divide in the northern and central Appalachians was located well east of its present position and in particular east of rocks containing zircon grains with  $>800$  Ma FT ages. The present-day drainage pattern south of the Roanoke River is thus similar, on a broad scale, to the drainage pattern that we envision in the northern and central Appalachians prior to the late early Oligocene-middle early Miocene and at least as early as the Early Cretaceous.

(2) The ZFT data indicate that during the Early Cretaceous, when “lower” Potomac Group fluvial-deltaic sediments were being deposited in the Coastal Plain, the Atlantic drainage divide was east of rocks containing  $>800$  Ma zircons—there was

essentially no eastward transport of detritus from the western Appalachians to the Coastal Plain (fig. 2D).

Absence of eastward transport from the western Appalachians may have existed as early as the Middle Jurassic, when the oldest post-rift sediments preserved in the offshore basins of the middle Atlantic margin were deposited [Poag and Sevon, 1989; Poag, 1992; Pazzaglia and Brandon, 1996; Gradstein and others (2012) time scale], or even earlier. Available ZFT data suggest that material from the western Appalachians did not contribute significantly to basin fill in the Late Triassic-Early Jurassic rift basins. ZFT ages from previous studies in the Hartsford-Deerfield, Newark, Taylorsville, and Richmond basins generally cannot be used to assess provenance of the basin fill because most of the rocks were heated to temperatures sufficiently high to partially to totally reset their zircon ages in the Mesozoic (Roden and Miller, 1991; Kohn and others, 1993; Steckler and others, 1993; Roden-Tice and Wintsch, 2002), including all of the rocks with reported single-grain ages (Kohn and others, 1993). However, in the present study detrital zircons separated from the Poolesville Member of the Late Triassic Manassas Sandstone in the northeastern Culpeper basin in Maryland (Appendix tables A1, A3; samples C&O-9, C&O-11) show no evidence of being reset in the Mesozoic. The samples yield late Paleozoic ZFT ages ( $263 \pm 40$  Ma,  $296 \pm 62$  Ma) typical of the ZFT ages found in bedrock throughout much of the Piedmont and main part of the Blue Ridge, indicating that, at least in this part of the Culpeper basin, rocks were not subjected to the high temperatures in the Mesozoic that affected most ZFT ages in other Triassic basins. As in our bedrock samples, the Manassas Sandstone did not yield any zircon grains with ZFT ages  $>800$  Ma (fig. 3), suggesting that the sampled rift-basin sediments were locally derived, with no input from western Appalachian rocks.

It is possible that rocks in parts of the Culpeper basin not sampled for the present study do contain detritus from the western Appalachians (see, for example, Fail, 2003). However, unless these rocks were subjected to localized, postdepositional heating that reset the zircons, analogous to the resetting that occurred in other rift basins, it seems somewhat unlikely that a thick sequence of rocks with a western provenance could have been present in the basin without at least some of the old zircons from those rocks being subsequently reworked into the Lower Cretaceous-Paleogene Atlantic Coastal Plain sediments.

(3) Up until the late early Oligocene-middle early Miocene, the ZFT data constrain the migration of the drainage divide only to the extent that they indicate that it was somewhere east of rocks in the far western Blue Ridge and Valley and Ridge yielding  $>800$  Ma zircons. Bedrock ZFT ages generally do not change in an obvious, consistent way from east to west across the Piedmont and main part of the Blue Ridge. Therefore, the FT ages of zircons eroded from the bedrock and deposited in the successively younger sediments in the Coastal Plain from the Early Cretaceous through the Paleogene do not effectively track the westward migration of the divide.

Pazzaglia and others (2002) and F. J. Pazzaglia (*in* Braun and others, 2003) suggest that in the ancestral Susquehanna River area a drainage divide that formed on the rift flank in the Mesozoic remained near the boundary between the Piedmont and Valley and Ridge until the early Miocene. Meanwhile, in areas where the Piedmont, and rift basins, are separated from the Valley and Ridge by the Blue Ridge (or similar rocks to the northeast), the drainage divide at least locally migrated west into the Blue Ridge during the Early Cretaceous, based on the Blue Ridge provenance interpreted for detritus in "upper" Potomac Group sediments in the Coastal Plain (Reinhardt and others, 1980a).

The ZFT data clearly show that beginning sometime between the late early Oligocene and middle early Miocene, the drainage divide of one or more rivers,

probably including the Susquehanna and possibly the Potomac and (or) Hudson, migrated west into the far western Blue Ridge-Valley and Ridge, where the river(s) encountered rocks yielding zircons with notably older FT ages. The river(s) began transporting western Appalachian detritus to the Coastal Plain, signaling a significant change in Appalachian drainage patterns.

Of the four periods of unusually high siliciclastic sedimentation rates in offshore basins of the middle Atlantic margin, the least understood in terms of driving processes in the source terrane is the most recent pulse that began in the Miocene and continues to the present day. This latest pulse produced almost 30 percent of the nearly  $1.5 \times 10^6$  km<sup>3</sup> total volume of Middle Jurassic and younger siliciclastic sediments estimated to be in the offshore basins [Pazzaglia and Brandon, 1996, fig. 5A, table 1; Pazzaglia and Gardner, 2000; Gradstein and others (2012) timescale]. The ZFT data indicate that prior to the late early Oligocene-middle early Miocene, Atlantic Coastal Plain sediments were dominated by material eroded from the Piedmont and main part of the Blue Ridge. Detritus from the western Appalachians was not yet reaching the Coastal Plain. The westward migration of the drainage divide and expansion of the drainage basin(s) of one or more east-flowing Atlantic rivers into the western Appalachians by the middle early Miocene gave the river(s) access to the large volume of relatively easily eroded Paleozoic sedimentary rocks of the Valley and Ridge. This arguably contributed at least in part to the sudden increase in the flux of sediments into the offshore basins that peaked in the middle Miocene and continues, at a lower rate, to the present day.

Pazzaglia and others (2002) and F. J. Pazzaglia (in Braun and others, 2003), in interpreting U-Th/He and AFT ages from the Appalachians, hypothesize that the drainage divide that formed on the rift flank in the Mesozoic and remained near the Piedmont-Valley and Ridge boundary until the early Miocene, shifted rapidly west to its present position on the Appalachian Plateau in the middle Miocene, sending a pulse of sediment into the offshore basins.

The relatively easily eroded rocks of the Valley and Ridge may explain in part their proposed jump in the drainage divide. Harbor (1996, 1998), Erickson (1998), and Harbor and others (1998, 2000) present a model of landscape evolution in the central and southern Appalachians that involves episodic rapid erosion and sediment flux and abrupt westward migration of the drainage divide. The presence of relatively easily eroded rocks west of the Blue Ridge and the capture of established along-strike river systems in the Valley and Ridge, leading to flexural isostatic deformation (Pazzaglia and Gardner, 1994) related to the sudden, rapid removal of large volumes of material from the Valley and Ridge and increased sediment load in the continental margin basins, are integral parts of their model.

Both the Harbor/Erickson and Pazzaglia/Braun references suggest that the rapid westward shift in the divide across the Valley and Ridge is progressing from north, where the drainage divide presently lies on the Appalachian Plateau-Adirondack Mountains, to the south. South of the Roanoke River, the headwaters of east-flowing Atlantic rivers that head on the Blue Ridge escarpment appear poised to capture drainage of west-flowing rivers, like the New River, that lie a short distance west in the Blue Ridge (Harbor and others, 2000).

The ZFT and lithic detritus data from Coastal Plain sediments suggest that, at least in the northern part of the study area, the process had begun by the early Miocene.

(4) Finally, detrital zircon FT ages in the Coastal Plain sediments and in sedimentary rocks in the Culpeper basin preserve compelling evidence that the asymmetry of ZFT ages of exposed bedrock in the eastern and western Appalachians that is so well defined at present (figs. 1, 2A, and 2B, table 2) was in evidence by no later than the Early Cretaceous and probably by the Late Triassic. This in turn has implications for the long-term erosional history of the Appalachians.

The pattern of younger ZFT ages in bedrock in the eastern Appalachians and older ages in the west is interpreted as reflecting the difference in thermotectonic history in the two regions. ZFT ages of bedrock samples from the main part of the Blue Ridge and Piedmont were partially to totally reset in the Paleozoic and (or) Mesozoic; the majority samples in the present study were totally reset at various times during the late Paleozoic Alleghanian orogeny. In contrast, most of the rocks presently exposed in the western Appalachians have never been buried to temperatures high enough to totally reset their ZFT ages; some rocks may have remained at sufficiently low temperatures that the zircons have undergone little if any postdepositional annealing.

In the Atlantic Coastal Plain sediments, beginning with the oldest Early Cretaceous sample and continuing up through the section, all of our samples contain a large population of detrital zircon grains yielding late Paleozoic FT ages (figs. 2C and 2D). The presence of these grains in the sediments indicates that rocks with reset, Alleghanian ZFT ages similar to the ZFT ages in rocks presently exposed in the main part of the Blue Ridge and Piedmont had already been exhumed and were being eroded by the Early Cretaceous. Similarly, detrital zircons with Alleghanian FT ages are found in samples of the Late Triassic Manassas Sandstone in the Culpeper basin (fig. 3), meaning that within the drainage basin for these sediments rocks with reset Alleghanian ZFT ages had been exhumed as early as the Late Triassic.

The presence of these rocks at the surface by the Late Triassic implies a period of deep and widespread erosion in the eastern Appalachians during and after the Alleghanian orogeny and prior to the onset of rifting in the Late Triassic. The erosion removed cover rocks containing zircons that were not reset during the Paleozoic, exhuming more deeply buried rocks with reset ages.

Some sense of the exhumation of rocks with reset zircons in a convergent setting is provided by ZFT studies from the Himalaya. Study of the FT ages of detrital zircons eroded from the Himalaya over the last 18 m.y. has shown that for at least that long there have been areas of rapid uplift within the Himalaya where the total elapsed time between a zircon cooling through the FT closure temperature, reaching the surface through uplift and erosion, entering the sedimentary cycle, and being deposited in downstream fluvial sediments is only ~1 to 5 m.y. (Zeitler and others, 1986; Cerveny and others, 1988). Even allowing for the possibility that rates in the Appalachians during the Alleghanian were not as high as in the present-day Himalaya, it is not hard to imagine that zircons that cooled through the ZFT closure temperature during the Alleghanian could have been exhumed, eroded, and deposited in rift basin sediments by the Late Triassic.

The degree of erosion in the Appalachians implied by the ZFT data supports previous interpretations that most of the Paleozoic topography in the ancestral Appalachian Mountains, which by the end of the Alleghanian orogeny may have been similar in size and relief to the modern central Andes, was removed by erosion during the Permian and Early Triassic (Pazzaglia and Brandon, 1996). Virtually all of this material is thought to have been carried to the west, into and far beyond the foreland basin (Pazzaglia and Brandon, 1996; Dickinson and Gehrels, 2003, 2009; Rahl and others, 2003). With the onset of eastward drainage from the Appalachians, detritus from rocks east of the drainage divide was transported to the Coastal Plain and offshore basins. Through the Early Cretaceous and up to the present time, bedrock in the eastern Appalachians with Alleghanian ZFT ages has continued to be exhumed, delivering Alleghanian-age zircons to Early Cretaceous and younger sediments in the Coastal Plain.

ZFT data further indicate that any sediments that accumulated in the Valley and Ridge and Appalachian Plateau during and after the Alleghanian orogeny ultimately had too short a residence time and (or) were sufficiently thin that the presently

exposed rocks were not heated to temperatures high enough to totally reset their ZFT ages.

#### CONCLUSIONS

The difference in ZFT single-grain ages from bedrock samples collected in the western Appalachians (Appalachian Plateau, Valley and Ridge, and far western Blue Ridge) compared to bedrock ZFT ages from the eastern Appalachians (Piedmont and main part of the Blue Ridge) reflects differences in the thermotectonic history of the two regions. Zircon grains yielding very old FT ages, >800 Ma, have only been found in the western Appalachians. Here the exposed rocks have typically been subjected to significantly lower paleotemperatures than bedrock in the east, where most ZFT ages were totally reset in the Paleozoic. The FT ages of detrital zircons in Coastal Plain sediments and Late Triassic Manassas Sandstone in the Culpeper rift basin suggest that rocks with reset ZFT ages, similar to ZFT ages in bedrock presently exposed in the eastern Appalachians, were exhumed by the Late Triassic, by a period of deep erosion in the eastern Appalachians during and following the late Paleozoic Alleghanian orogeny.

Detrital zircon suites from sands collected in the Atlantic Coastal Plain provide a record of detritus eroded from source terranes in the Appalachians during the Mesozoic and Cenozoic. The notable difference in bedrock ZFT single-grain ages from the eastern and western Appalachians can be used to track the changing provenance of Atlantic Coastal Plain sediments. The detrital zircon FT ages from Coastal Plain sediments in Virginia and Maryland indicate that from the Early Cretaceous through the late early Oligocene the dominant source of Coastal Plain sediments was rocks in the Piedmont and main part of the Blue Ridge, possibly with minor input from distant volcanic sources. The first appearance of detrital zircon grains yielding >800 Ma FT ages in middle early Miocene marginal marine sands of the Calvert Formation signals a major change in provenance. The only known source in the present-day watershed of the Atlantic Coastal Plain for zircon grains yielding these very old FT ages is bedrock in the western Appalachians.

