Detrital zircons and sediment dispersal in the Appalachian foreland

William A. Thomas¹, George E. Gehrels², Stephen F. Greb³, Gregory C. Nadon⁴, Aaron M. Satkoski⁵, and Mariah C. Romero⁶

¹Emeritus, University of Kentucky, and Geological Survey of Alabama, P. O. Box 869998, Tuscaloosa, Alabama 35486-6999, USA
²Department of Geosciences, University of Arizona, Tucson, Arizona 85721, USA
³Kentucky Geological Survey, University of Kentucky, Lexington, Kentucky 40506-0107, USA
⁴Department of Geological Sciences, Ohio University, Athens, Ohio 45701-2979, USA
⁵Department of Geoscience, University of Wisconsin, Madison, Wisconsin 53706-1692, USA
⁶Department of Earth, Atmospheric, and Planetary Sciences, Purdue University, West Lafayette, Indiana 47907, USA

ABSTRACT

Seven new detrital-zircon U-Pb age analyses along with a compilation of previously published data from Mississippian–Permian sandstones in the Appalachian foreland (total n = 3564) define the provenance of Alleghanian synorogenic clastic wedges, as well as characterize the detritus available to any more extensive intracontinental dispersal systems. The samples are from the cratonward-prograding Mauch Chunk–Pottsville clastic wedge centered on the Pennsylvania salient, the cratonward-prograding Pennington-Lee clastic wedge centered on the Tennessee salient, and a southwestward-directed longitudinal fluvial system along the distal part of the foreland. Grenville-age detrital zircons generally are abundant in all samples; however, ages of the Taconic and Acadian origens are dominant in some samples but are minor to lacking in others. Taconic–Acadian ages are dominant in the Mauch Chunk–Pottsville clastic wedge, in parts of the longitudinal system, and in the upper part (above Middle Pennsylvania) of the Pennington-Lee clastic wedge; but they are minor to lacking in the lower part (Upper Mississippian–Lower Pennsylvania) of the Pennington-Lee clastic wedge. New Hf isotopic analyses show a similar distinction between the two clastic wedges, supporting an interpretation of differences in provenance contributions during the early stages of basin filling. U-Pb ages and Hf isotopic ratios also indicate that the Mauch Chunk–Pottsville transverse dispersal fed the northern part of the longitudinal system. A few samples in the distal southwestern part of the Mauch Chunk–Pottsville clastic wedge and adjacent parts of the longitudinal system have unusually large populations of grains with Superior and Central Plains ages. The relative distance and isolation of these samples from the Canadian Shield, which is the primary source of Superior and Central Plains zircons, indicates likely recycling from synrift sediment, passive-margin strata, or Taconic–Acadian clastic wedges. Among the lesser components are a few grains with ages that correspond to Iapetan synrift igneous rocks and also to Pan-African–Brasiliano components of Gondwana accreted terranes. Synorogenic zircons of the Alleghanian orogeny are very rare (seven grains in the total of 3564).

INTRODUCTION

The late Paleozoic Appalachian orogen along eastern North America (Fig. 1) long has been recognized as the dominant source of clastic sediment spreading cratonward into orogenic foreland basins (e.g., King, 1959; Thomas, 1977) and beyond, into intracratonic basins and farther across the North American Midcontinent (e.g., Gehrels et al., 2011). The late Paleozoic orogen represents the final assembly of supercontinent Pangaea as a result of a succession of Ordovician–Permian (Taconic, Acadian, and Alleghanian) accretionary processes along the Neoproterozoic–Cambrian Iapetan rifted margin of Laurentia and the Cambrian–Ordovician passive margin (e.g., Hatcher et al., 1989a; Williams, 1995). The orogen includes the Precambrian Grenville province of supercontinent Rodinia assembly, synrift and passive-margin rocks of the Laurentian margin, and Ordovician through Permian synorogenic rocks and accreted terranes of the Appalachian and Ouachita orogenic belts (Fig. 1). The objectives of this article are to characterize the detrital-zircon populations of the late Paleozoic synorogenic clastic wedges within the Appalachian foreland and to evaluate the contributions of the various components of the provenance within the Appalachian orogen. This characterization of Appalachian detrital-zircon populations provides a template to determine possible Appalachian contributions to more distal intracontinental dispersal systems.

LATE PALEOZOIC SYNOROGENIC SEDIMENTARY DEPOSITS

Mississippian–Permian Alleghanian synorogenic clastic deposits vary significantly along the orogen. Between the New York and Alabama promontories, two late Paleozoic classic synorogenic clastic wedges filled foreland basins centered on the Pennsylvania and Tennessee embayments (Fig. 2). From the New York promontory northward to Newfoundland, late Paleozoic clastic sedimentation along the Appalachian orogen filled fault-bounded pull-apart basins along a regional system of dextral strike-slip faults (Fig. 1) (e.g., Thomas and Schenk, 1988; van de Poll, 1995). From the Alabama promontory westward along the Ouachita and Marathon embayments, late Paleozoic synorogenic clastic wedges...
Figure 1. Regional map of potential provenance elements in the Appalachian orogen in eastern North America: Precambrian provinces of the craton (modified from Van Schmus et al., 1993); Iapetan rift margin and synrift intracratonic faults of Laurentia, which outline the locations of synrift igneous and sedimentary rocks, as well as the approximate trace of the passive-margin shelf edge (from Thomas, 2014); generalized outlines of Taconic and Acadian synorogenic clastic wedges (from Thomas, 1977, and references therein); boundaries of Gondwanan accreted terranes (from Hibbard et al., 2007; Hatcher, 2010); trace of the Appalachian-Ouachita thrust front (compiled from Thomas et al., 1989b; Hatcher, 2010); locations of faults within the late Paleozoic Maritimes basin in the northern Appalachians (from Thomas and Schenk, 1988; van de Poll, 1995); and outline of late Paleozoic clastic wedges along the Ouachita orogen (from Thomas, 2006). Gray outline shows the location of the map in Figure 2. B.R.—Blue Ridge external basement massif; M.R.—Midcontinent rift system.
of deep-water turbidites (Fig. 1) have relatively small wavelength-to-amplitude ratios (Arbenz, 1989; Viele and Thomas, 1989). The shallow-marine to deltaic clastic wedges in the Pennsylvania and Tennessee embayments have large wavelength-to-amplitude ratios; these clastic wedges are the focus of this article.

The Mauch Chunk–Pottsville clastic wedge is centered on the Pennsylvania salient of the Appalachian thrust belt (Pennsylvania embayment of the rifted margin), and the Pennington-Lee clastic wedge is centered on the Tennessee salient of the thrust belt (Tennessee embayment of the rifted margin) (Figs. 1, 2) (Thomas, in Hatcher et al., 1989b). Sediment-dispersal patterns in both clastic wedges reflect generally semi-radial transverse drainages across the foreland basins toward the craton (Fig. 2) (e.g., Meckel, 1967; Thomas, 1977). In contrast to the transverse drainages, south- to southwest-directed longitudinal (orogen-parallel) drainage characterized the distal parts of the basins in the Early Pennsylvania (Fig. 2) (Archer and Greb, 1995; Grimm et al., 2013).

Sandstones of the transverse drainage systems in the proximal parts of the clastic wedges generally are more lithic, whereas those of the Early Pennsylvanian longitudinal drainage system along the distal parts of the basins are more quartzose (Becker et al., 2005; Grimm et al., 2013). On the basis of paleocurrents and sandstone petrography, the relatively lithic sandstones of the transverse drainage systems generally have been interpreted as being derived from unroofing of the internal belts of the Appalachian orogen southeast of the fossil land basins (Thomas, 1966; Meckel, 1967; Davis and Ehrlich, 1974; Edmunds et al., 1979; Donaldson and Shumaker, 1981; Donaldson et al., 1985). Quartz pebbles are common in Lower Pennsylvanian polymictic conglomerates. In Pennsylvania, a southeastward increase in quartz-pebble sizes indicates a source along the southeast side of the fossil basin in the Pennsylvania embayment (Meckel, 1967). In contrast, on the basis of paleocurrents, as well as more quartzose composition and concentrations of quartz pebbles, Lower Pennsylvanian sandstones in the longitudinal drainage system have been interpreted as derived from the Canadian Shield or northern Appalachians (Siever and Potter, 1956; Edmunds et al., 1979; Chesnut, 1994; Archer and Greb, 1995; Greb and Chesnut, 1996; Grimm et al., 2013), as has one sandstone in the proximal part of the Mauch Chunk–Pottsville clastic wedge (Robinson and Prave, 1995).
**DETRITAL-ZIRCON SAMPLING AND ANALYTICAL METHODS**

To document dispersal of detritus from the Appalachian orogen, samples have been collected and analyzed through the stratigraphic succession of the Mississippian–Permian synerogenic clastic wedges in the Appalachian basin (Fig. 2). The new analyses include U-Pb ages and Hf isotopic data (Fig. 3) from detrital-zircon grains. In addition, previously published data for U-Pb ages of detrital zircons are available for comparison (Fig. 4). The data presentation in Figures 3 and 4 is organized by depositional age to establish a time frame for evolution of drainage systems, as well as by distribution separately for transverse dispersal into the two clastic wedges and the longitudinal system in the distal part of the basin.