From New Jersey south to northern North Carolina, Miocene and younger fluvial-deltaic gravels deposited on the Piedmont and Coastal Plain by the major Atlantic rivers (the Hudson, Delaware, Susquehanna, Potomac, James, and Roanoke) that now head west of the Blue Ridge (or equivalent rocks to the northeast) contain abundant clasts of fossiliferous chert and quartzite and other distinctive rock types derived from Paleozoic rocks in the western Appalachians.

Together, the ZFT and lithic detritus data indicate that the drainage divide of one or more Coastal Plain rivers, probably including the ancestral Susquehanna and possibly the ancestral Potomac and (or) Hudson, migrated west into the western Appalachians sometime between the late early Oligocene and middle early Miocene. The lithic data suggest that the drainage divide of all of the rivers, with the possible exception of the Delaware, had migrated west into the Valley and Ridge, and the rivers were transporting western Appalachian detritus to the Atlantic Coastal Plain, by no later than late middle Miocene.

Migration of the drainage divide into the western Appalachians allowed detritus from the western Appalachians to reach the Atlantic margin for the first time since the Early Cretaceous and possibly for the first time since eastward drainage from the Appalachians was established. Atlantic Coastal Plain rivers thus gained access to the large volumes of relatively easily eroded Paleozoic sedimentary rocks of the western Appalachians, arguably accounting at least in part for the dramatic increase in sediment flux in the offshore basins of the middle Atlantic margin that peaked in the middle Miocene and continues to the present day.

## ACKNOWLEDGMENTS

We thank the late Robert Zimmermann for his early work that paved the way for all later FT studies in the Appalachians, and James Quick and Benjamin Morgan, III, for helping initiate our study. We thank the National Park Service for permission to collect samples in the National Parks, as part of ongoing cooperative USGS-National Park Service studies. We thank colleagues for their guidance and assistance in the field collecting samples: Ben Morgan, in Shenandoah National Park; Arthur Schultz, in Great Smoky Mountains National Park; Rick Bolich, North Carolina Department of Environment and Natural Resources, the RAL-2 core; and Milton Clare, National Park Service, the Beckley-Thurmond samples. We also thank William Burton, Wright Horton, and Michael Kunk for supplying several of the analyzed samples, and Sarah Bergstresser, Kim Buttleman, Peter Chirico, Elisabeth Rowan, and Bruce Wardlaw for help in preparing the figures. The study was supported by funding from the U.S. Geological Survey's National Cooperative Geologic Mapping Program. The paper was improved by comments from John Garver, Glen Izett, Helaine Markewich, Milan Pavich, Frank Pazzaglia, Jeffrey Rahl, and Mary Roden-Tice.

## APPENDIX I

## DATING ZIRCONS AT THE EXTREMES OF AGE AND TRACK DENSITY

C. W. NAESER

Determining the FT age of zircon grains with very low spontaneous FT densities, less than about  $10^5$  tracks/cm<sup>2</sup> (t/cm<sup>2</sup>), and very high track densities, greater than about  $3 \times 10^7$  t/cm<sup>2</sup>, presents analytical problems. The following comments on dealing with such grains are observations based on my 30-plus years of dating zircons using fission tracks.

*General Comments*

Spontaneous track density is a function of uranium concentration and age. The following discussion refers to dating zircon "grains" with low or high spontaneous track densities. In reality, most zircons are zoned with respect to uranium concentration; uranium concentration can vary by an order of magnitude between zones in some zircon grains. When we date a zoned zircon, we do not actually count tracks in the entire grain, but rather confine our counting to one zone, choosing the zone with the largest available counting area that has well-etched tracks and (for old grains or grains with unusually high uranium concentrations) a countable track density.

A single-grain ZFT age is calculated from the spontaneous track density and uranium concentration in the grain, determined from the induced track density in the external detector that covered the grain mount during thermal neutron irradiation (see "Methods"). In a zoned zircon, it is critical that induced track density be determined from exactly the same zone in the zircon that was counted to determine the spontaneous track density. One advantage of using the external detector method to date zircons is that it allows induced track density to be determined not only from the same grain in which spontaneous track density was determined but also from the same zone within the grain.

*Zircons with Very Low Spontaneous Track Densities*

When dating zircons with very low spontaneous track densities ( $< \sim 10^5$  t/cm<sup>2</sup>), typically zircons yielding young, upper Tertiary or Pleistocene FT ages, a major challenge is ensuring that the spontaneous fission tracks are well etched. The time required to etch fission tracks in zircon is generally inversely proportional to the total accumulated radiation damage, which is a function of the uranium concentration and age of the zircon grain. Spontaneous track density serves as an effective proxy for the total radiation damage (Gleadow, 1981; Bernet and others, 2004). Zircon grains with very low spontaneous track densities (low total accumulated radiation damage) require a longer etch time to fully develop spontaneous tracks because of anisotropic etching in grains with low radiation damage (Gleadow, 1980, 1981). For a given etching temperature, the time required to properly etch tracks may be more than twice the etch time a lab typically uses for older zircons.

A long etch time can generally be readily accommodated using a single etch when all of the zircon grains in a sample are from one age population (for example, when etching the primary zircons from a Pleistocene ash bed). The problem arises when very young grains with low spontaneous track densities are part of a detrital suite that contains zircons with a wide range of ages and track densities. In such suites, the

long etch times needed to properly etch the young grains may over etch the older grains and make them uncountable. The multiple-etch procedure described in the “Methods” section was developed to address this situation. Our experience suggests that there is a threshold of spontaneous track density that lies somewhere between  $\sim 10^5$  and  $\sim 10^6$  t/cm<sup>2</sup> beyond which there is sufficient radiation damage in zircons that etching becomes more isotropic (see also Gleadow, 1981) and multiple etch times are no longer needed.

Other challenges that come into play in dating young grains with very few (or no) spontaneous tracks include (1) determining when a grain has been etched long enough to fully etch tracks (Gleadow, 1980); (2) the need to develop a counting strategy that allows all properly etched grains, even those with no spontaneous tracks observed in the counting area, to be included in the analysis (Gleadow, 1980); and (3) the relatively large analytical uncertainties ( $\pm$ ) commonly associated with the ages due to the low numbers of spontaneous tracks present in the grains (see below).

#### *Zircons with Very High Spontaneous Track Densities*

Zircons with very high spontaneous track densities ( $> \sim 3 \times 10^7$  t/cm<sup>2</sup>), typically old grains, present their own problems. Relatively few ZFT ages older than Paleozoic have been reported in the literature—examples include C.W. Naeser (1971), Larson and others (1999), C.W. Naeser and others (2001a, 2002a), and Montario and Garver (2009). In the present study, a large number of old ages were determined—30 of the samples and 360 of the individual zircon grains yielded pre-Cambrian ZFT ages. So it is worth considering why so few old ZFT ages have been reported in the literature and some of the analytical problems and procedures associated with dating such old zircons.

One basic reason why relatively few old ZFT ages have been reported is that zircons in or derived from pre-Cambrian rocks are more likely to have gone through one or more cycles of thermal annealing that partially to totally reset their ages at some point in their history. A good example in the present study is the zircons from Proterozoic rocks in the eastern Appalachians that are reset to Paleozoic ages.

Second, even if resetting has been minimal and the zircons retain pre-Cambrian FT ages, they are often considered undatable because the spontaneous track densities are so high that distinguishing and counting overlapping individual tracks becomes difficult to impossible. Success in counting old grains depends on finding relatively low-uranium grains (or low-uranium zones within the grains) with countable spontaneous track densities. Even at very low uranium concentrations, however, there are limits on the track densities that can be counted, particularly when the counting is done, as it traditionally is in most labs, using an optical microscope (Bernet and others, 2004; Montario and Garver, 2009). In our lab, tracks are counted at 1250 $\times$  magnification using an optical microscope with a 100 $\times$  oil immersion lens and a 1 cm  $\times$  1 cm counting grid divided into 100 squares or, for very high track densities, 400 squares. The highest track density determined during the present study is  $4.74 \times 10^7$  t/cm<sup>2</sup>, which is probably very close to or at the maximum density that I can count with my microscope set up.

Recently, Montario and Garver (2008, 2009) have developed a scanning electron microscope—high-density fission-track (SEM-HDFT) method, which allowed them to count track densities as high as  $2 \times 10^8$  t/cm<sup>2</sup>. By allowing grains with higher spontaneous track densities to be counted than can be counted using traditional optical methods, this development has the potential to significantly increase the number of samples, and number of individual zircon grains in a sample, that can be dated.

To examine the nature of the old grains that were dated in the present study in more detail, I looked at the data from five samples with representative zircon grains. Three of the samples (OG-1, OG-2, and OG-3) are from Tertiary Coastal Plain sands, including one (OG-3) that was treated with the multiple-etch method (table 1, Appendix table A2). Two (C&O-13 and C&O-14) are from Paleozoic sandstones in the western Appalachians (Appendix table A1). Three (OG-1, C&O-13, C&O-14) yielded zircon grains with FT ages  $> 800$  Ma.

Figures A1 and A2 illustrate the range of ZFT age *versus* uranium concentration and spontaneous track density, respectively, for the 120 grains dated in the five selected samples. The grains range in age from 46 to 1574 Ma, uranium concentrations range from 16 to 395 ppm, and spontaneous track densities range from  $1.4 \times 10^6$  to  $4.74 \times 10^7$  t/cm<sup>2</sup>. The range in uranium concentration and spontaneous track density in these five samples essentially encompasses all 1,563 grains dated in the study as a whole. Nine grains, from five western Appalachian samples (GSM-14, GSM-15, C&O-19, GSM-34, T-2), yielded older ZFT ages (ranging from 1594–2960 Ma), but their uranium concentrations (15–36 ppm) and spontaneous track densities ( $1.7 \times 10^7$  to  $3.4 \times 10^7$  t/cm<sup>2</sup>) generally fall within the ranges shown on figures A1 and A2.

Figure A1 shows that for zircons yielding FT ages  $\leq \sim 450$  Ma, grains with a relatively wide range of uranium concentrations could be dated. In contrast, the only datable grains with FT ages  $> 450$  Ma contain  $< \sim 105$  ppm uranium. Thirty-six of the 120 grains yielded pre-Cambrian FT ages. Fifteen yielded ages greater than 800 Ma. In those 15 grains, uranium concentration ranges from 16 to 75 ppm; spontaneous

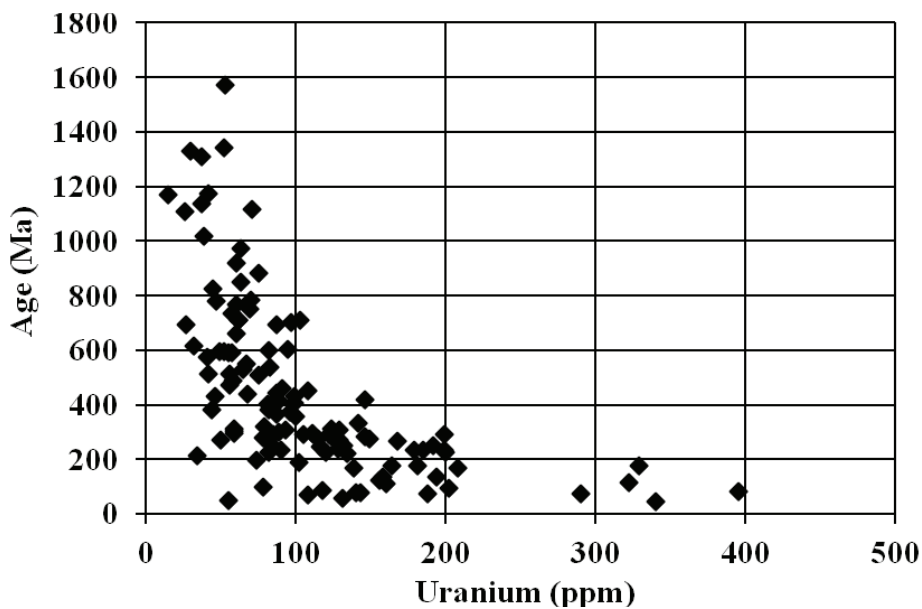


Fig. A1. Relationship of FT age and uranium concentration for the 120 zircon grains dated in samples OG-1, OG-2, OG-3, C&O-13, and C&O-14.

track density varies from  $1.02 \times 10^7$  to  $4.74 \times 10^7$  t/cm<sup>2</sup>. Past a threshold of 1000 Ma, uranium in the datable grains is  $\leq 71$  ppm; most contain  $< 50$  ppm uranium, a trend continued by the nine older grains in the population as a whole.

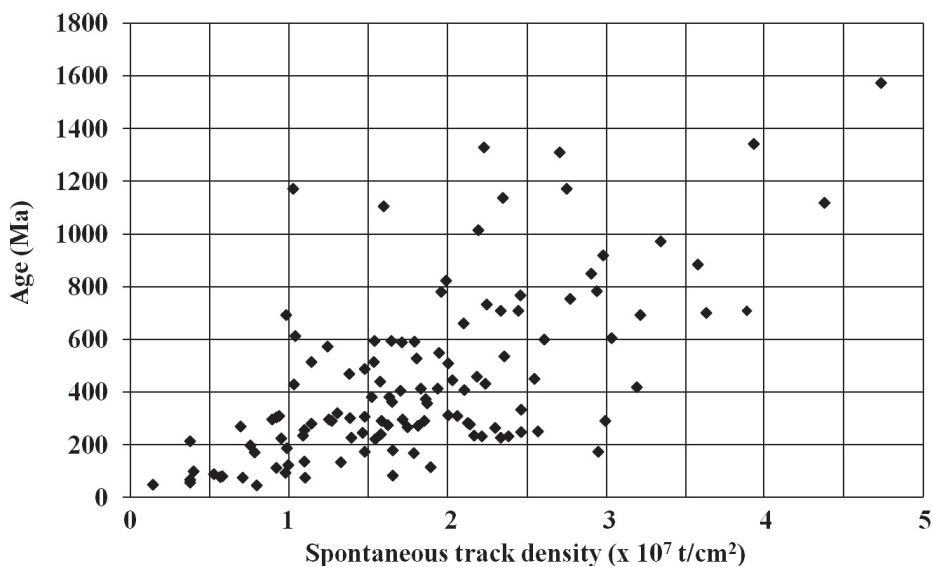


Fig. A2. Relationship of FT age and spontaneous FT density for the 120 zircon grains dated in samples OG-1, OG-2, OG-3, C&O-13, and C&O-14.

Figures A1 and A2 show that age alone is not always a predictor of which zircons will have countable track densities. The oldest grain in the five samples (1574 Ma) contains 53 ppm uranium and has a spontaneous track density of  $4.74 \times 10^7$  t/cm<sup>2</sup>. This is the highest spontaneous track encountered in any of the 1,563 grains dated in the study and, as noted above, is probably at the limit that can be counted with our counting procedures. Note, however, that in seven grains older than 1000 Ma spontaneous track densities are less than  $3 \times 10^7$  t/cm<sup>2</sup> and in two grains are less than  $2 \times 10^7$  t/cm<sup>2</sup>; all seven contain <50 ppm uranium. Conversely, although high spontaneous track densities are typically associated with very old grains, a grain as young as 175 Ma has a spontaneous track density in excess of  $2 \times 10^7$  t/cm<sup>2</sup>.

As in very young grains, another issue that can arise in dating very old grains is the potentially large analytical uncertainty on the ages. Analytical uncertainty on single-grain ages is calculated by combining the Poisson errors associated with the number of spontaneous tracks counted, the number of induced tracks counted, and the number of tracks counted in the neutron dosimeter (see “Methods”). Typically, the number of tracks counted in the neutron dosimeter is sufficiently large ( $\geq 2,500$  in the present study) that its contribution to the total calculated analytical uncertainty on an age is minimal compared to the uncertainty associated with the spontaneous and induced track counts.

In very young grains, it is usually the low number of spontaneous tracks that leads to large analytical uncertainties on the ages. In very old zircons, there are usually relatively large numbers of spontaneous tracks, even in low-uranium grains. However, one consequence of only being able to count spontaneous tracks in grains with low uranium concentration is that relatively few *induced* tracks are produced during thermal neutron irradiation at the neutron fluences typically used in our lab (nominally  $\sim 1 \times 10^{15}$  neutrons/cm<sup>2</sup>). In the 15 grains plotted on figures A1 and A2 that yielded ages >800 Ma, spontaneous-track counts ranged from 112 to 318, but induced-track counts ranged from only 5 to 18. The resulting  $2\sigma$  uncertainties on the individual grain ages (calculated as a percentage of the age) are 49 to 91 percent (*or* 24–46%  $1\sigma$ ). By comparison, the mean percent  $2\sigma$  error for grains <500 Ma is 28 percent (*or* 14%  $1\sigma$ ).

One seemingly obvious solution to low numbers of induced tracks would be to re-irradiate the grain mounts one or more times at higher neutron fluences to increase the number of tracks produced from the low-uranium grains. However, this procedure might not be practical for most labs because of the time and expense involved. And, it would be difficult analytically because at this time there is not a well-calibrated, recognized age standard for ZFT analysis that has a low enough uranium concentration that induced tracks would be countable at significantly higher neutron fluences.

Another way of potentially overcoming the problem of low induced track counts would be to use the SEM-HDFT method of Montarrio and Garver (2008, 2009). Being able to date grains with higher spontaneous track densities opens the possibility of dating grains with higher uranium concentrations, which in turn would result in more induced tracks being produced during thermal neutron irradiation.

TABLE A1

*Elevation, location, stratigraphic unit, stratigraphic age, and lithology of surface samples yielding dated zircon, Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain in West Virginia, Maryland, Virginia, Tennessee, North Carolina, South Carolina, and District of Columbia*

Sample	Elevation (-ft)	7.5-minute quadrangle (-m)	Location	Stratigraphic unit Stratigraphic age Lithology
<b>APPALACHIAN PLATEAU</b>				
<i>C&amp;O Canal-Potomac River traverse, Md.</i>				
C&O-14	2,070	631	Frostburg, Md.-Penn. I-68, south of Frostburg, Md.: road cut, south side of eastbound I-68, just NW of exit 34 (lat 39.6332°N., long 78.9248°W.)	Dunkard Group Late Pennsylvanian-Early Permian Sandstone
C&O-15	1,490	454	Cumberland, Md.- Penn.-W. Va. I-68, between Cumberland and Frostburg, Md.: road cut, SW side of eastbound I-68, mile post 38, just SE of Red Hill (lat 39.6370°N., long 78.8557°W.)	Rockwell Formation Early Mississippian Sandstone
<i>Beckley-Thurmond, W. Va.</i>				
T-1	2,370	722	Beckley, W. Va. U.S. 19, north of Beckley: first major road cut NE of exit from U.S. 64, on SE side of highway under power lines (lat 37.8451°N., long 81.2081°W.)	- <sup>1,2</sup> Early or Middle Pennsylvanian Sandstone
T-2	1,110	338	Thurmond, W. Va. New River Gorge road, west side of river SE of Thurmond: road cut, NW side of road (lat 37.9385°N., long 81.0653°W.)	Pocahontas Formation <sup>1</sup> Early Pennsylvanian Sandstone
T-3	1,400	427	Thurmond, W. Va. Glen Jean-Thurmond road: road cut, SE of road and railroad tracks, just NE of railroad crossing (lat 37.9321°N., long 81.1130°W.)	New River Formation, lower <sup>1</sup> Early Pennsylvanian Sandstone
<i>Morgantown, W. Va.</i>				
M-1	910	277	Lake Lynn, Penn.- W. Va. Cheat Lake, W. Va., area, SE of Ices Ferry Bridge: road cut, NE side of junction of Mont Chateau Rd. with abandoned road (lat 39.6666°N., long 79.8575°W.)	Conemaugh Formation <sup>3</sup> Late Pennsylvanian Sandstone
<i>Great Smoky Mountains region, Tenn.</i>				
GSM-34	800	244	Windrock, Tenn. S.R. 62, Oliver Springs: road cut, NE side of road, ~3 m NW of Morgan County-Roane County line (lat 36.0483°N., long 84.3478°W.)	Lee Formation Early Pennsylvanian Sandstone
GSM-35	1,360	415	Duncan Flats, Tenn. S.R. 116, New River-Stainville area: first major road cut SE of bridge over New River (lat 36.2107°N., long 84.3207°W.)	Wartburg Sandstone Early Pennsylvanian Sandstone
GSM-36	1,830	558	Lake City, Tenn. S.R. 116, SE of Graves Gap: small road cut, uphill (NE) side of road, about one-third of the way downhill between sharp switchbacks to the NW and SE (lat 36.1440°N., long 84.2418°W.)	Yowell Mountain Formation Middle Pennsylvanian Sandstone

TABLE A1  
(continued)

Sample	Elevation (-ft) (-m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology	
<b>VALLEY AND RIDGE</b>					
<i>C&amp;O Canal-Potomac River traverse, Md.</i>					
C&O-13	1,230	375	Bellevue, Md.-Penn.-W. Va.	I-68, Sideling Hill, Md.; NW side of westbound I-68 at west end of Sideling Hill road cut (lat 39.7197°N., long 78.2875°W.)	Rockwell Formation Early Mississippian Sandstone
C&O-16	490	149	Hancock, Md.-W. Va.-Penn.	I-68, between Hancock and Sideling Hill, Md.; large outcrop, SE side of Sandymile Rd., at SW end of bridge over I-68 (lat 39.7122°N., long 78.2298°W.)	Oriskany Formation Early Devonian Sandstone
C&O-17	430	131	Hedgesville, W. Va.-Md.	McCoy's Ferry, Md., south of I-70; railroad cut, NW side of CSX tracks, just NE of railroad bridge over McCoy's Ferry Rd. (lat 39.6092°N., long 77.9698°W.)	Tuscarora Sandstone Early Silurian Sandstone
C&O-18	400	122	Hedgesville, W. Va.-Md.	McCoy's Ferry Rd., Md., south of I-70; large outcrop, NE side of road, ~0.5 km NW of CSX railroad bridge (lat 39.6123°N., long 77.9727°W.)	Mahantango Formation Middle Devonian Sandstone
C&O-19	400	122	Williamsport, Md.-W. Va.	Williamsport, Md.; outcrop, NE side of CSX tracks and Bottom Rd., ~3 km NW of Williamsport (lat 39.6138°N., long 77.8437°W.)	Martinsburg Formation Ordovician Sandstone
<i>Shenandoah National Park region, Va.</i>					
SNP-31	700	213	Strasburg, Va.	S.R. 678 (Passage Creek road), Fort Valley, Massanutten Mountain: road cut beside pullout on NW side of road (lat 38.9430°N., long 78.3105°W.)	Massanutten Sandstone <sup>4</sup> Latest Silurian Sandstone
<i>Great Smoky Mountains region, Tenn.</i>					
GSM-20	1,100	335	Blockhouse, Tenn.	Little Mountain: road cut, east side of Montvale Rd., SE of Sixmile (lat 35.6502°N., long 83.9508°W.)	Grainger Formation <sup>5</sup> Early Mississippian Sandstone
GSM-33	2,000	610	Avondale, Tenn.	U.S. 25E, Clinch Mountain: road cut, SW side of unnamed road on SW side of U.S. 25E in Beans Gap, opposite intersection of U.S. 25E with unnamed road to NW (lat 36.3507°N., long 83.3980°W.)	Bays Formation Middle Ordovician Sandstone
<i>Other Valley and Ridge samples, W. Va. and Va.</i>					
V&R-1	4,850	1,478	Spruce Knob, W. Va.	Spruce Knob: outcrop, SE side of trail between parking lot and lookout tower at the top of Spruce Knob (lat 38.7005°N., long 79.5322°W.)	Mauch Chunk Group Pennsylvanian Sandstone
V&R-2	4,670	1,423	Spruce Knob, W. Va.	N.F. 104 (Spruce Knob road): road cut, SE side of road, just SW of side road to radio tower (lat 38.6923°N., long 79.5430°W.)	Mauch Chunk Group Late Mississippian-early Pennsylvanian Sandstone
V&R-3	4,236	1,291	Spruce Knob, W. Va.	N.F. 112 (Spruce Knob road): road cut, NW side of road, just NE of ~1,291-m (4,236-ft) bench mark (lat 38.7045°N., long 79.5208°W.)	Mauch Chunk Group Late Mississippian-early Pennsylvanian Sandstone

TABLE A1  
(continued)

Sample	Elevation (-ft) (-m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>VALLEY AND RIDGE</b>				
<i>Other Valley and Ridge samples, W. Va. and Va.</i>				
V&R-4	2,660	811	Circleville, W. Va. Spruce Knob area: large outcrop, NE side of C.R. 33-4 (Briery Gap Run road) downhill from Pocono Group Sandstone	Late Devonian-early Mississippian Sandstone
V&R-5	2,320	707	Circleville, W. Va. Spruce Knob area: first massive sandstone on NE side of C.R. 33-4 (Briery Gap Run road) uphill from junction with U.S. 33	Hampshire Formation Sandstone
V&R-6	1,609	490	Briery Branch, Va. Rockingham Co.: road cut, NE side of S.R. 257, just NW of ~490-m- (1,609-ft.) elevation road junction	Hampshire Formation Sandstone
V&R-7	4,200	1,280	Reddish Knob, Va.-W. Va. (lat 38.4457°N., long 79.1043°W.) Reddish Knob road, W. Va.: road cut, SE side of switchback just NE of Stony Run Overlook	Pocono Group Sandstone
V&R-8	2,040	622	Reddish Knob, Va.-W. Va. Briery Branch Dam, Va.: large quarry SE of Briery Branch Dam and NE of S.R. 924	Late Devonian-early Mississippian Sandstone
<b>FAR WESTERN BLUE RIDGE</b>				
<i>Shenandoah National Park region, Va.</i>				
SNP-28	770	235	Bentonville, Va. S.R. 630 (Thompson Hollow Rd.), SE of Bentonville: road cut, SE side of road, south of junction with Brush Mountain Rd	Harpers Formation <sup>4</sup> Early Cambrian Conglomerate
SNP-29	840	256	Bentonville, Va. S.R. 662, SE of Compton: well-exposed road cut, NE side of road	Weverton Formation(?) <sup>4</sup> Early Cambrian Sandstone
SNP-32	640	195	Front Royal, Va. East of Front Royal: road cut, north side of S.R. 647 (Dismal Hollow Rd.)	Harpers Formation <sup>4</sup> Early Cambrian Sandstone
<i>Great Smoky Mountains region, Tenn.</i>				
GSM-11	1,020	311	Pigeon Forge, Tenn. Walden Creek: large road cut, NE side of U.S. 321, SW of intersection with road to Walden Creek	Shields Formation <sup>5</sup> Neoproterozoic Sandstone
GSM-12	1,100	335	Kinzel Springs, Tenn. Kinzel Springs: large road cut, NW side of U.S. 321, on second major curve NW of Kinzel Springs	Wilhite Formation <sup>5</sup> Neoproterozoic Sandstone
GSM-13	900	274	Tallasssee, Tenn. Chilhowee Dam: north side of U.S. 129, opposite a point about halfway between NE end of Chilhowee Dam and power lines to the west	Wilhite Formation <sup>5</sup> Neoproterozoic Sandstone