**Sample Collection and Processing**

Approximately 12 kg of medium- to coarse-grained sandstone was collected from a restricted stratigraphic interval for each detrital-zircon sample and then processed utilizing methods outlined by Gehrels (2000), Gehrels et al. (2008), and Gehrels and Pecha (2014). Zircon grains were extracted using traditional methods of jaw crushing and pulverizing, followed by density separation using a Wfely table. The resulting heavy-mineral fraction was further purified using a Frantz LB-1 magnetic barrier separator and heavy liquids. A representative split of the zircon yield was incorporated into a 2.5-cm epoxy mount along with multiple fragments of the U-Pb primary standard Sri Lanka SLF and Hf standards R33, Mud Tank, FC-1, Plesovice, Temora, and 91500. The mounts were sanded down to ~20 μm, polished to 1 μm, and imaged by back-scattered electrons (BSE) and cathodoluminescence (CL) using a Hitachi 3400N scanning electron microscope (SEM) and a Gatan Chroma CL2 detector system at the Arizona LaserChron SEM Facility (www.georizonasem.org). Prior to isotopic analysis, mounts were cleaned in an ultrasonic bath of 1% HNO₃ and 1% HCl in order to remove surficial common Pb.

**U-Pb Geochronologic Analysis**

Uranium-lead geochronology of individual zircon crystals was conducted by laser ablation–inductively coupled plasma mass spectrometry (LA-ICPMS) at the Arizona LaserChron Center (www.laserchron.org). The isotopic analyses involved ablation of zircon using a Photon Machines Analyte G2 excimer laser (λ = 193 nm) coupled to either a Nu Instruments multicollector ICPMS or a Thermo Element2 single-collector ICPMS. Ultra-pure helium carried the ablated material from the HeEx cell into the plasma source of the ICPMS.

Analyses conducted with the Nu ICPS utilized Faraday collectors for measurement of ²³⁸U and ²³⁷Th, either Faraday collectors or ion counters for ²⁰⁶Pb, ²⁰⁷Pb, and ²⁰⁸Pb, and ion counters for ²⁰⁶Pb, ²⁰⁷Hg, and ²⁰⁸Hg (see Supplemental Table S1 for specific methods used for each sample), depending on grain size. For larger grains, a 30-μm-diameter spot was used, and masses 206, 207, 208, 232, and 238 were measured with Faraday detectors, whereas the smaller 202 and 204 ion beams were measured with ion counters. The acquisition routine included a 15 s integration on peaks with the laser off (for backgrounds), fifteen 1 s integrations with the laser firing, and a 30 s delay to ensure that the previous sample was completely purged from the system. Smaller grains were analyzed with all Pb isotopes in ion counters, using a 20 μm beam diameter. Analyses consisted of a 12 s integration on peaks with the laser off (for backgrounds), twelve 1 s integrations with the laser firing, and a 30 s delay to purge the previous sample.

An average of 275 analyses was conducted on each sample with one U-Pb measurement per grain. Grains were selected in random fashion; crystals were rejected only if they contained cracks or inclusions or were too small to be analyzed. The use of high-resolution BSE and CL images provided assistance in grain selection and spot placement.

Data reduction was accomplished using the “agecalc” Microsoft Excel spreadsheet, which is the standard Arizona LaserChron Center reduction protocol (Gehrels et al., 2008; Gehrels and Pecha, 2014). Data were filtered for discordance, ²⁰⁶Pb/²³⁸U precision, and ²⁰⁶Pb/²⁰⁷Pb precision as indicated in the notes in Supplemental Table S1 (see footnote 1). Data are presented on normalized age-probability diagrams (Fig. 3), which sum all relevant analyses and uncertainties and divide each curve by the number of analyses such that all curves contain the same area. Age groups are characterized by the ages of peaks in age probability and by the range of constituent ages.

**Hf Isotopic Analysis**

Hafnium isotopic analyses were conducted utilizing the Nu multicollector LA-ICPMS system at the Arizona LaserChron Center following methods reported in Cecil et al. (2011) and Gehrels and Pecha (2014). An average of 45 Hf analyses was conducted per sample; grains were selected to represent each of the main age groups and to avoid crystals with discordant or imprecise ages. CL images were utilized to ensure that all Hf analyses are within the same domain as the U-Pb pit, although in most analyses Hf laser pits were located directly on top of the U-Pb analysis pits. Complete Hf isotopic data and Hf evolution plots of individual samples are presented in Supplemental Table S2.

Hafnium data are presented using Hf evolution diagrams (Fig. 3), where initial ε₁⁷⁷Hf/¹⁷⁶Hf ratios are expressed in ε notation, which represents the Hf isotopic composition at the time of zircon crystallization relative to the chondritic uniform reservoir (CHUR) (Bouvier et al., 2008). Internal precision for ε₁⁷⁷Hf and εHf is reported for each analysis on Hf evolution plots in Supplemental Table S2 (see footnote 2) and as the average for all analyses (2.4 epsilon units at 2σ) on Figure 3. On the basis of the in-run analysis of zircon standards, the external precision is 2–2.5 epsilon units (2σ). Hf isotopic evolution of typical continental crust is shown with arrows on εHf, evolution diagrams, which are based on a ¹⁷⁷Lu/¹⁷⁶Hf ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999).

*Supplemental Table S1. Zircon U-Pb geochronologic analyses by laser ablation–multicollector–inductively coupled plasma mass spectrometry; Mississippian–Permian sandstones. Please visit http://doi.org/10.1130/GES01525.S1 or the full-text article on www.gsapubs.org to view the Supplemental Table.*

*Supplemental Table S2. Hf isotopic data: Mississippian–Permian sandstones. Please visit http://doi.org/10.1130/GES01525.S2 or the full-text article on www.gsapubs.org to view the Supplemental Table.*
Figure 3. Relative U-Pb age-probability plots (lower panel) and Hf evolution diagram (upper panel) showing results from analyses of Mississippian–Permian sandstones in the Appalachian foreland (analytical data and location information are in Supplemental Tables S1 [see footnote 1] and S2 [see footnote 2]). Lower panel: Relative age-probability plots for seven analyzed samples. Vertical colored bands represent the age ranges of potential provenance provinces in the Appalachians and North American craton. The plots are color coded as in Figure 2: blue—Mauch Chunk–Pottsville clastic wedge; red—Pennington-Lee clastic wedge; green—longitudinal dispersal system. Upper panel: εHf data for six samples (data points are color coded and shown by symbols that are explained in the lower panel). The average uncertainty of Hf isotopic analyses (2.6 epsilon units at 2σ) is shown in the upper right. The Hf evolution diagram shows the Hf isotopic composition at the time of zircon crystallization, in epsilon units, relative to the chondritic uniform reservoir (CHUR) (Bouvier et al., 2008) and to the depleted mantle (DM) (Vervoort and Blichert-Toft, 1999). Shown for reference is the evolution of typical continental crust (black arrow), which is based on a 176Lu/177Hf ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999). Shown for reference is the evolution of typical continental crust (black arrow), which is based on a 176Lu/177Hf ratio of 0.0115 (Vervoort and Patchett, 1996; Vervoort et al., 1999). Reference fields, which are shown by colored areas (explanation in lower right of upper panel), summarize published Hf isotopic data for the Appalachians (from Appalachian-derived detrital grains; Mueller et al., 2007, 2008), the Gander and Avalon accreted terranes (Willner et al., 2013, 2014; Pollock et al., 2015; Henderson et al., 2015), the Grenville orogen (Bickford et al., 2010; Gehrels and Pecha, 2014), Meso-proterozoic rocks of the Granite-Rhyolite province and Paleoproterozoic rocks of the Central Plains orogen (Goode and Vervoort, 2006; Bickford et al., 2008; Gehrels and Pecha, 2014), and the Penokean and Superior provinces of the Canadian Shield (Gehrels and Pecha, 2014).
Figure 4. Relative age-probability plots showing previously published results from U-Pb analyses of sandstones in the Appalachian foreland (analytical data, location, and stratigraphic information are available in the cited references). Vertical colored bands represent the age ranges of potential provenance provinces in the Appalachians and North American craton. The plots are color coded as in Figures 2 and 3: blue—Mauch Chunk–Pottsville clastic wedge; red—Pennington-Lee clastic wedge; green—longitudinal dispersal system. The plots omit a total of six analyzed grains, which have ages younger than the stratigraphically documented depositional ages.
Our Hf isotope data are interpreted within the standard framework of juvenile (positive) values indicating magma consisting mainly of material extracted from the mantle during or immediately prior to magmatism, versus more evolved (negative) values that record incorporation of significantly older crust. Vertical arrays on εHf, diagrams are interpreted to represent magmas that contain both material derived from the mantle during (or immediately prior to) magmatism and significantly older crustal materials. For comparison with our new data, color-shaded fields in Figure 3 encompass the main clusters of data points previously reported for potential provenance provinces (original data are in the cited references for Figure 3).