TABLE A1  
(continued)

Sample	Elevation (-ft) (~m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>FAR WESTERN BLUE RIDGE</b>				
<i>Great Smoky Mountains region, Tenn.</i>				
GSM-14	865	264	Tallessee, Tenn. Buzzard Roost: ~12 m up bank, NE side of U.S. 129, directly north of gap between Harrison Island and unnamed island to the west in the Little Tennessee River (lat 35.5420°N., long 84.0837°W.)	Sanduck Formation <sup>5</sup> Neoproterozoic Sandstone
GSM-15	1,725	526	Kinzel Springs, Tenn. Foothills Parkway: ~9-12 m above road level, NW side of Parkway opposite unnamed overlook, just NE of mile 3 marker (lat 35.7080°N., long 83.8558°W.)	Hesse Quartzite <sup>5</sup> Early Cambrian Quartzite
GSM-16	2,540	774	Cades Cove, Tenn.-N.C. Rich Mountain Rd., Tenn.: outcrop, NW side of road, on west side of Rich Mountain Rd.-Indian Grave Gap Rd. intersection (lat 35.6235°N., long 83.8157°W.)	Cades Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-18	1,920	585	Gatlinburg, Tenn. S.R. 73 (Little River road): road cut, SE side of road, between mile 46 and mile 47 of Little River (lat 35.6660°N., long 83.6243°W.)	Thunderhead Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-19	1,435	437	Wear Cove, Tenn. S.R. 73 (Little River road) in Little River Gorge: road cut, NW side of road, opposite junction of Meigs Creek with Little River, between mile 40 and mile 41 of Little River (lat 35.6693°N., long 83.6763°W.)	Cades Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-21	1,590	485	Gatlinburg, Tenn. Starkeytown: outcrop, NW side of Mill Creek road, SW of Starkeytown (lat 35.7310°N., long 83.5783°W.)	Thunderhead Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-22	1,070	326	Richardson Cove, Tenn. S.R. 416, SW of Richardson Cove: SE end of major road cut on NE side of road (lat 35.8107°N., long 83.4615°W.)	Shields Formation <sup>5</sup> Neoproterozoic Sandstone
GSM-23	1,560	475	Jones Cove, Tenn. East end of Webb Mountain: outcrop ~2.4 m up bank, SE side of Rocky Flats Rd. and Dunn Creek, just downstream from junction with Matthew Creek (lat 35.7925°N., long 83.3015°W.)	Roaring Fork Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-24	~2,500' ~762'		Gatlinburg, Tenn. Cove Mountain: King Hollow Branch (lat 35.7090°N., long 83.6050°W.) <sup>7</sup>	Unnamed <sup>7</sup> Mesoproterozoic Metagranitoid
GSM-25	2,200	671	Hartford, Tenn.-N.C. Foothills Parkway, Tenn.: large road cut, NW side of road, opposite NE end of large scenic overlook, overlooking Possum Hollow (lat 35.8129°N., long 83.2236°W.)	Cochran Formation <sup>5</sup> Early Cambrian Sandstone
GSM-26	1,240	378	Hartford, Tenn.-N.C. Pigeon River, Tenn.: road cut, SE side of river and Hartford-Denton service road, just NE of I-40 overpass, at ~mile 19 of the river (lat 35.8150°N., long 83.1773°W.)	Cochran Formation <sup>5</sup> Early Cambrian Sandstone
GSM-30	1,960	597	Gatlinburg, Tenn. S.R. 73 (Little River road): SW end of road cut on NW side of road, across from pullout, between mile 47 and mile 48 of Little River (lat 35.6637°N., long 83.6135°W.)	Thunderhead Sandstone <sup>5</sup> Neoproterozoic Metasandstone

TABLE A1  
(continued)

Sample	Elevation (-ft) (-m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>FAR WESTERN BLUE RIDGE</b>				
<i>Great Smoky Mountains region, Tenn.</i>				
GSM-31	2,400	732	Calderswood, Tenn.-N.C. Parson Branch Rd., Tenn.: road cut, NW side of road, SW of junction with Bunker Hill Rd. (lat 35.5322°N., long 83.9117°W.)	Cades Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-37	1,160	354	Richardson Cove, Tenn. Bird Creek road, south of S.R. 416: road cut, NE side of abandoned loop on Bird Creek road (lat 35.7950°N., long 83.4578°W.)	Pigeon Siltstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-38	1,210	369	Richardson Cove, Tenn. S.R. 416, SE of Laurel: road cut, NE side of dead-end road that intersects S.R. 416 at east end of Little Pigeon River bridge (lat 35.7772°N., long 83.4053°W.)	Pigeon Siltstone <sup>5</sup> Neoproterozoic Metasandstone
<b>MAIN BLUE RIDGE</b>				
<i>C&amp;O Canal-Potomac River traverse, Md. and Va.</i>				
C&O-1	300	91	Harpers Ferry area, Md.: north side of Potomac River and C&O Canal, north of Lock No. 35 (lat 39.3370°N., long 77.7512°W.)	Anietiam Formation Early Cambrian Sandstone
C&O-3	675	206	Hillsboro: Short Hill Mountain, south of North Fork Catoclin Creek, ~0.6 km west of Hillsboro, on SE side of Short Hill fault (lat 39.1985°N., long 77.7323°W.)	Weverton Formation Early Cambrian Sandstone
C&O-8	1,560	475	Gambrell State Park: outcrop, NE side of ridge road just north of junction with Park service road from the NE, ~1.6 km NE of intersection with High Knob road (lat 39.4783°N., long 77.4927°W.)	Weverton Formation Early Cambrian Sandstone
<i>Shenandoah National Park region, Va.</i>				
SNP-1	3,840	1,170	Fork Mountain radio tower (lat 38.4792°N., long 78.4160°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-2	2,700	823	Fork Mountain: road cut, NE side of radio tower road, NE of Staunton River (lat 38.4647°N., long 78.4105°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-3	2,540	774	Fork Mountain: road cut, NE side of radio tower road, north of Staunton River (lat 38.4627°N., long 78.3993°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-4	2,060	628	Fork Mountain: road cut, SW side of radio tower between Staunton River and Rapidan River drainages (lat 38.4642°N., long 78.3860°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-6	1,300	396	Rapidan River: outcrop in riverbed, opposite (west of) junction of Rapidan River road and S.R. 649 (Quaker Run road) (lat 38.4623°N., long 78.3663°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses

TABLE A1  
(continued)

Sample	Elevation (-ft) (~m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>MAIN BLUE RIDGE</b>				
<i>Shenandoah National Park region, Va.</i>				
SNP-7	1,290	393	Madison, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-10	900	274	Madison, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-13	1,770	540	Thornton Gap, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-19	3,240	988	Big Meadows, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-20	2,400	732	Big Meadows, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-21	2,100	640	Big Meadows, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-22	1,700	518	Big Meadows, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-23	1,070	326	Thornton Gap, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-24	2,460	750	Chester Gap, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-25	3,115	949	Bentonville, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-27	1,220	372	Thornton Gap, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-30	710	216	Bentonville, Va.	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			S.R. 649 (Quaker Run road): road cut on inside of hairpin curve, on Shenandoah National Park boundary (lat 38.4577°N., long 78.3513°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			S.R. 662: outcrop south of road and Rapidan River, between Staunton River-Rapidan River junction and Graves Mill (lat 38.4358°N., long 78.3655°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			U.S. 211: road cut, NW side of road, between Piedmont Picnic Area and Thornton Gap (lat 38.6613°N., long 78.3033°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			Appalachian Trail: outcrop on Appalachian Trail, NE of Spittler Knoll Overlook on Skyline Drive (lat 38.5485°N., long 78.4142°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			Redgate Rd.: road cut, NE side of road, just uphill from second switchback from the top <sup>9</sup> (lat 38.5498°N., long 78.4235°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			Redgate Rd.: road cut, east side of road, uphill from fifth switchback from the top (lat 38.5488°N., long 78.4258°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			Redgate Rd.: road cut, NE side of road uphill from National Park Service gate, between sixth and seventh switchbacks from the top (lat 38.5507°N., long 78.4328°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			U.S. 211: outcrop in Pass Run stream bed, NW of junction of U.S. 211 with road to Shenandoah National Park Headquarters (lat 38.6633°N., long 78.3737°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			Skyline Drive: road cut, SW side of road, between Jenkins Gap and Hogwallow Flat Overlooks (lat 38.8017°N., long 78.1775°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			Skyline Drive: road cut, NW side of road, between Little Hogback and Little Devil Stairs Overlooks (lat 38.7575°N., long 78.2673°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			U.S. 211: road cut, NE side of road, between Sperryville and Thornton Gap, south of Piedmont Picnic Area (lat 38.6608°N., long 78.2897°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
			S.R. 622 (Buck Mountain Rd.), SE of Limeton: road cut, NW side of road (lat 38.8480°N., long 78.2648°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses

TABLE A1  
(continued)

Sample	Elevation (-ft) (-m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>MAIN BLUE RIDGE</b>				
<i>Shenandoah National Park region, Va.</i>				
SNP-36	2,600	792	Sherando, Va. Blue Ridge Parkway below Meadow Mt.: road cut, NW side of Parkway ~350 m SW of ~806-m (2,644-ft) bench mark (lat. 37.8952°N., long. 78.9952°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-37	1,080	329	Sherando, Va. South Fork Rockfish River: outcrop in river on north side of S.R. 664, ~400 m east of ~346-m- (1,136-ft) elevation road junction (lat. 37.8792°N., long. 78.9545°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-39	600	183	Greenfield, Va. S.R. 6: road cut, NE side of road, ~0.7 km NW of ~184-m- (605-ft-) elevation road junction (lat. 37.8963°N., long. 78.8312°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
SNP-40	600	183	Greenfield, Va. S.R. 6: road cut, east side of road, south of bridge over North Fork Rockfish River (lat. 37.9057°N., long. 78.8325°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
PM-7	650	198	Massies Comer, Va. S.R. 729, NW of Ben Venue, at SE end of Meetinghouse Mtn: first large outcrop NE of U.S. 211, on NE side of road (lat. 38.7255°N., long. 78.0687°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
K03-6-10M <sup>10</sup>	515	157	Rochelle, Va. Burtonville area: C.R. 609, west of Burtonville, just before Buckner Run bridge (lat. 38.2832°N., long. 78.3735°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
K03-6-10N <sup>10</sup>	580	177	Rochelle, Va. Burtonville area: C.R. 645 east of U.S. 29, just south of Burtonville (lat. 38.2627°N., long. 78.3508°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses Robertson River Igneous Suite Neoproterozoic Metagranitoids
<i>Blue Ridge Parkway, James River gorge area, Va.</i>				
BRP-1	690	210	Big Island, Va. S.R. 130 west of Blue Ridge Parkway, on NE side of James River: road cut, SE side of intersection of S.R. 130 and Bedford Hydro Plant road (lat. 37.5762°N., long. 79.3742°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
BRP-2	2,890	881	Snowden, Va. Blue Ridge Parkway mile 72.6: road cut, NW side of Parkway, opposite Terrapin Mountain Overlook (lat. 37.5448°N., long. 79.4652°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
BRP-4	2,160	658	Snowden, Va. Blue Ridge Parkway mile 70.1: road cut, NW side of Parkway between Petites Gap and James River Valley Overlook (lat. 37.5572°N., long. 79.4428°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses
BRP-6	1,180	360	Snowden, Va. Blue Ridge Parkway mile 66.6: road cut, NE side of Parkway, SE of Falling Rock Creek (lat. 37.5628°N., long. 79.4083°W.)	Unnamed <sup>8</sup> Mesoproterozoic Metagranitoids and orthogneisses

TABLE A1  
(continued)

Sample	Elevation (-ft) (~m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>MAIN BLUE RIDGE</b>				
<i>Grandfather Mountain region, Tenn. and N.C.</i>				
BR-2	2,920	890	Mountain City, Tenn. U.S. 421, NE of Evergreen Church: large road cut, SW side of highway, ~25 m north of mile 21 marker (lat 36.3869°N., long 81.7590°W.)	Cranberry Gneiss <sup>11</sup> Mesoproterozoic Metagranitoid and gneiss
BR-6	1,470	448	Buffalo Cove, N.C. U.S. 321, SE of Nelsons Chapel: road cut, NE side of highway, just NW of Kirby Mountain Rd. (lat 36.0356°N., long 81.5950°W.)	Proterozoic Schist
BR-7	2,800	853	Globe, N.C. U.S. 321, NW of Robbins Gap: road cut, NE side of highway (lat 36.0965°N., long 81.6409°W.)	Blowing Rock Gneiss <sup>13</sup> Mesoproterozoic Gneiss
BR-8	1,380	421	Maple Springs, N.C. U.S. 421, NW of Maple Springs: road cut, NE side of highway (lat 36.1810°N., long 81.3881°W.)	Unnamed <sup>14</sup> Proterozoic and (or) Paleozoic Gneiss
BR-11	5,260	1,603	Grandfather Mountain, N.C. Grandfather Mountain visitors center: prominent outcrop at NE end of parking lot (lat 36.0963°N., long 81.8313°W.)	Grandfather Mountain Formation <sup>15</sup> Neoproterozoic
BR-12	4,720	1,439	Grandfather Mountain, N.C. Grandfather Mountain Nature Center: prominent outcrop on north side of small, northern parking lot (lat 36.0908°N., long 81.8360°W.)	Arkose Grandfather Mountain Formation <sup>15</sup> Neoproterozoic
BR-13	4,250	1,295	Grandfather Mountain, N.C. U.S. 221: road cut, NW side of junction with Blue Ridge Parkway access road (lat 36.0861°N., long 81.8309°W.)	Arkose Grandfather Mountain Formation <sup>15</sup> Neoproterozoic
<i>Great Smoky Mountains region, Tenn. and N.C.</i>				
GSM-1	6,400	1,951	Clingmans Dome, N.C.: outcrop, east side of Clingmans Dome lookout tower trail (lat 35.5590°N., long 83.4962°W.)	Copperhill Formation <sup>5</sup> Neoproterozoic
GSM-2	6,280	1,914	Clingmans Dome, N.C.: outcrop NW of road at NE end of Forney Ridge parking loop (lat 35.5575°N., long 83.4940°W.)	Metagraywacke Copperhill Formation <sup>5</sup> Neoproterozoic
GSM-3	5,520	1,683	Clingmans Dome, N.C.: road cut, west side of road between ~1,697-m (5,567-ft) and ~1,666-m (5,465-ft) bench marks (lat 35.5988°N., long 83.4533°W.)	Metagraywacke Copperhill Formation <sup>5</sup> Neoproterozoic
GSM-4	2,280	695	Smokemont, N.C. Tow String Creek road: road cut, NW side of road, ~0.25 km inside Great Smoky Mountains National Park boundary (lat 35.5410°N., long 83.2908°W.)	Metagraywacke Unnamed <sup>5</sup> Mesoproterozoic
GSM-5	2,540	774	Smokemont, N.C. U.S. 441 (Newfound Gap road): road cut, SW side of road, between ~781-m (2,561-ft) and ~745-m (2,444-ft) bench marks, SW of Shell Bark Branch of Oconalufee River (lat 35.5773°N., long 83.3455°W.)	Metagranitoid Copperhill Formation <sup>5</sup> Neoproterozoic Metagraywacke

TABLE A1  
(continued)

Sample	Elevation (-ft) (~m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>MAIN BLUE RIDGE</b>				
<i>Great Smoky Mountains region, Tenn. and N.C.</i>				
GSM-6	4,260	1,298	Clingmans Dome, N.C.- Tenn. U.S. 441 (Newfound Gap road), N.C.: road cut, SW side of road, on NE side of Thomas Ridge (lat 35.5962°N., long 83.4083°W.)	Copperhill Formation <sup>5</sup> Neoproterozoic Metagraywacke
GSM-7	4,640	1,414	Clingmans Dome, N.C.- Tenn. U.S. 441 (Newfound Gap road), N.C.: road cut, NW side of road, at SE end of Thomas Ridge (lat 35.5862°N., long 83.3985°W.)	Copperhill Formation <sup>5</sup> Neoproterozoic Metagraywacke
GSM-8	4,840	1,475	Clingmans Dome, N.C.- Tenn. U.S. 441 (Newfound Gap road), Tenn.: road cut, SW side of road, NE of Morton Overlook (lat 35.6170°N., long 83.4215°W.)	Anakeesta Formation <sup>5</sup> Neoproterozoic Metasandstone
GSM-9	3,460	1,055	Mount Le Conte, Tenn.- N.C. U.S. 441 (Newfound Gap road), Tenn.: road cut, NE side of road, NW of "The Loop" and opposite Chimney Tops trailhead (lat 35.6353°N., long 83.4693°W.)	Thunderhead Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-10	2,440	744	Gatlinburg, Tenn. U.S. 441 (Newfound Gap road); outcrop, SW side of road, NW of Steep Branch of West Prong Little Pigeon River (lat 35.6443°N., long 83.5087°W.)	Thunderhead Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-17	1,385	422	Mount Le Conte, Tenn.- N.C. NW of Greenbrier Ranger Station, Tenn.: outcrop, SW bank of Little Pigeon River, NE of Greenbrier road (lat 35.7338°N., long 83.4123°W.)	Roaring Fork Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-28	3,895	1,187	Fines Creek, N.C. S.R. 209, Betsy Gap, NE of Cove; road cut, NE side of road in Madison County, ~1.5 m SE of county-line sign (lat 35.6885°N., long 82.8983°W.)	Spring Creek Metagranitoid <sup>16</sup> Mesoproterozoic Metasandstone
GSM-29	2,360	719	Fines Creek, N.C. Lower Fines Creek Rd.; road cut, NW side of road, ~15 m SW of Panther Creek Rd. (lat 35.6697°N., long 82.9942°W.)	Spring Creek Metagranitoid <sup>16</sup> Mesoproterozoic Metasandstone
GSM-32	1,500	457	Calderwood, Tenn.-N.C. Parson Branch Rd., Tenn.: outcrop, south bank of Parson Branch just SE of Parson Branch Rd. (lat 35.5025°N., long 83.9298°W.)	Elkmont Sandstone <sup>5</sup> Neoproterozoic Metasandstone
GSM-40	2,080	634	Smokemont, N.C. Blue Ridge Parkway between mile 468 and 469; road cut, SE side of Parkway, on first major bend NE of Oconaluftee River bridge (lat 35.5088°N., long 83.2977°W.)	Unnamed <sup>5</sup> Mesoproterozoic Metagranitoid
GSM-41	3,560	1,085	Smokemont, N.C. Blue Ridge Parkway ~mile 464.5; road cut, SW side of Parkway (lat 35.5162°N., long 83.2555°W.)	Copperhill Formation <sup>5</sup> Neoproterozoic Metagraywacke
GSM-42	4,260	1,298	Bunches Bald, N.C. Blue Ridge Parkway ~mile 462.5; road cut, SSE side of Parkway, SW of road to Barnett Knob lookout tower (lat 35.5243°N., long 83.2318°W.)	Copperhill Formation <sup>5</sup> Neoproterozoic Metagraywacke

TABLE A1  
(continued)

Sample	Elevation (-ft) (~m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>MAIN BLUE RIDGE</b>				
<i>Great Smoky Mountains region, Tenn. and N.C.</i>				
GSM-46	4,980	1,518	Cruso, N.C.	Ashe Metamorphic Suite Neoproterozoic Gneiss
GSM-47	3,900	1,189	Shining Rock, N.C.	Ashe Metamorphic Suite Neoproterozoic Gneiss
GSM-48	3,200	975	Shining Rock, N.C.	Unnamed Early Paleozoic Granitoid
GSM-49	2,280	695	Shining Rock, N.C.	Ashe Metamorphic Suite Neoproterozoic Gneiss
<b>PIEDMONT</b>				
<i>C&amp;O Canal-Potomac River traverse, Md., Va., and D.C.</i>				
C&O-9	260	79	Buckeystown, Md.-Va.	Manassas Sandstone, Poolesville Member Late Triassic Sandstone
C&O-10	260	79	Buckeystown, Md.-Va.	Urbania Formation Early(?) Cambrian Sandstone
C&O-11	200	61	Seneca, Md.-Va.	Manassas Sandstone, Poolesville Member Late Triassic Sandstone
C&O-12	230	70	Germentown, Md.	Marburg Formation Neoproterozoic-Early Cambrian Sandstone
C&O-21	310	94	Frederick, Md.	Frederick Limestone, Rocky Springs Station Member Late Cambrian Sandstone
C&O-22	~280	~85	Frederick, Md.	Grove Limestone Late Cambrian-Early Ordovician Sandstone

TABLE A1  
(continued)

Sample	Elevation (-ft) (-m)	7.5-minute quadrangle	Location	Stratigraphic unit Stratigraphic age Lithology
<b>PIEDMONT</b>				
<i>C&amp;O Canal-Potomac River traverse, Md., Va., and D.C.</i>				
K91-5-20A <sup>10</sup>	330	101	Seneca, Md.-Va.	Beach Mill Rd., SE of Leighs, Va.; outcrop ~115 m north of road, SE of Jefferson Branch of Pre-Devonian Schist
K91-5-21E <sup>10</sup>	85	26	Washington West, D.C.-Md.-Va.	Rock Creek Park, D.C.; outcrop east of Rock Creek and National Zoological Park, south of Irving St.
K91-5-21F <sup>10</sup>	10	3	Washington West, D.C.-Md.-Va.	Chain Bridge, Va.; outcrop, SW side of Potomac River, ~60 m south of Chain Bridge (lat 38.9288°N., long 77.1174°W.)
K91-5-22B <sup>10</sup>	125	38	Falls Church, Va.-Md.	Turkey Run Recreation Area, Va.; outcrop between Potomac River and George Washington Memorial Parkway
K91-5-22D <sup>10</sup>	165	50	Falls Church, Va.-Md.	Glen Echo-Goldsboro Rd. area, Md.; outcrop NW of Goldsboro Rd., ~90 m north of Goldsboro Rd.-MacArthur Blvd. intersection (lat 38.9718°N., long 77.1383°W.)
<i>Great Smoky Mountains region, N.C. and S.C.</i>				
GSM-50	2,500	762	Brevard, N.C.-S.C.	U.S. 276, south of Brevard, N.C.; road cut, NE side of road, on SW side of Bill Raines Mountain (lat 35.1693°N., long 82.7332°W.)
GSM-53	1,020	311	Cleveland, S.C.	U.S. 276, NW of Cleveland; road cut, SW side of highway, near SE end of the straight stretch of highway SE of intersection with Gap Creek road (lat 35.0760°N., long 82.5333°W.)
<i>Other Piedmont surface samples, Va. and N.C.</i>				
PM-1	250	76	Richardsville, Va.	Fauquier Co., SE of Morrisville; outcrop, SW bank of Rock Run creek downstream of S.R. 651 (lat 38.4505°N., long 77.6792°W.)
PM-4	20	6	Fredericksburg, Va.	Fredericksburg; outcrop, SE side of Rappahannock River opposite east end of Laucks Island (lat 38.3195°N., long 77.4767°W.)
K03-6-12H <sup>10</sup>	200	61	Columbia, Va.	Columbia area: C.R. 6, on east edge of Columbia (lat. 37.7502°N., long 78.1597°W.)
RE1-255 <sup>20</sup>	810	247	Southeast Eden, N.C.	Martin Marietta Reidsville quarry; sample estimated to be ~9.1 m below original land surface (lat 36.3770°N., long 79.7242°W.)

TABLE A1  
(continued)

Sample	Elevation (-ft)	7.5-minute quadrangle (-m)	Location	Stratigraphic unit Stratigraphic age Lithology
<b>COASTAL PLAIN</b>				
<i>Coastal Plain surface samples, Md. and Va.</i>				
CP-1	15	5	Colonial Beach North, Va.-Md. East bank, Potomac River, Md.: outcrop ~1.1 km north of Harry W Nice Memorial Bridge (U.S. 301 (lat 38.3730°N., long 76.9845°W.))	Calvert Formation, Popes Creek Sand Member Middle early Miocene <sup>21</sup> Sand
OC	3	1	Tunstall, Va. Pamankey River: outcrop, SE side of river, ~3 km NW of Tunstall (lat 37.6230°N., long 77.1147°W.)	Old Church Formation Late early Oligocene <sup>21</sup> Sand

Analytical data are in Appendix table A3.

1. Interstate; S.R., State Route; C.R., County Route, N.F., National Forest road.

2. Stratigraphy from Cardwell and others (1968) and Milton Clare (National Park Service, New River Gorge National River, personal communication, 2004).

3. Formation uncertain; sample collected near the boundary between the Lower Pennsylvanian New River Formation and Middle Pennsylvanian Kanawha Formation.

4. Stratigraphy from Cardwell and others (1968).

5. Stratigraphy from Southworth and others (2009a).

6. Stratigraphy from Southworth and others (2012).

7. Stratigraphy from King and others (1968).

8. Unnamed, Southworth and others (2012); sample is float; latitude and longitude are approximate; elevation at sample site is estimated to be within 30 m of the outcrop.

9. Unnamed Mesoproterozoic metagranitoids and orthogneisses of the Blue Ridge in Virginia and Maryland (as in Southworth and others, 2009a, 2010a). Includes a diverse assemblage of rocks historically mapped as "Pedlar" and "Livingston" formations (or massifs) (for example, Gathright, 1976; Spencer, 1994).