### RESULTS OF DETRITAL-ZIRCON ANALYSES

New analyses include seven samples for U-Pb age data (Supplemental Table S1 [see footnote 1], Fig. 3) and six samples for Hf isotopic ratios (Supplemental Table S2 [see footnote 2], Fig. 3). The U-Pb age data are described here in order of depositional age (oldest to youngest) and are placed in the context of the two transverse dispersal systems in the clastic wedges and in the longitudinal system in the distal part of the basin. The Hf isotopic ratios are described separately.

### U-Pb Age Data

#### Stony Gap Sandstone Member (Sample KY-21-SG)

Sandstone was collected from the Upper Mississippian Stony Gap Sandstone Member of the Pennington Formation at a site on the leading edge of the Appalachian thrust belt in eastern Kentucky in the distal part of the foreland basin (Fig. 2). The sandstone has dominant concentrations of detrital-zircon ages in the ranges of 1238–936 Ma and 474–372 Ma with peaks at 1091 and 426 Ma, respectively (Fig. 3). Secondary concentrations are in the ranges of 2966–2558 Ma with a peak at 2718 Ma and of 1815–1254 Ma with peaks at 1660, 1508, and 1347 Ma. A few grains have ages of 2116–1876 Ma and 637–532 Ma. The Stony Gap Sandstone Member, regionally, is the lower member of the Hinton Formation within the Mauch Chunk–Pottsville clastic wedge northeast of this collecting site (Fig. 2) (e.g., Thomas, in Hatcher et al., 1988b); the sandstone unit has been correlated to this distal location as the Stony Gap Sandstone Member within the Pennington Formation (Group) (e.g., Thomas, 1959; Wilpolt and Marden, 1959). This sample location is within the area of overlap of the Mauch Chunk–Pottsville clastic wedge with the Pennington-Lee clastic wedge, leaving the provenance uncertain; however, regional distribution and inferred continuity of the Stony Gap Sandstone Member are consistent with the distal part of the Mauch Chunk-Pottsville clastic wedge.

#### Sharon Conglomerate Member of the Pottsville Formation (Northern Sample OH-4-SN)

The Sharon Conglomerate Member of the Lower Pennsylvanian Pottsville Formation in northwestern Pennsylvania and northeastern Ohio laps onto an erosional unconformity that cuts down section northward to as low as Upper Devonian strata (Fuller, 1955; Wanless, 1975). Paleocurrents in the Sharon Conglomerate Member in northwestern Pennsylvania and northeastern Ohio indicate longitudinal (southwestward) drainage (Fig. 2) (Meckel, 1967) that was separated from coeval transverse (northwestward) drainage during Pottsville deposition in eastern Pennsylvania (Edmunds et al., 1999). A sample of the Sharon Conglomerate from northeastermost Ohio (Fig. 2) has a dominant concentration between 1302 and 972 Ma with a strong peak at 1037 Ma and a weak peak at 1162 Ma (Fig. 3). Another prominent concentration at 491–361 Ma has a peak at 443 Ma. Minor concentrations are between 1881 and 1302 Ma with peaks at 1648, 1458, and 1366 Ma; and between 682 and 538 Ma with a peak at 618 Ma. A few grains are scattered between 2846 and 2675 Ma and between 972 and 777 Ma.

#### Sharon Conglomerate Member of the Pottsville Formation (Southern Sample OH-1-SN)

The sample location in southern Ohio is within the longitudinal dispersal system; however, paleocurrents and paleotopography indicate transverse (northwestward) drainage locally during deposition of the Sharon Conglomerate Member (Fuller, 1955; Rice and Schwitering, 1988; Ketering, 1992). The regional drainage and quartz-pebble distribution patterns suggest that the local variations around the sample site reflect distributaries within the transition from the Mauch Chunk-Pottsville transverse drainage into the longitudinal drainage. The sandstone sample has one dominant mode at 1056–894 Ma with a peak at 1012 Ma and another at 501–380 Ma with a peak at 465 Ma (Fig. 3). The sample includes a secondary mode at 1278–1070 Ma with peaks at 1232 and 1162 Ma. The sample also has a minor concentration between 1791 and 1292 Ma with peaks at 1554 and 1332 Ma, and another between 711 and 554 Ma with a peak at 616 Ma. A few ages are scattered between 2695–2148, 2095–1883, and 336–330 Ma. The youngest grain is 330 Ma, which is the age of the earliest Alleghanian orogeny and also near the depositional age of the Sharon. Similarities in the detrital-zircon populations indicate that the two Sharon samples are parts of the same longitudinal dispersal system.

#### Corbin Sandstone (Sample KY-18-CB)

A sample of the Corbin Sandstone represents the youngest part of the southwest-directed longitudinal fluvial system along the distal part of the Appalachian foreland basin (Fig. 2) (Archer and Greb, 1995; Greb and
Chesnut, 1996). The dominant concentration of detrital-zircon ages is in the range 1191–924 Ma with a prominent peak at 1076 Ma and a secondary peak at 1176 Ma (Fig. 3). Another important concentration at 1843–1543 Ma has a prominent peak at 1652 Ma and less pronounced peaks at 1808 and 1744 Ma. The sample includes strong secondary concentrations at 2813–2531 and 499–406 Ma, with peaks at 2716 and 456 Ma, respectively. Another secondary concentration at 1543–1211 Ma has peaks at 1502 and 1390 Ma. A few grains are scattered at 3591–2986, 1987–1896, and 822–609 Ma. The concentration of grains with ages of 2813–2531 Ma, which corresponds to the Superior province of the Canadian Shield, is distinctly greater than in any other samples, except the Mississippian Stony Gap Sandstone Member (sample KY-21-SG) of the Pennington Formation, which is stratigraphically below the Corbin Sandstone in the same general area. In contrast, other sandstones (samples OH-4-SN and OH-1-SS) of the longitudinal dispersal system have only minor numbers of grains of Superior age.

**Grundy-Norton Stratigraphic Interval (Sample VA-1-GN)**

A sample of a sandstone from the Lower Pennsylvanian Grundy-Norton stratigraphic interval in the distal part of the transverse Pennington-Lee dispersal system (Fig. 2) has a strongly dominant mode of detrital-zircon ages at 1252–934 Ma with peaks at 1175 and 1067 Ma (Fig. 3). A secondary mode at 1479–1252 Ma has a peak at 1454 Ma. Minor concentrations at 1770–1544, 625–517, and 462–322 Ma have peaks at 1588, 619, and 370 Ma, respectively. A few grains are scattered between 2720 and 2659, and at 1895 Ma. The youngest grain at 322 Ma is the only grain with an Alleghanian age; 322 Ma is near the depositional age of the interval.

**Princess No. 7 Coal (Sample KY-19-PR7)**

A sample of a sandstone above the Middle Pennsylvanian (Desmoinesian) Princess No. 7 coal (Fig. 2) has a dominant peak of detrital-zircon ages at 1089 Ma, within a concentration in the range of 1254–901 Ma (Fig. 3). The sample includes a secondary concentration between 1550 and 1254 Ma with peaks at 1471 and 1318 Ma. Minor concentrations are in the ranges of 1733–1615, 661–551, and 470–373 Ma with peaks at 1656, 631, and 417 Ma, respectively. A few grains are scattered at 2763–2668, 2153, and 1839 Ma.

**Proctor Sandstone Member (Sample WV-1-PR)**

The Proctor Sandstone Member of the Greene Formation is the youngest exposed sandstone in the Dunkard Group in the Permian System in West Virginia (Fig. 2). A dominant mode of detrital-zircon ages of 1275–944 Ma has a prominent peak at 1051 Ma and another peak at 1166 Ma (Fig. 3). A relatively weak secondary mode at 1524–1296 Ma has peaks at 1469 and 1339 Ma, and another at 488–364 Ma has peaks at 487 and 432 Ma. Minor modes at 1692–1624 and 628–585 Ma have peaks at 1653 and 625 Ma, respectively. A few grains are scattered at 2810–2664, 1856, 1755–1754, 1565–1560, 757–718, and 533 Ma. The youngest detrital zircon in this stratigraphically highest sample is 364 Ma, within the age range of the Acadian orogeny.

**Hf Isotopic Data**

Hafnium isotopic analyses have been conducted on detrital-zircon grains from six samples that represent deposition in the two clastic wedges and longitudinal system during Mississippian–Permian time (Fig. 3). For each sample, zircon grains from each age group were analyzed with emphasis on younger (<800 Ma) grains and on avoiding grains with significant discordance or poor precision.

Precambrian grains from these samples yield juvenile to intermediate εHf values, most of which overlap with values from Paleoproterozoic–Mesoproterozoic igneous rocks of the Grenville, Granite-Rhyolite, and Central Plains provinces (Fig. 3). There is no discernible pattern in the εHf values with age or basinial setting. Neoproterozoic grains in both clastic wedges yield εHf values that are quite variable, ranging from −13 to +7.