10. Sample from approximately same location as Gathright's (1976, plate 2) sample R-4448.

11. Collected by Michael J. Kunk, U.S. Geological Survey, Reston, Va.

12. Stratigraphy based on Rankin and others (1972).

13. Sampled rocks mapped as Wilson Creek Gneiss (Mesoproterozoic) by Bryant and Reed (1970) and as unnamed rocks in the Crossnore plutonic-volcanic group (pCcg) (Neoproterozoic) by Rankin and others (1972).

14. Sample collected in Blowing Rock Gneiss, near Wilson Creek Gneiss contact (Bryant and Reed, 1970).

15. Sampled rocks mapped as "pg" ("Precambrian and (or) Paleozoic") by Rankin and others (1972).

16. Stratigraphy from Bryant and Reed (1970) (pCga) and Rankin and others (1972).

17. Stratigraphy from Carter and Wiener (1999) and Southworth and others (2012).

18. Mileage from Lord (1981).

19. Stratigraphy, age, and lithology from Kunk and others (2005) and Michael J. Kunk (personal communication, 2014).

20. Stratigraphy from Mixon and others (2000).

21. Collected by J. Wright Horton, Jr., U.S. Geological Survey, Reston, Va.; unit is unnamed, age is unknown (J. W. Horton, Jr., personal communication, 2005).

22. See text.

TABLE A2

*Location, depth below surface, stratigraphic unit, stratigraphic age, and lithology of subsurface samples yielding dated zircon, Blue Ridge, Piedmont, and Coastal Plain in Virginia and North Carolina*

Corehole	Depth below surface		Stratigraphic unit	Stratigraphic age	Lithology
Sample number	(~ft)	(~m)			
<b>MAIN BLUE RIDGE</b>					
<i>USGS well LC-1, Va.</i> <sup>1</sup>					
LC-2	996.5	303.7	Unnamed	Mesoproterozoic	Metagranite
<b>PIEDMONT</b>					
<i>USGS-NASA Langley corehole, Va.</i> <sup>2</sup>					
NL-2081	2,081.4	634.4	Langley Granite	Neoproterozoic	Granite
<i>USGS Bayside #2 corehole, Va.</i> <sup>3</sup>					
BA-2372	2,372.0	723.0	Unnamed	Neoproterozoic	Granite
BA-2378	2,380.5	725.6	Unnamed	Neoproterozoic	Granite
<i>RAL-2 well, N.C.</i> <sup>4</sup>					
RAL-2-182	182.5	55.6	Unnamed	Neoproterozoic-Paleozoic	Gneiss
<b>COASTAL PLAIN</b>					
<i>Oak Grove corehole, Va.</i> <sup>5</sup>					
OG-1	162.5	49.5	Calvert Formation <sup>6</sup>	Latest early-early middle Miocene <sup>6</sup>	Sand
OG-2	202.5	61.7	Nanjemoy Formation <sup>6</sup>	Early Eocene <sup>6</sup>	Sand
OG-10	315.5	96.2	Nanjemoy Formation <sup>6</sup>	Early Eocene <sup>6</sup>	Sand
OG-3	420.5	128.2	Aquia Formation <sup>6</sup>	Early-middle Paleocene <sup>6,7</sup>	Sand
OG-4	466.1	142.1	“Upper” Potomac Group <sup>8</sup>	Early Cretaceous <sup>8,9</sup>	Sand
OG-5	645.5	196.7	“Upper” Potomac Group <sup>8</sup>	Early Cretaceous <sup>8,9</sup>	Sand
OG-8	1,144.8	348.9	“Lower” Potomac Group <sup>8</sup>	Early Cretaceous <sup>8,10</sup>	Sand
OG-9	1,346.1	410.3	“Lower” Potomac Group <sup>8</sup>	Early Cretaceous <sup>8,10</sup>	Sand

Analytical data are in Appendix table A3

S.R., State Route; a.s.l., above sea level.

<sup>1</sup> Location: Round Hill, Va.-W. Va. 7.5-minute quadrangle, Loudoun County, Va.: east side of S.R. 719, between Round Hill and Eubanks (lat 39.1478°N., long 77.7690°W.); ground-surface elevation ~185.9 m (610 ft) a.s.l. Rock is garnetiferous leucocratic metagranite (unit Ygt of Southworth and others, 2006a). Sample from William C. Burton, U.S. Geological Survey, Reston, Va.

<sup>2</sup> Location: Newport News North, Va. 7.5-minute quadrangle, NASA Langley Research Center, Hampton: corehole is located a short distance north of Langley Boulevard and SW of Building 1190 in an open grassy area (lat 37.0956°N., long 76.3858°W.); ground-surface elevation 2.4 m (7.9 ft) a.s.l.; corehole is in the western annular trough of the Chesapeake Bay impact crater, ~19 km outside the central crater (Powars and others, 2001; Horton and others, 2005b). Sample description from Horton and others (2005a). Sample from J. Wright Horton, Jr., U.S. Geological Survey, Reston, Va.

<sup>3</sup> Location: New Point Comfort, Va. 7.5 minute quadrangle, Matthews County: Bayside (lat 37.3252°N., long 76.2926°W.); ground-surface elevation 1.2 m (4 ft) a.s.l.; corehole is in the western annular trough of the Chesapeake Bay impact crater, ~8 km outside the central crater (Horton and others, 2005b, 2008). Sample description from Horton and others (2002) and J. Wright Horton, Jr., U.S. Geological Survey, Reston, Va. (personal communication, 2009). Sample from J. Wright Horton, Jr.

<sup>4</sup> Location: Lake Wheeler, N.C. 7.5-minute quadrangle, Raleigh: North Carolina State University Lake Wheeler site, North Carolina State University Research Units, SE of Lake Wheeler Rd.; well is NW of unnamed road (lat 35.7378°N., long 78.6754°W.); ground-surface elevation ~111.2 m (365 ft) a.s.l. Stratigraphic unit and age from J. Wright Horton, Jr. (personal communication, 2002).

<sup>5</sup> Location: Rollins Fork, Va. 7.5-minute quadrangle, Northern Neck: 3.7 km (2.3 miles) WSW of Oak Grove (lat ~38.1698°N., long ~77.0375°W.) (Mixon and others, 2000); ground-surface elevation 54.85 m (180 ft) a.s.l. (Reinhardt and others, 1980b).

<sup>6</sup> Gibson and others (1980), Reinhardt and others (1980b); for OG-1, see also text.

<sup>7</sup> Vandenberghe and others (2012).

<sup>8</sup> Reinhardt and others (1980a).

TABLE A2  
(continued)

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<sup>9</sup> Four pollen samples recovered from “upper” Potomac Group sands in Oak Grove corehole at depths ranging from 181.8 to 238.0 m (596.5–781 ft) are assigned to pollen Subzone II-B by Reinhardt and others (1980a), indicating an Albian age (for example, Reinhardt and others, 1980a; Hochuli and others, 2006).

<sup>10</sup> Pollen recovered from a sample at 410.9 m (1,348 ft) depth near the base of the “lower” Potomac Group in the Oak Grove corehole is assigned to pollen Zone I by Reinhardt and others (1980a), most likely indicating a Barremian(?)–Aptian (Reinhardt and others, 1980a) or Aptian (for example, Doyle, 1992; Hochuli and others, 2006) age. Pollen recovered from 289.7 m (950.4 ft) depth, about 6.9 m (22.6 ft) above the “upper”/“lower” Potomac Group boundary at 296.6 m (973 ft) depth (Estabrook and Reinhardt, 1980; Reinhardt and others, 1980a), is interpreted as uppermost part of pollen Zone I or basal part of Subzone II-A (Reinhardt and others, 1980a), variously interpreted as indicating a late Aptian or Albian age (for example, Reinhardt and others, 1980a; Doyle, 1992; Hochuli and others, 2006).

TABLE A3

Zircon fission-track ages of samples from the Appalachian Plateau, Valley and Ridge, Blue Ridge, Piedmont, and Coastal Plain in West Virginia, Maryland, Virginia, Tennessee, North Carolina, South Carolina, and District of Columbia

Sample	Number of grains counted	$\rho_s \times 10^6$ ( $t/cm^2$ )	Spontaneous tracks counted	$\rho_i \times 10^6$ ( $t/cm^2$ )	Induced tracks counted	$\rho_d \times 10^5$ ( $t/cm^2$ )	Dosimeter tracks counted	$P(\chi^2)$ (%)	Age <sup>3</sup> (Ma $\pm 2\sigma$ )	Central age <sup>3</sup> (Ma $\pm 2\sigma$ )
<b>APPALACHIAN PLATEAU</b>										
<i>C&amp;O Canal-Potomac River traverse, Md.</i>										
C&O-14	10	15.7	2,574	4.33	355	4.07	2,970	<1	455.2 $\pm$ 54.2*	484 $\pm$ 132*
C&O-15	20	22.8	6,699	4.79	703	4.07	2,970	<1	591.8 $\pm$ 51.7*	598 $\pm$ 74*
<i>Beckley-Thurmond, W. Va.</i>										
T-1	12	21.0	1,417	5.18	175	4.34	3,168	<1	538.5 $\pm$ 88.4*	513 $\pm$ 130*
T-2	14	14.7	966	4.17	137	4.34	3,168	<1	471.4 $\pm$ 87.7*	456 $\pm$ 137*
T-3	10	17.4	3,125	3.64	327	4.34	3,168	<1	630.9 $\pm$ 76.7*	623 $\pm$ 124*
<i>Morgantown, W. Va.</i>										
M-1	10	18.5	3,784	5.65	578	4.34	3,168	<1	438.8 $\pm$ 42.2	436 $\pm$ 109
<i>Great Smoky Mountains region, Tenn.</i>										
GSM-34	11	21.2	1,654	4.04	158	4.29	4,685	<1	680.5 $\pm$ 115.1*	623 $\pm$ 197*
GSM-35	6	17.2	731	4.80	102	4.29	4,685	6	473.5 $\pm$ 101.1*	--
GSM-36	10	22.7	4,817	4.92	522	4.29	4,685	1	603.5 $\pm$ 58.3*	601 $\pm$ 90*
<b>VALLEY AND RIDGE</b>										
<i>C&amp;O Canal-Potomac River traverse, Md.</i>										
C&O-13	10	25.4	1,989	4.37	171	4.07	2,970	<1	715.4 $\pm$ 117.0*	758 $\pm$ 206*
C&O-16	20	21.7	7,030	4.38	711	4.07	2,970	<1	613.0 $\pm$ 53.2*	620 $\pm$ 110*
C&O-17	19	24.0	5,893	3.79	465	4.07	2,970	3	775.7 $\pm$ 80.0*	776 $\pm$ 104*
C&O-18	4	23.4	723	5.18	80	4.07	2,970	1	562.6 $\pm$ 134.2*	564 $\pm$ 273*
C&O-19	11	24.2	3,316	3.04	208	4.07	2,970	<1	961.6 $\pm$ 141.9*	952 $\pm$ 268*
<i>Shenandoah National Park region, Va.</i>										
SNP-31	10	13.8	1,860	1.72	116	3.43	2,500	83	824.0 $\pm$ 161.1*	--
<i>Great Smoky Mountains region, Tenn.</i>										
GSM-20	10	16.7	1,164	3.80	132	4.17	3,042	31	562.4 $\pm$ 105.3*	--
GSM-33	11	22.4	2,397	4.46	239	4.29	4,685	20	653.4 $\pm$ 90.7*	--

TABLE A3  
(continued)

Sample	Number of grains counted	$\rho_s \times 10^6$ (t/cm <sup>2</sup> )	Spontaneous tracks counted	$\rho_i \times 10^6$ (t/cm <sup>2</sup> )	Induced tracks counted	$\rho_d \times 10^5$ (t/cm <sup>2</sup> )	Dosimeter tracks counted	P( $\chi^2$ ) (%)	Age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )	Central age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )
<b>VALLEY AND RIDGE</b>										
<i>Other Valley and Ridge samples, W. Va. and Va.</i>										
V&R-1	10	22.1	4,658	4.89	514	4.23	3,080	<1	585.2 $\pm$ 58.3*	601 $\pm$ 142*
V&R-2	10	18.1	2,767	4.90	374	4.23	3,080	1	481.7 $\pm$ 55.8	480 $\pm$ 84
V&R-3	10	17.2	3,477	4.03	408	4.23	3,080	2	551.8 $\pm$ 61.1	539 $\pm$ 81
V&R-4	10	18.6	3,443	4.15	385	4.23	3,080	<1	577.9 $\pm$ 65.5*	582 $\pm$ 163*
V&R-5	10	20.6	2,230	5.05	273	4.23	3,080	2	529.8 $\pm$ 70.6*	528 $\pm$ 101*
V&R-6	10	17.2	3,016	4.17	366	4.23	3,080	4	534.3 $\pm$ 62.2*	545 $\pm$ 90*
V&R-7	10	21.5	3,149	3.18	233	4.23	3,080	<1	854.4 $\pm$ 120.0*	780 $\pm$ 215*
V&R-8	10	14.9	3,113	3.59	374	4.23	3,080	<1	539.5 $\pm$ 62.2*	509 $\pm$ 102*
<b>FAR WESTERN BLUE RIDGE</b>										
<i>Shenandoah National Park region, Va.</i>										
SNP-28	9	22.9	4,427	4.13	399	3.43	2,500	1	581.2 $\pm$ 65.1*	598 $\pm$ 102*
SNP-29	10	13.1	2,681	2.22	227	3.43	2,500	25	616.9 $\pm$ 88.8*	--
SNP-32	9	15.3	1,836	2.62	157	3.43	2,500	<1	611.1 $\pm$ 104.5*	600 $\pm$ 174*
<i>Great Smoky Mountains region, Tenn.</i>										
GSM-11	8	21.5	2,988	6.16	428	4.69	3,416	<1	503.1 $\pm$ 54.8*	513 $\pm$ 174*
GSM-12	8	23.7	2,057	5.57	242	4.42	3,224	<1	574.1 $\pm$ 80.6*	596 $\pm$ 176*
GSM-13	10	24.8	3,733	3.55	267	4.42	3,224	40	918.9 $\pm$ 120.8*	--
GSM-14	9	29.7	3,439	4.45	258	4.42	3,224	<1	878.8 $\pm$ 117.6*	883 $\pm$ 250*
GSM-15	9	21.1	2,934	3.11	216	4.42	3,224	<1	894.5 $\pm$ 130.0*	894 $\pm$ 238*
GSM-16	10	18.0	3,989	4.99	554	4.42	3,224	7	489.6 $\pm$ 47.6	--
GSM-18	10	15.8	3,596	5.72	651	4.17	3,042	<1	358.0 $\pm$ 33.1	354 $\pm$ 52
GSM-19	10	18.2	3,451	6.18	585	4.17	3,042	22	381.6 $\pm$ 36.8	--
GSM-21	9	18.2	2,641	4.99	361	4.17	3,042	<1	470.0 $\pm$ 55.4*	464 $\pm$ 109*
GSM-22	6	20.5	3,173	4.43	342	4.17	3,042	14	590.4 $\pm$ 70.5	--
GSM-23	10	17.7	3,557	3.92	394	4.17	3,042	6	575.2 $\pm$ 64.5	--
GSM-24	10	12.5	3,809	4.21	642	4.17	3,042	24	383.7 $\pm$ 35.6	--
GSM-25	10	23.3	3,240	5.54	385	4.28	3,118	<1	551.4 $\pm$ 62.6*	612 $\pm$ 199*

TABLE A3  
(continued)

Sample	Number of grains counted	$\rho_s \times 10^6$ (t/cm <sup>2</sup> )	Spontaneous tracks counted	$\rho_i \times 10^6$ (t/cm <sup>2</sup> )	Induced tracks counted	$\rho_d \times 10^5$ (t/cm <sup>2</sup> )	Dosimeter tracks counted	$P(\chi^2)$ (%)	Age <sup>3</sup> (Ma $\pm 2\sigma$ )	Central age <sup>3</sup> (Ma $\pm 2\sigma$ )
<b>FAR WESTERN BLUE RIDGE</b>										
<i>Great Smoky Mountains region, Tenn.</i>										
GSM-26	10	23.4	1,806	3.76	145	4.28	3,118	<1	800.2 $\pm$ 141.1* 737 $\pm$ 201*	
GSM-30	10	14.6	1,644	5.56	314	4.28	3,118	<1	348.5 $\pm$ 44.7* 350 $\pm$ 78*	
GSM-31	10	15.9	2,182	5.34	366	4.28	3,118	<1	395.4 $\pm$ 46.9 367 $\pm$ 70	
GSM-37	10	23.1	2,367	4.52	231	4.29	4,685	90	666.8 $\pm$ 94.0*	--
GSM-38	11	20.5	2,607	4.52	288	4.29	4,685	67	592.5 $\pm$ 75.6*	--
<b>MAIN BLUE RIDGE</b>										
<i>C&amp;O Canal-Potomac River traverse, Md. and Va.</i>										
C&O-1	10	14.5	952	4.05	133	4.42	3,224	22	486.8 $\pm$ 91.7	--
C&O-3	10	14.7	2,958	5.33	535	4.42	3,224	<1	379.2 $\pm$ 38.0 382 $\pm$ 74	
C&O-8	10	16.3	4,036	8.58	1,060	4.22	3,078	15	251.8 $\pm$ 19.6	--
<i>USGS well LC-1, Va.</i>										
LC-2	7	19.2	1,150	7.89	236	4.23	3,080	13	321.3 $\pm$ 47.4	--
<i>Shenandoah National Park region, Va.</i>										
SNP-1	9	25.8	2,392	10.4	480	4.27	3,114	<1	331.4 $\pm$ 35.2 333 $\pm$ 65	
SNP-2	8	11.7	1,441	4.95	306	4.42	3,224	<1	324.4 $\pm$ 42.4 322 $\pm$ 70	
SNP-3	10	8.52	2,073	3.88	472	4.27	3,114	50	293.0 $\pm$ 31.7	--
SNP-4	10	12.4	2,009	5.77	468	4.42	3,224	15	296.3 $\pm$ 32.2	--
SNP-6	7	14.8	1,883	6.80	433	4.42	3,224	54	300.1 $\pm$ 33.7	--
SNP-7	10	13.6	4,041	6.20	921	4.27	3,114	5	292.7 $\pm$ 23.8	--
SNP-10	7	28.5	3,084	13.4	726	4.27	3,114	34	283.6 $\pm$ 25.5	--
SNP-13	9	11.5	1,680	5.03	369	4.42	3,224	84	313.8 $\pm$ 37.7	--
SNP-19	10	14.0	4,281	4.63	706	4.27	3,114	3	401.1 $\pm$ 35.6 404 $\pm$ 48	
SNP-20	10	17.0	4,146	5.83	709	4.27	3,114	32	387.2 $\pm$ 34.4	--
SNP-21	10	9.78	3,059	3.34	522	4.27	3,114	<1	388.0 $\pm$ 39.3 384 $\pm$ 81	
SNP-22	9	17.5	3,445	6.11	602	4.27	3,114	35	379.1 $\pm$ 36.1	--
SNP-23	6	14.5	1,959	3.86	261	4.27	3,114	<1	492.9 $\pm$ 67.3 481 $\pm$ 111	
SNP-24	10	13.5	4,937	4.51	828	4.07	2,970	9	376.6 $\pm$ 31.5	--

TABLE A3  
(continued)

Sample	Number of grains counted	$\rho_s \times 10^6$ (t/cm <sup>2</sup> )	Spontaneous tracks counted	$\rho_i \times 10^6$ (t/cm <sup>2</sup> )	Induced tracks counted	$\rho_d \times 10^5$ (t/cm <sup>2</sup> )	Dosimeter tracks counted	P( $\chi^2$ ) <sup>2</sup> (%)	Age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )	Central age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )
<b>MAIN BLUE RIDGE</b>										
<i>Shenandoah National Park region, Va.</i>										
SNP-25	10	32.2	6,210	8.59	829	4.07	2,970	3	469.7 $\pm$ 38.8	456 $\pm$ 52
SNP-27	11	14.8	2,345	5.15	408	3.43	2,500	62	307.6 $\pm$ 35.2	--
SNP-30	10	32.0	3,643	7.92	451	3.43	2,500	60	428.2 $\pm$ 46.1	--
SNP-36	5	9.75	621	3.55	113	3.70	2,698	27	317.0 $\pm$ 65.0	--
SNP-37	10	9.78	4,306	3.84	845	3.70	2,698	23	294.5 $\pm$ 24.9	--
SNP-39	10	18.9	3,859	6.74	690	3.70	2,698	46	322.5 $\pm$ 29.4	--
SNP-40	10	22.3	4,646	7.55	787	3.70	2,698	<1	340.0 $\pm$ 29.3	346 $\pm$ 44
PM-7	10	16.1	4,400	5.79	794	3.70	2,698	66	319.6 $\pm$ 27.5	--
K03-6-10M	10	13.6	2,448	7.63	685	4.29	4,685	75	240.5 $\pm$ 21.9	--
K03-6-10N	9	9.87	2,249	5.08	579	4.29	4,685	14	261.0 $\pm$ 25.5	--
<i>Blue Ridge Parkway, James River gorge area, Va.</i>										
BRP-1	5	30.9	2,205	9.74	348	4.27	3,114	23	418.5 $\pm$ 50.6	--
BRP-2	8	22.1	1,962	10.1	450	4.27	3,114	24	290.9 $\pm$ 32.1	--
BRP-4	9	22.3	1,891	10.1	428	4.27	3,114	4	294.7 $\pm$ 33.3	298 $\pm$ 46
BRP-6	9	19.0	4,922	8.42	1,089	4.27	3,114	31	301.3 $\pm$ 22.9	--
<i>Grandfather Mountain region, Tenn. and N.C.</i>										
BR-2	8	22.9	1,082	11.6	275	4.34	3,168	<1	267.3 $\pm$ 37.3	324 $\pm$ 85
BR-6	8	11.1	1,581	5.31	379	4.34	3,168	13	283.0 $\pm$ 33.6	--
BR-7	10	16.0	3,088	5.56	537	4.34	3,168	<1	387.0 $\pm$ 38.7	381 $\pm$ 56
BR-8	6	20.2	858	8.01	170	4.34	3,168	<1	340.9 $\pm$ 58.5	355 $\pm$ 111
BR-11	9	14.7	3,068	4.70	490	4.34	3,168	<1	420.3 $\pm$ 43.5	394 $\pm$ 80
BR-12	6	16.7	2,196	6.41	421	4.34	3,168	<1	352.0 $\pm$ 39.5	356 $\pm$ 124
BR-13	10	12.6	3,002	5.21	618	4.34	3,168	66	328.4 $\pm$ 31.3	--
<i>Great Smoky Mountains region, Tenn. and N.C.</i>										
GSM-1	9	19.7	2,771	10.6	745	4.69	3,416	15	272.9 $\pm$ 24.4	--
GSM-2	10	21.3	3,543	11.0	912	4.69	3,416	5	284.8 $\pm$ 23.3	--
GSM-3	7	19.9	2,456	10.4	641	4.69	3,416	23	281.0 $\pm$ 26.7	--

TABLE A3  
(continued)

Sample	Number of grains counted	$\rho_s \times 10^6$ (t/cm <sup>2</sup> )	Spontaneous tracks counted	$\rho_i \times 10^6$ (t/cm <sup>2</sup> )	Induced tracks counted	$\rho_d \times 10^5$ (t/cm <sup>2</sup> )	Dosimeter tracks counted	P( $\chi^2$ ) <sup>2</sup> (%)	Age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )	Central age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )
<b>MAIN BLUE RIDGE</b>										
<i>Great Smoky Mountains region, Tenn. and N.C.</i>										
GSM-4	10	16.6	3,727	9.28	1,039	4.69	3,416	7	263.4 $\pm$ 20.6	--
GSM-5	8	21.3	2,627	11.7	724	4.69	3,416	10	266.4 $\pm$ 24.1	--
GSM-6	9	17.0	3,605	8.53	906	4.69	3,416	5	291.6 $\pm$ 23.9	--
GSM-7	8	17.9	2,907	9.71	787	4.69	3,416	52	271.1 $\pm$ 23.7	--
GSM-8	9	17.1	3,562	8.31	866	4.69	3,416	72	301.2 $\pm$ 25.0	--
GSM-9	8	20.3	2,985	10.5	773	4.69	3,416	11	283.1 $\pm$ 24.8	--
GSM-10	10	18.0	3,128	8.76	761	4.69	3,416	24	301.0 $\pm$ 26.4	--
GSM-17	9	15.1	2,103	6.53	454	4.42	3,224	1	319.2 $\pm$ 34.9	322 $\pm$ 52
GSM-28	8	23.2	1,790	8.91	344	4.28	3,118	43	346.4 $\pm$ 42.6	--
GSM-29	10	18.3	1,694	6.86	318	4.28	3,118	58	354.4 $\pm$ 45.1	--
GSM-32	9	14.5	2,401	4.78	397	4.28	3,118	15	401.0 $\pm$ 45.8	--
GSM-40	10	14.3	4,353	6.56	1,001	4.29	4,685	<1	291.5 $\pm$ 22.1	288 $\pm$ 36
GSM-41	10	13.2	2,300	5.62	488	4.29	4,685	6	315.3 $\pm$ 32.8	--
GSM-42	10	16.2	3,274	5.98	606	4.29	4,685	2	360.2 $\pm$ 33.5	360 $\pm$ 46
GSM-46	9	15.3	3,018	6.86	675	4.29	4,685	<1	299.5 $\pm$ 27.0	296 $\pm$ 43
GSM-47	10	15.5	3,227	6.30	657	4.29	4,685	19	328.2 $\pm$ 29.7	--
GSM-48	4	17.8	515	6.22	90	4.29	4,685	49	380.8 $\pm$ 87.7	--
GSM-49	10	14.4	2,280	6.82	540	4.29	4,685	2	283.1 $\pm$ 28.3	286 $\pm$ 40
<b>PIEDMONT</b>										
<i>C&amp;O Canal-Potomac River traverse, Md., Va., and D.C.</i>										
C&O-9	10	8.93	1,759	4.44	437	4.22	3,078	2	265.9 $\pm$ 30.0	263 $\pm$ 40
C&O-10	10	13.9	2,791	4.32	434	4.22	3,078	2	419.7 $\pm$ 45.9	419 $\pm$ 65
C&O-11	10	12.3	2,739	5.48	608	4.22	3,078	<1	296.9 $\pm$ 28.7	296 $\pm$ 62
C&O-12	10	9.97	2,357	3.75	443	4.22	3,078	43	349.2 $\pm$ 38.3	--
C&O-21	15	19.9	6,065	3.60	549	3.43	2,500	33	578.8 $\pm$ 56.5	--
C&O-22	2	25.1	629	6.22	78	3.43	2,500	29	427.6 $\pm$ 104.1	--
K91-5-20A	5	14.0	973	6.13	213	4.17	3,042	70	297.5 $\pm$ 46.3	--