Zircon grains with early Paleozoic U-Pb ages yield interesting geographic and temporal patterns (Fig. 3). Using the three phases of Appalachian magmatism (Taconic, Acadian, and Alleghanian) as a temporal guide, the two clastic wedges and longitudinal system contain abundant Taconic- and Acadian-age grains. Samples from the Pennington-Lee clastic wedge yield mainly intermediate (−5 to +5) εHf values, which are also present in samples from the Mauch Chunk–Pottsville clastic wedge and the longitudinal system. Samples from the latter two systems also contain grains with more negative and more positive εHf values, which suggests that the sources contained more heterogeneous crustal materials than those for the Pennington-Lee clastic wedge.

### APPALACHIAN POSSIBLE PROVENANCE COMPONENTS

#### Canadian Shield

The Canadian Shield of the eastern North American craton includes several distinct age provinces: Superior, Penokean, Central Plains, and Grenville (Fig. 1). These, as well as the Granite-Rhyolite province, are covered by Paleozoic sedimentary rocks across the Midcontinent. Sedimentary thickness and facies distributions along the present eroded limits of the Paleozoic cover strata, as well as erosional remnants on the Shield and xenoliths in diatremes, indicate that much of the Shield was covered before Mississippian time and, therefore, not available as a primary source of late Paleozoic sediment (Sloss, 1988; Cecile and Norford, 1993). Earlier, during Iapetan rifting of Laurentia and initial passive-margin transgression (e.g., Sloss, 1988), the exposed craton provided a primary
source of zircons with ages from Superior to Grenville (Fig. 3), which were dispersed irregularly to parts (but not all) of the rifted margin (e.g., Cawood and Nemchin, 2001; Eriksson et al., 2004; Thomas et al., 2004a, 2004b; Allen, 2009; Chakraborty et al., 2012) and were reworked by passive-margin transgression (e.g., Konstantinou et al., 2014). The Shield has been interpreted to be a primary source of sediment supplied to the distal margins of Appalachian foreland basins, and these interpretations can be evaluated herein with detrital-zircon data.

Grenville Province

The Grenville province encompasses the Elzevirian and Shawinigan orogenies and the Ottawan and Rigolet phases of the Grenville orogeny, ranging through a time of approximately 1300 to 950 Ma (Fig. 5) (Bartholomew and Hatcher, 2010; Rivers et al., 2012). The Grenville province includes inliers of older, partially reworked crystalline rocks of various ages, including components of the Granite-Rhyolite province (1500–1320 Ma, reworked in the Grenville province of southern Canada), the Labrador province (1700–1600 Ma, reworked in the Grenville province of eastern Canada) (Rivers et al., 2012), and the Mars Hill terrane (1800 Ma, reworked in the southern part of the Grenville Blue Ridge external basement massif) (Fig. 1) (Ownby et al., 2004). As shown on Figure 3, igneous rocks of the Grenville orogen and sediments derived from these rocks yield εHf values that range from –5 to +10 (Mueller et al., 1996; Pollock et al., 2010; Willner et al., 2013; Mueller et al., 2014; Henderson et al., 2015). Relative enrichment in zirconium during the Grenville orogeny generated extraordinarily abundant zircons of that age (Moecher et al., 2007; Willner et al., 2013; Mueller et al., 2014). Detrital zircons from late Neoproterozoic to Cambrian sedimentary cover strata generally are dominated by Pan-African–Brasiliano ages of 760–530 Ma; older components of Gondwana, including ages of 2730–2550 and 2160–1140 Ma, especially Eburnian–Trans-Amazonian ages of 2160–1950 Ma, are variably represented in the sedimentary detritus (Fig. 6) (Pollock et al., 2010; Willner et al., 2013; Henderson et al., 2015). Detrital zircons from the Cambrian to Devonian cover succession of the Suwannee terrane have age concentrations at 650–510 Ma and 2250–2000 Ma (Fig. 6), corresponding to Pan-African–Brasiliano and Eburnian–Trans-Amazonian, respectively (Mueller et al., 1994, 2014). Within the Devonian–Permian fill of the fault-bounded composite Maritimes basin (Fig. 1) (e.g., van de Poll et al., 1995), Devonian–Mississippian sandstones in the St. Marys sub-basin have detrital-zircon age

Figure 5. Diagram of ages of potential primary sources of detrital zircons for the Appalachian foreland. Black bars indicate crystallization ages of zircons; gray bars indicate ages of xenocrysts, inclusions, and protoliths within the primary igneous rocks. Data are from references cited in the text. Inset A: Relative age–probability plot of data from Taconic and Acadian igneous rocks (from Sinha et al., 2012).

Gondwanan Accreted Terranes

Accreted terranes of Gondwanan affinity extend along the internal parts of the Appalachian orogen (Fig. 1) (e.g., Hatcher et al., 2007; Hibbard et al., 2007; Hatcher, 2010). Three major composite terranes—Ganderia, Avalonia, and Meguma—along the orogen from the New York promontory to the Newfoundland embayment (Fig. 1) had been accreted by the late Paleozoic (e.g., Hibbard and Karabinos, 2013). From the Pennsylvania embayment southward to the Alabama promontory, the Carolinia composite terrane comprises the internal part of the Appalachian orogen (Fig. 1) (Hibbard, 2000; Hatcher, 2010). The Suwannee terrane (documented by drill data in the subsurface beneath the Gulf and Atlantic Coastal Plains) was accreted in the Pennsylvanian (Fig. 1) (Thomas et al., 1989a; Thomas, 2010; Mueller et al., 2014). The Gondwanan terranes have Neoproterozoic metavolcanic, metasedimentary, and plutonic basement rocks with ages of 800–520 Ma, corresponding to Pan-African–Brasiliano events in Gondwana (Fig. 5) (e.g., Pollock et al., 2010; Willner et al., 2013; Mueller et al., 2014; Henderson et al., 2015); Sm-Nd systematics from the Suwannee terrane indicate interaction with Mesoproterozoic (1330–1040 Ma) lithosphere (Fig. 5) (Heatherington et al., 1996; Mueller et al., 2014).
Figure 6. Relative age-probability plots of previously published results from U-Pb analyses of zircons from sedimentary cover rocks in accreted Gondwanan terranes (analytical data, location, and stratigraphic information are available in the cited references). Vertical colored bands represent the age ranges of potential provenance provinces for sedimentary rocks in Gondwanan accreted terranes. The plots are color coded to distinguish between different Gondwanan terranes.
concentrations of 760–550 Ma and 2200–2000 Ma (Fig. 6) (Murphy and Hamilton, 2000). As shown on Figure 3, igneous and sedimentary rocks from the Gander and Avalon terranes yield εHf, values for Meso- and Paleoproterozoic grains that are somewhat more evolved than those of North American cratonic provinces, and highly variable εHf, values for Neoproterozoic–early Paleozoic grains (Willner et al., 2013, 2014; Henderson et al., 2015; Pollock et al., 2015).

The accreted terranes are potential sources of detritus for the late Paleozoic Appalachian foreland; however, the ages of many of the zircons within the terranes are not distinct from those of other potential Appalachian sources. Two age ranges are characteristic of Gondwana, 2200–2000 Ma (Eburnian–Trans-Amazonian) and 800–520 Ma (Pan-African–Brasiliano); however, Pan-African–Brasiliano zircons cannot be distinguished on the basis of age alone from lapetan synrift igneous zircons. Although some detrital zircons in the late Paleozoic Appalachian foreland basin have ages of 2200–2000 and 800–520 Ma, neither age group is abundant.

Iapetan Synrift Rocks

Neoproterozoic to Early Cambrian synrift volcanic and plutonic rocks (Fig. 1) mark the lapetan rifted margin of Laurentia (e.g., Thomas, 2014). The synrift rocks are exposed along Appalachian external basement massifs, reflecting thrust translation of the rifted margin (e.g., Thomas, 1991); however, synrift rocks constitute a small proportion of the erosion surface. Synrift rocks also are distributed along intracratonic synrift fault systems inboard from the lapetan rifted margin, including igneous rocks along some fault systems and sedimentary rocks that fill intracratonic grabens (e.g., Thomas, 2014).

Synrift igneous rocks along the lapetan rifted margin range in age from 765 to 530 Ma (Fig. 5) (compilation in Thomas, 2014), but no comprehensive systematic distribution pattern is evident. Detrital zircons from synrift igneous rocks (535 ± 5 Ma) along the intracratonic Southern Oklahoma fault system inboard from the lapetan rifted margin in the Ouachita embayment have strongly positive εHf, values, indicating juvenile magmas (Thomas et al., 2016); however, Hf data are not yet available for synrift igneous rocks along the lapetan rift margin, including igneous rocks along some fault systems and sedimentary rocks that fill intracratonic grabens (e.g., Thomas, 2014).

Sandstones in the synrift fill of the Birmingham intracratonic graben (Rome Formation, Fig. 7), inboard from the lapetan rifted margin, have detrital zircons with ages that correspond to each of the provinces of the Laurentian craton from Superior to Grenville (Thomas et al., 2004b). The ages of detrital zircons available for recycling from the synrift sedimentary rocks vary locally along the rifted margin. Because no rocks older than Grenville, except some inliers in the Grenville province, are exposed in the Appalachians, recycling from the synrift sedimentary rocks is the only available Appalachian source of the older detrital zircons. Detrital zircons with ages corresponding to those of the synrift igneous rocks are rare in the synrift sedimentary rocks.

Cambrian–Ordovician Passive-Margin Sedimentary Rocks

A classic passive-margin shelf succession of a basal sandstone and overlying massive carbonate platform records diachronous transition from rift to passive margin and subsequent passive-margin transgression during the Cambrian (e.g., Sloss, 1988). By the Ordovician, transgression had covered most of the older basement rocks of the Canadian Shield (Sloss, 1988). The shelf carbonates include widespread interbeds of mature quartzose sandstone and disseminated quartz sand, which were supplied from the Shield and distributed widely across parts of the carbonate platform by trade winds (e.g., Pickell, 2012; Konstantinou et al., 2014; Thomas et al., 2016). Outboard from the shelf edge, off-shelf mud-dominated slope-and-rise deposits include carbonate mud and quartz sand from the shelf, as well as olistoliths of carbonate rocks, sandstone, synrift volcanic rocks, and basement rocks (e.g., Viele and Thomas, 1988; Hanson et al., 2016).

The basal transgressive sandstones of the passive-margin succession are dominated by detrital zircons with ages of 1300–950 Ma (Fig. 8), consistent with sedimentary reworking of the Grenville-age basement rocks during transgression. Like the synrift sedimentary rocks, the passive-margin succession locally contains some older zircons. Detrital zircons from the Superior province dominate the widely distributed quartz sand within the carbonate shelf; but zircons from other provinces of the Canadian Shield, including Grenville, are significant components of the population (Fig. 8) (Pickell, 2012; Konstantinou et al., 2014). In the Ouachita thrust belt, quartz sandstone (Blakely Sandstone, Fig. 8) within the allochthonous off-shelf mud-dominated passive-margin succession contains detrital zircons that are dominated by ages of the Grenville and Superior provinces but include ages of other craton provinces (Gleason et al., 2002), suggesting deposition from grain flows that were fed by trade-wind–driven sand dispersal across the carbonate platform and over the shelf edge onto the continental slope. Although no grain-flow deposits have been recognized along the Appalachian thrust belt, and no quartz sands within the carbonate platform are known to extend to the Appalachian shelf edge, the example from the Ouachita thrust belt suggests another possible component for recycling in addition to the other passive-margin components in the Appalachians.
Figure 7. Relative age probability plots of previously published results from U-Pb analyses of zircons from synrift sedimentary rocks along the Iapetan rifted margin of Laurentia (analytical data, location, and stratigraphic information are available in the cited references). Vertical colored bands represent the age ranges of potential provenance provinces in the North American craton, as well as Iapetan synrift igneous rocks. The plots are color coded to distinguish between different parts of the rift margin and a synrift intracratonic graben.
Figure 8. Relative age-probability plots of previously published results from U-Pb analyses of zircons from passive-margin sedimentary rocks along the Laurentian shelf and shelf margin (analytical data, location, and stratigraphic information are available in the cited references). Vertical colored bands represent the age ranges of potential provenance provinces in the North American craton, as well as Iapetan synrift igneous rocks. The plots are color coded to distinguish between different parts of the passive margin and adjacent craton.
Taconic Synorogenic Rocks

The Taconic orogeny included a succession of arc-accretion events and foreland subsidence (Drake et al., 1989). Zircons with ages between 490 and 420 Ma generally correspond in age to the Taconic orogeny (Fig. 5), defined in the broadest sense (e.g., Drake et al., 1989). The eroded roots of Taconic volcanic systems have ages of 490–440 Ma (Shaw and Wasserburg, 1984; Tucker and Robinson, 1990; Sevigny and Hanson, 1993; Sinha et al., 1997; Karabinos et al., 1998; Coler et al., 2000; Miller et al., 2000; Aleinikoff et al., 2002). Successively accreted magmatic arcs along the southern part of the New York promontory have ages of 485–470 Ma (east-dipping subduction) and 454–442 Ma (west-dipping subduction) (Karabinos et al., 1998). Along the Virginia promontory and Pennsylvania embayment, zircons from a pre-collisional arc complex have ages of 489–470 Ma and from synorogenic arc plutons have ages of 472–441 Ma; plutons associated with post-orogenic delamination have ages of 438–423 Ma (Sinha et al., 2012). Other examples along the margin have a similar history (van Staal et al., 2007; Tull et al., 2014). Widespread K-bentonite beds in the foreland stratigraphy include zircons with U-Pb ages of 453.1 ± 1.3 and 454.5 ± 0.5 Ma (Tucker and McKerrow, 1995). As shown on Figure 3, detrital grains in sediments derived from the southern Appalachians include Taconic-age zircons with highly variable (~12 to +6) εHf values (Mueller et al., 2008).

Taconic synorogenic clastic wedges are potential sources for late Paleozoic recycling. Figure 9 illustrates data from ten previously published analyses from Taconic clastic wedges, as well as from one newly analyzed sample from the lower Upper Ordovician Colvin Mountain Sandstone (sample AL-1-CM; Supplemental Table S3†) on the Alabama promontory in the marine reworked distal southwestern part of a clastic wedge centered on the Tennessee embayment (Bayona and Thomas, 2006). Grenville ages dominate the detrital-zircon populations in the Taconic clastic wedges (Fig. 9). Lesser components of the Taconic detrital-zircon population represent pre-Grenville Laurentian cratonic provinces, most abundantly Granite-Rhyolite from recycling or from Grenville inliers, and also minor concentrations of Central Plains, Penokean, and Superior ages (Fig. 9). Although synorogenic igneous rocks potentially are available as primary sources of detrital zircons, only one sandstone analyzed from the Taconic synorogenic clastic wedges has zircon grains (two) of Taconic age (Fig. 9) (Park et al., 2010), indicating no significant source for recycling of Taconic-age zircons from Taconic synorogenic sandstones.

Acadian Synorogenic Rocks

Separate phases of the Acadian orogeny reflect accretion of composite terranes along the Laurentian margin (e.g., Hibbard and Karabinos, 2013). Plutons contemporaneous with the Acadian orogeny (420–350 Ma; Fig. 5) are more common in the northern Appalachians than in the southern Appalachians (Osberg et al., 1989; Eusden et al., 2000; Miller et al., 2000; Hibbard and Karabinos, 2013). Acadian plutons in the Pennsylvania embayment have ages of 381–362 Ma (Sinha et al., 2012). Bentonite beds in the Appalachian foreland confirm syndepositional volcanism during Devonian orogenic events (Tucker et al., 1998). As shown on Figure 3, detrital grains in sediments derived from the southern Appalachians include Acadian-age zircons with highly variable (~10 to +6) εHf values (Mueller et al., 2008).

Sandstones in the Acadian clastic wedge are potential sources for late Paleozoic recycling. In addition to data from seven previously published analyses from the Acadian clastic wedge centered on the Pennsylvania embayment, Figure 10 shows data from one newly analyzed sample from the Devonian Frog Mountain Sandstone (sample AL-2-FM; Supplemental Table S3† [see footnote †] on the Alabama promontory. The marine reworked Frog Mountain Sandstone has multiple internal unconformities and ranges in age from Early through Middle Devonian or younger (Ferrill, 1984); the feldspathic sandstones indicate base- ment sources along the orogen (Ferrill and Thomas, 1988). The Acadian synorogenic sandstones have abundant Grenville-age zircons; however, Taconic-age grains dominate some samples (Fig. 10). The Acadian sandstones include the same variety of older ages as in the Taconic clastic wedge (Fig. 10). Acadian synorogenic zircons generally are rare in the Acadian clastic wedge (Fig. 10).

Alleghanian Synorogenic Rocks

Alleghanian plutons (Fig. 5) in the southern Appalachian Piedmont have ages of 330–300 Ma (Sinha and Zietz, 1982; Samson et al., 1995; Coler et al., 2000), whereas those in New England have ages of 330–270 Ma (Aleinikoff et al., 1988; Zartman and Hermes, 1987; Tomascak et al., 1996). Tonsteins (volcanic ash beds) within Pennsylvanian-age coal beds in the Appalachian basin have ages of 316 ± 1 Ma (Upper Banner coal; U-Pb zircon) and 311.2 ± 0.7 Ma (Fire Clay coal; 40Ar/39Ar, respectively (Lyons et al., 1992, 1997; Kunk and Rice, 1994). As shown in the reference field in Figure 3, detrital grains in sediments derived from the southern Appalachians include Alleghanian-age zircons with highly variable (~8 to +6) εHf values (Mueller et al., 2008).

Zircons with ages of the Grenville province and the Taconic and Acadian synorogenic plutons dominate the detrital-zircon populations of the Alleghany clastic wedges, which contain less abundant zircons from other recycled pre-Alleghanian primary sources (Figs. 3, 4). Although Alleghanian synorogenic igneous rocks are scattered along the orogen (e.g., Hibbard and Karabinos, 2013), only seven detrital zircons in the 3564 reported analyses (both new and previously published) have ages younger than 331 Ma (Figs. 3, 4).