TABLE A3  
(continued)

Sample	Number of grains counted	$\rho_s \times 10^6$ (t/cm <sup>2</sup> )	Spontaneous tracks counted	$\rho_i \times 10^6$ (t/cm <sup>2</sup> )	Induced tracks counted	$\rho_d \times 10^5$ (t/cm <sup>2</sup> )	Dosimeter tracks counted	$P(\chi^2)$ (%)	Age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )	Central age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )
<b>PIEDMONT</b>										
<i>C&amp;O Canal-Potomac River traverse, Md., Va., and D.C.</i>										
K91-5-21E	10	21.4	1,405	10.3	339	4.17	3,042	32	270.4 $\pm$ 34.2	--
K91-5-21F	9	16.2	2,227	7.37	505	4.17	3,042	23	287.4 $\pm$ 30.2	--
K91-5-22B	9	16.4	2,780	7.35	624	4.17	3,042	27	290.3 $\pm$ 27.8	--
K91-5-22D	10	15.5	4,241	7.72	1,058	4.17	3,042	40	261.8 $\pm$ 20.3	--
<i>Great Smoky Mountains region, N.C. and S.C.</i>										
GSM-50	10	14.1	2,995	6.63	704	4.29	4,685	<1	285.3 $\pm$ 25.3	289 $\pm$ 46
GSM-53	10	19.7	3,758	10.9	1,043	4.29	4,685	<1	242.4 $\pm$ 18.4	239 $\pm$ 34
<i>Other Piedmont surface samples, Va. and N.C.</i>										
PM-1	10	14.0	1,810	4.90	317	3.70	2,698	2	329.1 $\pm$ 42.0	329 $\pm$ 60
PM-4	8	19.2	2,357	7.33	449	3.70	2,698	<1	303.2 $\pm$ 33.3	274 $\pm$ 54
K03-6-12H	8	17.0	1,365	8.99	360	4.29	4,685	12	254.8 $\pm$ 31.1	--
REI-255	10	25.2	1,506	7.72	231	3.43	2,500	79	347.8 $\pm$ 51.1	--
<i>USGS-NAASA Langley corehole, Va.</i>										
NL-2081	9	20.1	1,980	7.88	388	4.73	3,450	58	374.6 $\pm$ 43.5	--
<i>USGS Bayside #2 corehole, Va.<sup>4</sup></i>										
BA-2372	9	15.0	1,770	4.84	285	3.43	2,500	74	331.8 $\pm$ 44.3	--
BA-2378	10	14.9	1,842	4.39	271	3.43	2,500	53	362.2 $\pm$ 49.3	--
<i>RAL-2 well, N.C.</i>										
RAL-2-182	9	17.0	1,688	8.71	433	4.22	3,078	5	257.7 $\pm$ 29.3	--
<b>COASTAL PLAIN</b>										
<i>Oak Grove corehole, Va.<sup>4</sup></i>										
OG-1	30	17.3	6,089	6.20	1,090	4.30	3,129	<1	372.9 $\pm$ 27.9*	390 $\pm$ 145*
OG-2	28	13.6	7,990	7.61	2,239	4.30	3,129	<1	240.7 $\pm$ 14.4	252 $\pm$ 47
OG-10	27	13.4	8,116	9.35	2,825	4.22	3,075	<1	190.9 $\pm$ 10.8	176 $\pm$ 48
OG-3 short etch <sup>5</sup>	30	16.9	12,268	10.4	3,778	4.30	3,129	<1	219.4 $\pm$ 11.3	217 $\pm$ 54
OG-3 long etch <sup>6</sup>	12	9.72	3,601	5.53	1,024	4.30	3,129	<1	237.2 $\pm$ 18.8	186 $\pm$ 90

TABLE A3  
(continued)

Sample	Number of grains counted	$\rho_s \times 10^6$ ( $t/cm^2$ )	Spontaneous tracks counted	$\rho_i \times 10^6$ ( $t/cm^2$ )	Induced tracks counted	$\rho_d \times 10^{5.1}$ ( $t/cm^2$ )	Dosimeter tracks counted	$P(\chi^2)$ (%)	Age <sup>3</sup> (Ma $\pm 2\sigma$ )	Central age <sup>3</sup> (Ma $\pm 2\sigma$ )
<b>COASTAL PLAIN</b>										
<i>Oak Grove corehole, Va.</i> <sup>4</sup>										
OG-4 short etch <sup>5</sup>	29	16.4	9,394	8.65	2,480	4.30	3,129	<1	255.2 $\pm$ 14.7	249 $\pm$ 31
long etch <sup>6</sup>	16	4.90	2,630	2.40	644	4.30	3,129	<1	274.7 $\pm$ 26.1	265 $\pm$ 49
OG-5 short etch <sup>5</sup>	30	13.7	11,351	7.52	3,107	4.30	3,129	<1	246.3 $\pm$ 13.3	238 $\pm$ 27
long etch <sup>6</sup>	13	9.54	3,867	4.99	1,012	4.30	3,129	<1	257.4 $\pm$ 20.4	265 $\pm$ 56
OG-8 short etch <sup>5</sup>	28	14.1	8,574	7.82	2,371	4.22	3,075	<1	239.4 $\pm$ 14.1	243 $\pm$ 33
long etch <sup>6</sup>	29	10.6	9,102	5.30	2,270	4.22	3,075	<1	264.9 $\pm$ 15.7	259 $\pm$ 27
OG-9	30	14.3	10,254	6.78	2,429	4.22	3,075	<1	278.6 $\pm$ 16.1	279 $\pm$ 18
<i>Other Coastal Plain samples, Md. and Va.</i>										
CP-1	30	14.5	9,454	4.44	1,443	3.43	2,500	<1	349.5 $\pm$ 24.2*	344 $\pm$ 89*
OC	30	15.5	9,185	9.69	2,862	4.73	3,450	<1	238.1 $\pm$ 13.0	260 $\pm$ 71

Analyst, C.W. Naeser.

$\rho_s$ , spontaneous track density;  $\rho_i$ , induced track density (reported induced track density =  $2 \times$  measured value); -, not determined. \*, indicates samples containing one or more zircon grains that yield a  $>800$  Ma FT age. Locality data are in Appendix tables A1 and A2.

<sup>1</sup>  $\rho_d$ , track density in muscovite detector covering National Institutes of Standards and Technology (NIST) standard glass SRM 962 (Carpenter and Reimer, 1974); listed value was calculated by interpolation between values determined for standards placed at the top and bottom of the irradiation tube.

<sup>2</sup> Measure of probability that all individual grains counted in a sample are from a single age population; values of  $P(\chi^2) < 5\%$  are generally taken as an indication of a real spread in single-grain ages (Galbraith, 1981; Green and others, 1989).

<sup>3</sup> Age calculated from the fission-track age equation of Hurford and Green (1983), using the sum of all spontaneous and the sum of all induced tracks counted in individual grains in the sample, and the following values:  $\lambda_p = 1.551 \times 10^{10}$ /yr,  $g = 0.5$ ,  $\eta = 319.6$  (SRM 962). Standard deviation calculated by combining Poisson errors on spontaneous and induced counts and on counts in detector covering standard glass NIST SRM 962 (McGee and others, 1985). The "central age" (Galbraith and Laslett, 1993) is reported for samples that fail the  $\chi^2$  test ( $P(\chi^2) < 5\%$ ).

<sup>4</sup> Listed in order of increasing depth below surface (Appendix table A2).

<sup>5</sup> Etched at 214 °C for 32 hours.

<sup>6</sup> Etched at 214 °C for 64 hours (OG-3, OG-5, OG-8) or 88 hours (OG-4).

TABLE A4  
 Depth below surface, stratigraphic unit, stratigraphic age, and apatite fission-track age of Coastal Plain sand samples, Oak Grove corehole, Virginia

Sample	Depth below surface (-ft) (~m)	Stratigraphic unit	Stratigraphic age	Number of grains counted	$\rho_a \times 10^6$ ( $\mu\text{cm}^2$ )	$\rho_i \times 10^6$ ( $\mu\text{cm}^2$ )	$\rho_i \times 10^6$ ( $\mu\text{cm}^2$ )	$\rho_a \times 10^6$ ( $\mu\text{cm}^2$ )	$P(\chi^2)$ (%)	Age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )	Central age <sup>3</sup> (Ma $\pm$ 2 $\sigma$ )
OG-3	420.5	Aquia Formation <sup>4</sup>	Early-middle Paleocene <sup>4,5</sup>	7	0.703 (258)	2.62 (481)	0.452 (2,747)	0.452 (2,747)	96	129.1 $\pm$ 20.5	--
OG-6	776.5	"Upper" Potomac Group <sup>6</sup>	Early Cretaceous <sup>6,7</sup>	29	1.95 (2,562)	6.84 (4,503)	0.452 (2,747)	0.452 (2,747)	<1	136.9 $\pm$ 8.6	141 $\pm$ 14
OG-7	984.5	"Lower" Potomac Group <sup>6</sup>	Early Cretaceous <sup>6,8</sup>	30	1.93 (2,620)	6.47 (4,400)	0.452 (2,747)	0.452 (2,747)	<1	143.1 $\pm$ 8.9	147 $\pm$ 16
OG-8	1,144.8	"Lower" Potomac Group <sup>6</sup>	Early Cretaceous <sup>6,8</sup>	30	1.78 (3,859)	5.98 (6,484)	0.452 (2,747)	0.452 (2,747)	<1	143.0 $\pm$ 8.0	143 $\pm$ 14
OG-9	1,346.1	"Lower" Potomac Group <sup>6</sup>	Early Cretaceous <sup>6,8</sup>	30	1.99 (3,578)	6.15 (5,531)	0.452 (2,747)	0.452 (2,747)	<1	155.3 $\pm$ 8.9	154 $\pm$ 19

Analyst, C.W. Naeser.

For corehole location, see Appendix table A2.

Samples were dated by the external detector method (see "Methods"); apatite grains from a given sample were mounted in epoxy, polished to expose internal grain surfaces, and etched in 7% nitric acid for 40 seconds at 23 °C. External detectors were etched in 48% HF for 17 minutes at 24 °C.  $\rho_a$ , spontaneous track density;  $\rho_i$ , induced track density (reported induced track density = 2  $\times$  measured value); --, not determined. Number in parentheses is number of tracks counted.

<sup>4</sup>  $\rho_a$ , track density in muscovite detector covering National Institutes of Standards and Technology (NIST) standard glass SRM 963 (Carpenter and Reimer, 1974); listed value was calculated by interpolation between values determined for standards placed at the top and bottom of the irradiation tube.

<sup>5</sup> Measure of probability that all individual grains counted in a sample are from a single age population; values of  $P(\chi^2) < 5\%$  are generally taken as an indication of a real spread in single-grain ages (Galbraith, 1981; Green and others, 1989).

<sup>6</sup> Calculated from the fission-track age equation of Hurford and Green (1983), using the sum of all spontaneous tracks and the sum of all induced tracks counted in the individual grains in the sample, and the following values:  $\lambda_D = 1.551 \times 10^{-10}/\text{yr}$ ;  $g = 0.5$ ;  $\zeta = 10752$ , determined using standard glass NIST SRM 963 and the Fish Canyon Tuff and Durango apatite fission-track age standards (Hurford, 1990). Standard deviation calculated by combining Poisson errors on spontaneous and induced counts and on counts in detector covering standard glass NIST SRM 963 (McGee and others, 1985). The central age (Galbraith and Laslett, 1993) is reported for samples that fail the  $\chi^2$  test ( $P(\chi^2) < 5\%$ ).

<sup>7</sup> Gibson and others (1980), Reinhardt and others (1980b).

<sup>8</sup> Vandenbergh and others (2012).

<sup>9</sup> Reinhardt and others (1980a).

<sup>10</sup> Four pollen samples recovered from "upper" Potomac Group sands in Oak Grove corehole at depths ranging from 181.8 to 238.0 m (596.5–781 ft) are assigned to pollen Subzone II-B by Reinhardt and others (1980a), indicating an Albian age (for example, Reinhardt and others, 1980a; Hochuli and others, 2006).

<sup>11</sup> Pollen recovered from a sample at 410.9 m (1,348 ft) depth near the base of the "lower" Potomac Group in the Oak Grove corehole is assigned to pollen Zone I by Reinhardt and others (1980a), most likely indicating a Barremian(?)-Aptian (Reinhardt and others, 1980a) or Aptian (for example, Doyle, 1992; Hochuli and others, 2006) age. Pollen recovered from 289.7 m (950.4 ft) depth, about 6.9 m (22.6 ft) above the "upper"/"lower" Potomac Group boundary at 296.6 m (973 ft) depth (Estabrook and Reinhardt, 1980; Reinhardt and others, 1980a), is interpreted as uppermost part of pollen Zone I or basal part of Subzone II-A (Reinhardt and others, 1980a), variously interpreted as indicating a late Aptian or Albian age (for example, Reinhardt and others, 1980a; Doyle, 1992; Hochuli and others, 2006).

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