PROVENANCE OF MISSISSIPPIAN–PERMIAN SANDSTONES IN THE APPALACHIAN FORELAND

Mauch Chunk–Pottsville Clastic Wedge

One new analysis and seven previously published analyses characterize the Mauch Chunk–Pottsville clastic wedge (Fig. 2). The stratigraphically lowest and most distal sample is from the Upper Mississippian Stony Gap Sandstone Member (sample KY-21-SG, Figs. 2, 3). Published data include Upper Mississippian
Figure 9. Relative age-probability plots of results from U-Pb analyses of zircons from sedimentary rocks in Taconic synorogenic clastic wedges in the Appalachians (analytical data and location information for sample AL-1-CM are in Supplemental Table S3 [see footnote 3]; analytical data, location, and stratigraphic information for previously published analyses are available in the cited references). Vertical colored bands represent the age ranges of potential provenance provinces in the North American craton, Iapetan synrift igneous rocks, Taconic synorogenic igneous rocks, and Gondwanan accreted terranes. The plots are color coded to distinguish between different Taconic clastic wedges along the Appalachians.
Figure 10. Relative age-probability plots of results from U-Pb analyses of zircons from sedimentary rocks in the Acadian synorogenic clastic wedge in the Appalachians (analytical data and location information for sample AL-2-FM are in Supplemental Table S3 [see footnote 3]; analytical data, location, and stratigraphic information for previously published analyses are available in the cited references). Vertical colored bands represent the age ranges of potential provenance provinces in the North American craton, Iapetan synrift igneous rocks, Taconic and Acadian synorogenic igneous rocks, and Gondwanan accreted terranes. The plots are color coded to distinguish between the Acadian clastic wedge and distal foreland along the Appalachians.
sandstones in the proximal (Mauch Chunk Formation) and southwestern mid-distal parts (Hinton Formation, Princeton Sandstone, and Bluestone Formation) of the clastic wedge (Figs. 2, 4) (Park et al., 2010). Lower Pennsylvanian Tumbling Run Member of the Pottsville Formation and Pottsville Formation undifferentiated; Becker et al., 2005) and Middle Pennsylvanian (Sharp Mountain Member of the Pottsville Formation; Gray and Zeitler, 1997) sandstones are from the proximal part of the Mauch Chunk–Pottsville clastic wedge (Figs. 2, 4). Within the regional context of generally cratonward paleocurrents, southward paleocurrents in the Sharp Mountain Member of the Pottsville Formation indicate longitudinal sediment dispersal (Meckel, 1967; Robinson and Prave, 1995); however, this system directly overlies an unconformity.

A consistent concentration of ages in all eight samples indicates a Grenville source (Figs. 3, 4, 11), either primary from Appalachian massifs or recycled. Another prominent concentration indicates Taconic and Acadian sources within the Appalachian orogen. The Taconic–Acadian peak exceeds or equals the Grenville peak, except that the Taconic–Acadian peak decreases upward through the two stratigraphically higher samples in the Upper Mississippian part (Princeton and Bluestone, Fig. 4) of the clastic wedge. The Taconic–Acadian peak is even more dominant in the Lower Pennsylvanian sandstones than in the underlying Mississippian sandstones (Figs. 4, 11). A secondary concentration in all eight samples corresponds to the Granite-Rhyolite province, from either inliers in Grenville terranes or recycling from synrift clastic deposits (Figs. 3, 4, 11). All of the samples have a few grains with ages that correspond to ages of Iapetan synrift igneous rocks or accreted Gondwanan Pan-African–Brasiliano terranes (Figs. 3, 4). The Stony Gap Sandstone Member has distinct secondary concentrations of Superior and Central Plains ages (sample KY-21-SG, Fig. 3), in contrast to most samples from the Mauch Chunk–Pottsville clastic wedge (Fig. 4); the Hinton sample (Fig. 4) (Park et al., 2010) from the more proximal part of the clastic wedge has a similar but smaller concentration of Superior and Central Plains zircons, suggesting a common provenance and dispersal pathway. Because of the distance and isolation from primary sources in the Canadian Shield, the Superior and Central Plains zircons suggest probable recycling from synrift sedimentary rocks of the lapetan rifted margin or from passive-margin strata (e.g., Thomas et al., 2004a, 2004b). The similarities in detrital-zircon populations support assignment of the Stony Gap to the dispersal system of the Mauch Chunk–Pottsville clastic wedge rather than the Pennington-Lee clastic wedge.

**Longitudinal Fluvial System**

The Early Pennsylvanian longitudinal fluvial system of quartzarenites and quartz-pebble conglomerates trends southwestward along the distal side of the Appalachian foreland basin (Archer and Greb, 1995). On the basis of paleocurrents and distribution of quartz pebbles, previous interpretations have focused on southwestward dispersal of sediment from a source on the north, either the Canadian Shield or the northern Appalachians (e.g., Siever and Potter, 1956; Meckel, 1967).

The Lower Pennsylvanian Sharon Conglomerate in the northern part of the longitudinal system (Fig. 2) laps onto an unconformity, and the sandstones assigned to the Sharon may not be laterally continuous (e.g., Ruppert et al., 2010). Nevertheless, the detrital-zircon populations are similar (Fig. 3). Both Sharon samples (OH-4-SN and OH-1-SS, Fig. 3) have prominent Grenville modes and a more dominant Taconic–Acadian peak. In both samples, a minor peak at 618–616 Ma is the strongest representation in any of the Mississippian–Permain Appalachian sandstones of ages equivalent to either lapetan synrift rocks or accreted Gondwanan Pan-African–Brasiliano terranes (Fig. 3); in contrast to positive εHf values from synrift rocks in Oklahoma (Thomas et al., 2016), the generally negative εHf values in Sharon sample OH-1-SS (Fig. 3) favor accreted terranes. The Sharon samples contain a few older grains, including Superior.

Farther south, downstream (Fig. 2), the Corbin Sandstone (sample KY-18-CB, Fig. 3) has both Grenville and Taconic–Acadian concentrations; the Grenville is more dominant. In the Corbin Sandstone, distinct secondary concentrations have ages of the Superior (2813–2531 Ma) and Central Plains (1845–1540 Ma) provinces; but these ages are very weakly expressed in both Sharon samples (Fig. 3). The substantial downstream increase of these components suggests introduction of locally derived sediment from one of the transverse systems. The general paucity of grains older than Granite-Rhyolite in the other Mississippian–Permain sandstones distinguishes the Upper Mississippian Stony Gap Sandstone Member (sample KY-21-SG, Fig. 3) and the Corbin Sandstone as the only ones with substantial Superior and Central Plains detritus, suggesting some unique local provenance for the Stony Gap and either recycling or continuing supply for the Corbin.

Published data from four sandstones (Raccoon Mountain Formation; Lee Formation; upper Raleigh Sandstone, equated to Sewanee Sandstone by Grimm et al., 2013; and Sewanee Conglomerate; Fig. 4) represent the longitudinal fluvial system south of the Corbin sample site (Fig. 2). In each of these sandstones except the Sewanee, the dominant concentration is of Grenville age (Fig. 4). A secondary concentration of Taconic–Acadian age varies from sample to sample, from dominant in the Sewanee to lacking in the Lee (Fig. 4). The four samples each have secondary concentrations of Central Plains and Superior ages, but these are weaker than the equivalent concentrations in the Corbin (Figs. 3, 4).

Because of a lack of an obvious source in the Appalachians, the minor concentration of Superior grains in the upper Raleigh has been inferred to indicate a primary source in the Canadian Shield for the longitudinal sandstones (Eriksson et al., 2004; Grimm et al., 2013). The scarcity of Superior-age grains in the Sharon samples in the northern, more upstream sandstones somewhat isolates the concentration of Superior-age grains in the Corbin (Fig. 3) and sandstones farther south (Fig. 4). Along with a secondary concentration of Superior-age grains in the proximal Lower Pennsylvanian Tumbling Run (Fig. 4), the strong secondary concentration in the distal Upper Mississippian Stony Gap (Fig. 3) indicates probable dispersal through a somewhat restricted southern part of the transverse Mauch Chunk–Pottsville clastic wedge to feed the longitudinal system with recycled grains from lapetan synrift deposits or...
Figure 11. Composite relative age-probability plots (derived from data in Figs. 3 and 4) to illustrate variations through the stratigraphic succession and between the Mauch Chunk–Pottsville clastic wedge, Pennington-Lee clastic wedge, and Early Pennsylvanian longitudinal dispersal system in the Appalachian foreland. Vertical colored bands represent the age ranges of potential provenance provinces in the Appalachians and North American craton. The plots are color coded as in Figures 2, 3, and 4: blue—Mauch Chunk–Pottsville clastic wedge; red—Pennington-Lee clastic wedge; green—longitudinal dispersal system. Penn.—Pennsylvanian; Miss.—Mississippian; N—number of separate samples; n—number of individual grain analyses.
passive-margin sandstones (e.g., Thomas et al., 2004a). The secondary Central Plains concentrations in the Corbin and longitudinal sandstones to the south also contrast with minor components in the Sharon samples but are similar to a secondary concentration in the Stony Gap (Figs. 3, 4). The strong Taconic–Acadian peaks in the Sharon samples require a source in the Appalachians rather than in the Canadian Shield for the upstream components of the longitudinal system.

Differences in details of peak ages suggest variations in sediment input along the longitudinal fluvial system. In the downstream direction along the longitudinal system, the Taconic–Acadian peak is more prominent than the Grenville peak in the two Sharon samples, somewhat reduced in the Corbin sample, lacking in the Lee sample, greater than Grenville in the Sewanee sample, and reduced in the upper Raleigh and Raccoon Mountain samples (Fig. 4). The stronger Taconic–Acadian peak is similar to that in most samples from the Mauch Chunk–Pottsville clastic wedge, suggesting that the transverse system fed the longitudinal system in the north. The southward decrease in the Taconic–Acadian peak is consistent with a lesser Taconic–Acadian component in the Lower Pennsylvanian part of the Pennington-Lee clastic wedge; however, the non-systematic variation suggests local inputs at various times.

**Pennington-Lee Clastic Wedge**

Detrital-zircon age data for the Pennington-Lee clastic wedge are from samples scattered through the stratigraphic succession from Lower Pennsylvanian to lower Permian (Fig. 2). Data from one new sample (VA-1-GN, Fig. 3) and three published samples (Pocahontas Formation; Bottom Creek Formation; and lower Raleigh Sandstone, equated to Bottom Creek Formation by Grimm et al., 2013; Fig. 4) (Eriksson et al., 2004; Becker et al., 2005; Grimm et al., 2013) represent the Lower Pennsylvanian deposits of the transverse dispersal system in the proximal part of the north-northwestward–prograding Pennington-Lee clastic wedge (Fig. 2). In addition, a sample of Lower Pennsylvanian coarse lithic clasts are within a braid plain with northwest-flowing streams, reflecting a local proximal source on the southeast (Osborne, 1988, 1991). Two samples represent the Middle Pennsylvanian: the stratigraphically highest preserved sandstone (Atokan Cross Mountain Formation) in the southern part of the clastic wedge in the Appalachian basin in the footwall of the leading Appalachian thrust fault in northeastern Tennessee (Figs. 2, 4) (Thomas et al., 2004a), and a stratigraphically higher sandstone above the Middle Pennsylvanian (Desmoinesian) Princess No. 7 coal (sample KV-19-PR7, Figs. 2, 3). Four samples (two combined in plot 18 in Fig. 4) are from Upper Pennsylvanian sandstones (Conemaugh Group and Monongahela Group; Figs. 2, 4) (Dodson, 2008) in the northwesterly prograding clastic wedge. Three samples from lower Permian sandstones (WV-1-PR, Fig. 3; Washington Formation and Greene Formation, Fig. 4) (Becker et al., 2006) represent the upper part of the clastic wedge.

All of the samples have a dominant Grenville concentration (Figs. 3, 4, 11); other components of the detrital-zircon population vary with stratigraphic level. Except for a small Acadian peak in the Bottom Creek, the Lower Pennsylvanian sandstones have few to no grains with Taconic or Acadian ages (Figs. 3, 4, 11). The contrast in relative abundance of Taconic–Acadian grains suggests an important difference in proportion of components in the respective provenance regions of the Pennington-Lee and Mauch Chunk–Pottsville clastic wedges (Fig. 11), a distinction also indicated by Hf ratios (Fig. 3). Above the Lower Pennsylvanian, however, most sandstones in the Pennington-Lee clastic wedge have Taconic–Acadian peaks equal to or greater than the Grenville peaks, similar to the Mauch Chunk–Pottsville clastic wedge (Fig. 11). The evident upward increase in Taconic–Acadian grains may reflect greater unroofing and/or more extensive integration of drainage networks, perhaps paralleling progressive increase in depth of unroofing as indicated by petrographic data (Davis and Ehrlich, 1974). Although the stratigraphically lower Cross Mountain has a dominant Taconic–Acadian concentration (Fig. 4), the younger sandstone above the Princess No. 7 coal has only a minor Taconic–Acadian concentration (Fig. 3), indicating an irregular upward increase through the Middle Pennsylvanian.

Generally, the sandstones in the Pennington-Lee clastic wedge have moderate concentrations of Granite-Rhyolite age (Figs. 3, 4, 11), but older ages of detrital zircons are rare. An exception is the Middle Pennsylvanian Cross Mountain sample, which has minor concentrations of Central Plains and Superior ages (Fig. 4).

Although depositional ages of the Pennington-Lee clastic wedge overlap the ages of Alleghanian synorogenic igneous rocks, only six grains with Alleghanian ages have been documented in the clastic wedge. In Lower Pennsylvanian sandstones, detrital zircons with ages of 325 Ma in the Bottom Creek (Fig. 4) and 322 Ma in the Grundy-Norton (sample VA-1-GN, Fig. 3) are the only grains with ages as young as the Alleghanian orogeny; both ages are approximately equal to the stratigraphically documented depositional ages of the sampled horizon. The Monongahela samples include zircon grains with ages of 322 and 315 Ma (Fig. 4). Two lower Permian sandstones have one detrital-zircon grain each (305 Ma in Greene, 314 Ma in Washington; Fig. 4) within the age range of the Alleghanian orogeny, but the youngest detrital zircon in the lower Permian Proctor sample is 364 Ma (sample WV-1-PR, Fig. 3), within the age range of the Acadian orogeny.

### SUMMARY OF PROVENANCE AND MISSISSIPPIAN–PERMIAN SEDIMENT DISPERSAL IN THE APPALACHIAN FORELAND

Two major age components—Grenville and Taconic–Acadian—characterize the detrital-zircon populations in Mississippian to Permian sandstones in the Appalachian basin. Other age contributors are relatively minor but have some local concentrations.
Grenville

Grenville-age (1300–950 Ma) detrital zircons are dominant in many sandstones and are a strong component in the others (Fig. 11). No clear indications of systematic lateral or vertical variations in sediment contributions from Grenville sources are evident (Figs. 3, 4). Grenville-age detrital zircons may have been supplied from primary sources in the Appalachian basement massifs (Fig. 5), from recycling of detrital zircons in Appalachian sedimentary rocks spanning the stratigraphic succession from Iapetan synrift to Acadian synorogenic deposits (Figs. 7–10), or most likely from both primary and secondary sources.

Taconic–Acadian

Detrital zircons with ages of 490–350 Ma constitute a prominent mode in many of the samples, but the relative abundance differs through the sample set from most dominant to completely lacking (Figs. 3, 4, 11). Taconic and Acadian plutons provide primary sources of zircons with ages of 490–420 and 420–350 Ma, respectively (Fig. 5). The Taconic and Acadian clastic wedges contain only very rare synorogenic zircons; however, the Acadian clastic wedge does have Taconic-age detrital zircons available for recycling (Figs. 9, 10).

The distribution of detrital zircons indicates a greater proportion of Taconic–Acadian rocks in the Mauch Chunk–Pottsville drainage system than in the Early Pennsylvanian part of the Pennington-Lee system; however, Taconic–Acadian contributions increased irregularly through time in the Pennington-Lee system (Fig. 11). The distribution of Taconic–Acadian components also indicates that sediment (with dominant Taconic–Acadian peaks) from the transverse Mauch Chunk–Pottsville drainage merged into the northern upstream part of the longitudinal system, and downstream variability suggests intermittent contributions from the transverse drainages during the Early Pennsylvanian.

The HR isotopic data support a distinction in sources of detritus for the two clastic wedges, as well as diversion of the Mauch Chunk–Pottsville dispersal system into the longitudinal system. Taconic–Acadian zircon grains with intermediate (–5 to +5) εHf, values are scattered through the foreland sandstones, but samples from the Pennington-Lee clastic wedge generally have only those values. In contrast, samples from the Mauch Chunk–Pottsville clastic wedge and the longitudinal system also contain grains with more negative and more positive εHf values, suggesting a provenance with more heterogeneous crustal materials than in the provenance for the Pennington-Lee clastic wedge.

Detrital Zircons in Minor Concentrations

Many (but not all) of the samples have at least a few grains with ages of 2950–2530 Ma. The ultimate primary source for these grains is the Superior province of the Canadian Shield, which provided sediment to synrift basins along the Iapetan rifted margin of Laurentia and to the passive-margin shelf. Two samples (KY-21-SG [Stony Gap] and KY-18-CB [Corbin]) have strong secondary concentrations of Superior-age grains, with peaks at 2718 and 2716 Ma (Fig. 3). Because these samples are distant from the Canadian Shield and are isolated within the recognized dispersal systems (distal Mauch Chunk–Pottsville clastic wedge and mid-stream longitudinal system, respectively), recycling from synrift or passive-margin sedimentary deposits is the most likely source for the Superior-age grains. Both geographically proximal and stratigraphically in succession, the samples may represent either a local source followed by recycling or a persistent local source along this specific part of the Appalachian orogen. Other sandstones in the Mauch Chunk–Pottsville clastic wedge (Tumbling Run, Fig. 4) and in the southern part of the longitudinal system (Raccoon Mountain, Lee, Sewanee, and upper Raleigh; Fig. 4) have minor concentrations of Superior-age grains, suggesting some continuity of sub-regional supply. The local supply for recycling might have been a concentration of Superior grains in synrift sandstones (Irishtown and Rome, Fig. 7) or in passive-margin sandstones, such as in the Midcontinent and Ouachita margin (Midcontinent and Blakely, Fig. 8). Some Taconic (Fig. 9) and Acadian (Fig. 10) sandstones contain Superior-age grains, although none as abundant as in the Stony Gap and Corbin (Fig. 3).

In most of the samples, generally minor, secondary concentrations with ages of 2000–1320 Ma correspond in age to several provinces (Trans-Hudson, Penokean, Central Plains, Granite-Rhyolite) of the Laurentian craton and Canadian Shield (Fig. 1); generally, abundance of detrital grains decreases with increasing age of the province. The Grenville province includes reworked enclaves of some of these older rocks, providing a potential primary source. Some Iapetan synrift sediment accumulations, as well as younger Appalachian sedimentary rocks, contain detrital grains of these ages, providing a source for recycling.

Accreted terranes of Gondwanan affinity form much of the Appalachian internides, but detrital zircons from potential Gondwanan sources are rare in the foreland detritus. The Lower Pennsylvanian Lee and Sewanee sandstones (Fig. 4) in the longitudinal system contain a few grains of Eburnian–Trans-Ama- zonian ages, suggesting an unusual minor contribution from accreted terranes through transverse drainage into the longitudinal drainage. Detrital zircons in the age range of 765–530 Ma are rare but are scattered throughout many of the samples with no obvious trends in space or time (Figs. 3, 4). The Pan-African–Brasiliano zircons cannot be distinguished on the basis of age alone from Iapetan synrift igneous zircons of the Laurentian rifted margin. Although the synrift igneous rocks are distributed along the Appalachian external basement massifs, and Gondwanan terranes form much of the Appalachian internides (Fig. 1), the general paucity of detrital zircons of these ages indicates only very minor contributions from either.

Although plutons with ages (330–270 Ma) of the Alleghanian orogeny are distributed along the Appalachian internides, only seven detrital grains have ages within that range (Figs. 3, 4). The lack of synorogenic grains suggests either lack of unroofing or lack of integrated drainage from the internides (e.g., Thomas et al., 2004a). A similar lack of synorogenic grains also characterizes...
sandstones in the Taconic and Acadian clastic wedges (Figs. 9, 10), suggesting that Appalachian clastic wedges are “one orogeny behind” in the detrital-zircon record (Thomas et al., 2004a).

Other Interpretations of Provenance and Sediment Dispersal

Previously, petrographic analyses of sandstones in the Pennington-Lee clastic wedge were used to infer progressive unroofing of sedimentary rocks, low- to medium-grade metamorphic rocks, plutons, and migmatites through the Lower to Upper Pennsylvanian succession (Davis and Ehrlich, 1974). The petrographic upward gradient parallels an upward increase in Taconic–Acadian detrital zircons through the Pennsylvanian in the Pennington-Lee clastic wedge (Fig. 11), as well as an upward decrease in grains older than the Granite-Rhyolite province (Figs. 3, 4). No genetic relationship between the upward increase in metamorphic grade of the source rocks and the ages of detrital zircons is evident.

Many previous reports on the quartz-pebble–bearing quartzarenites of the longitudinal system have inferred that the quartz pebbles were supplied from the Canadian Shield or igneous rocks in the northern Appalachians (e.g., Siever and Potter, 1956; Heimlich et al., 1975; Edmunds et al., 1979). The new samples from the Sharon Conglomerate (samples OH-4-SN and OH-1-SS, Fig. 3) in the northern part of the Appalachian longitudinal system are most proximal to the Canadian Shield (Figs. 1, 2). Both Sharon samples contain only a few zircon grains with ages that correspond to the older provinces (Superior, Penokean, and Central Plains) of the Canadian Shield and, instead, are dominated by Taconic–Acadian and Grenville ages (Fig. 3).

Recycling

The distribution of zircon ages within various successive sedimentary accumulations implies multiple recycling. For example, some Iapetan synrift sediment accumulations contain only Grenville-age detrital zircons, whereas other synrift sedimentary deposits along the rifted margin and in a synrift intracratonic graben contain detrital zircons older than 1300 Ma (Fig. 7), which presumably were derived directly from primary sources in the Canadian Shield. The synrift rocks provide a source of recycled detrital zircons as old as the Superior province (Cawood and Nemchin, 2001; Thomas et al., 2004a, 2004b). Similarly, passive-margin sandstones along the Laurentian margin contain a range of ages of zircons from the continental interior (Fig. 8). Both the Taconic and Acadian clastic wedges provided a large source for recycling a wide range of ages of detrital zircons (Figs. 9, 10).

APPALACHIAN SIGNATURE IN DETRITAL-ZIRCON POPULATIONS

The probability plots for each of the samples (both new and previously published), as well as various combinations of plots including a plot of all analyses, show great commonality of populations (Figs. 3, 4, 11, 12). These data lead to a comprehensive characterization of the ages of detrital zircons that are available to be more widely dispersed beyond the Appalachian foreland, and thus provide a template of an “Appalachian signature” for recognition of detrital-zircon populations from Appalachian sources. The primary

Figure 12. Composite relative age-probability plot of all results of U-Pb analyses from the late Paleozoic succession in the Appalachian foreland (compiled from data in Figs. 3 and 4) to illustrate the “Appalachian signature” of detrital-zircon populations. Vertical colored bands represent the age ranges of potential provenance provinces in the Appalachians and North American craton. N—number of separate samples; n—number of individual grain analyses.
characteristics are (1) a general lack of grains older than 1500 Ma, (2) a dominance of Grenville-age grains, (3) a paucity of grains from accreted Gondwana terranes or from Iapetan synrift rocks, (4) a strong component of Taconic and Acadian zircons, and (5) a general lack of Alleghanian-age grains (Fig. 12). The range of εHf values for zircons older than 900 Ma is consistent with values from Laurentian craton provinces. The εHf values for Taconic and Acadian zircons range from positive to negative and indicate variations in the provenance. The longitudinal system may have diverted much of the detritus along strike of the Appalachian foreland, limiting dispersal onto the craton, during the Early Pennsylvanian. At other times, sediment may have been transported across the Appalachian foreland and onto the craton, and the recognition of Appalachian-derived detritus can be based on the distribution shown in Figure 12.

CONCLUSIONS

Sediment-dispersal patterns interpreted from stratigraphic and sedimentologic data for late Paleozoic synorogenic sediment in the Appalachian foreland uniformly indicate a primary provenance in the “Alleghanian orogen” (summary in Thomas, in Hatcher et al., 1989b); however, the Alleghanian orogen is a complex composite of disparate elements, including Grenville-age crystalline rocks in Appalachian basement massifs, lapetan synrift igneous rocks and sedimentary deposits, passive-margin sandstone and carbonate successions, Taconic and Acadian synorogenic igneous rocks and accreted terranes, Taconic and Acadian clastic wedges, and Alleghanian synorogenic igneous rocks and accreted terranes. The sedimentary rocks have detrital-zircon populations of the primary sources, constituting a source for recycled zircons.

Detrital-zircon U-Pb age populations are remarkably similar both laterally and vertically throughout the Pennington-Lee and Mauch Chunk-Pottsville synorogenic clastic wedges and the Lower Pennsylvanian longitudinal system. The most evident distinction is expressed by differences in relative abundance of Taconic–Acadian and Grenville zircons. The Taconic–Acadian probability peaks are equal to or greater than the Grenville peak for samples in the Mauch Chunk–Pottsville clastic wedge and much of the longitudinal system, but are less in the lower part of the Pennington-Lee clastic wedge. Similarly, εHf values in the Pennington-Lee clastic wedge are mostly intermediate, but range from positive to negative in the Mauch Chunk–Pottsville clastic wedge and much of the longitudinal system. These relationships show that differences in provenance distinguish the early parts of the two clastic wedges and that the Mauch Chunk–Pottsville transverse dispersal system was the primary source for the longitudinal system.

Interpretations of an Appalachian source for detrital-zircon populations in distant places require sediment dispersal from the Appalachian foreland. The compiled detrital-zircon data from the Appalachian foreland provide clear constraints on recognition of Appalachian detritus (Fig. 12).

ACKNOWLEDGMENTS

This research, including sample collecting and analyses, has been funded by National Science Foundation (NSF) award EAR-1304880. Beth Welke assisted in the field work. Dreadnought Stubbs, a student at Ohio University, conducted the U-Pb analyses of samples OH-A-SN and OH-1-SS. All analyses were conducted at the Arizona LaserChron Center with the support of NSF award EAR-1338583. A constructive review of the manuscript by Tim Lawton for Geosphere is gratefully acknowledged.

REFERENCES CITED


