Paleotectonic Implications of a Mid- to Late-Ordovician Provenance Shift, as Recorded in Sedimentary Strata of the Ouachita and Southern Appalachian Mountains

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ABSTRACT

North American Ordovician strata record a large shift in their neodymium isotopic composition ($\Delta\epsilon_{Nd} = \sim 7$) at around 450 Ma. As part of a continuing effort to understand this phenomenon, we studied the provenance of Middle and Upper Ordovician clastic sedimentary rocks along a transect through the southern Appalachian and Ouachita Mountains using a combination of high-resolution graptolite-neodymium isotopic analysis and U-Pb dating of detrital zircon. Taconian (Blountian)-age clastic sediment (ca. 465 Ma) in the southern Appalachians ($\epsilon_{Nd} = -8$) carries a neodymium isotopic signature distinct from strata of the same age in the Ouachita region ($\epsilon_{Nd} = -15$). However, the Blountian signature ($\epsilon_{Nd} = -8$) becomes firmly established in the eastern Ouachita region by 455 Ma (Arkansas), and by 450 Ma in the westernmost part of the Ouachita fold belt (Oklahoma). In the Ouachitas, craton-dominated sources ($\epsilon_{Nd} = -15$) apparently mixed with orogenic sources ($\epsilon_{Nd} = -8$) in variable proportions over a several-million-year period before orogenic sources became dominant. We conclude from this that, superimposed on a general westward regional shift in sediment sources with time, there were also complex local effects involving multiple (unmixed) sediment sources that persisted long after the initial pulse of orogenic material arrived. The combined "simultaneous" nature of the isotopic shift, an Ordovician sea-level high stand, and the emergence of the Appalachian-Taconian-Caledonian orogenic belt as a primary sediment source, leads us to conclude that by 450 Ma, seafloor south of North America was being supplied by well-mixed, isotopically homogeneous sediment delivered from uplifted fold-thrust belts and foreland basins of the Appalachian Taconian highlands. U-Pb detrital zircon ages from bracketing sandstone units reinforce the Nd evidence for a complete changeover in provenance between 465 Ma (abundant Archean-age zircons) and 440 Ma (no Archean-age zircons) in the Ouachita region.

Introduction

North American Ordovician strata record a large, continent-wide shift in neodymium isotopic composition ($\Delta\epsilon_{Nd} = \sim 7$) at around 450 Ma. Patchett et al. (1999) concluded that the shift, from more evolved ("cratonic") to more juvenile ("orogenic") sources, was produced by the emergence of the Appalachian-Taconian-Caledonian orogen as a dominant sediment source for North America and its margins. Because the precise timing of the continent-wide isotopic shift is poorly resolved at most locations, it has been difficult to establish firm links between this isotopic shift and regional sediment dispersal patterns (e.g., Gleason et al. 1997; Thomas 1997). Graptolites (rapidly evolving early Paleozoic colonial planktonic marine organisms) are abundant in Ordovician black shales, providing exceptional time resolution in these sequences, down to the submillion year level in ideal cases (Finney et al. 1996). Thus, combining neodymium isotopic analysis with detailed graptolite biostratigraphy has the potential to overcome the time-resolution problem and also can provide additional constraints on dispersal pathways through the precise regional correlation of marine black shale sequences.

The Ouachita region (fig. 1) was the first area in which the Ordovician North American isotopic

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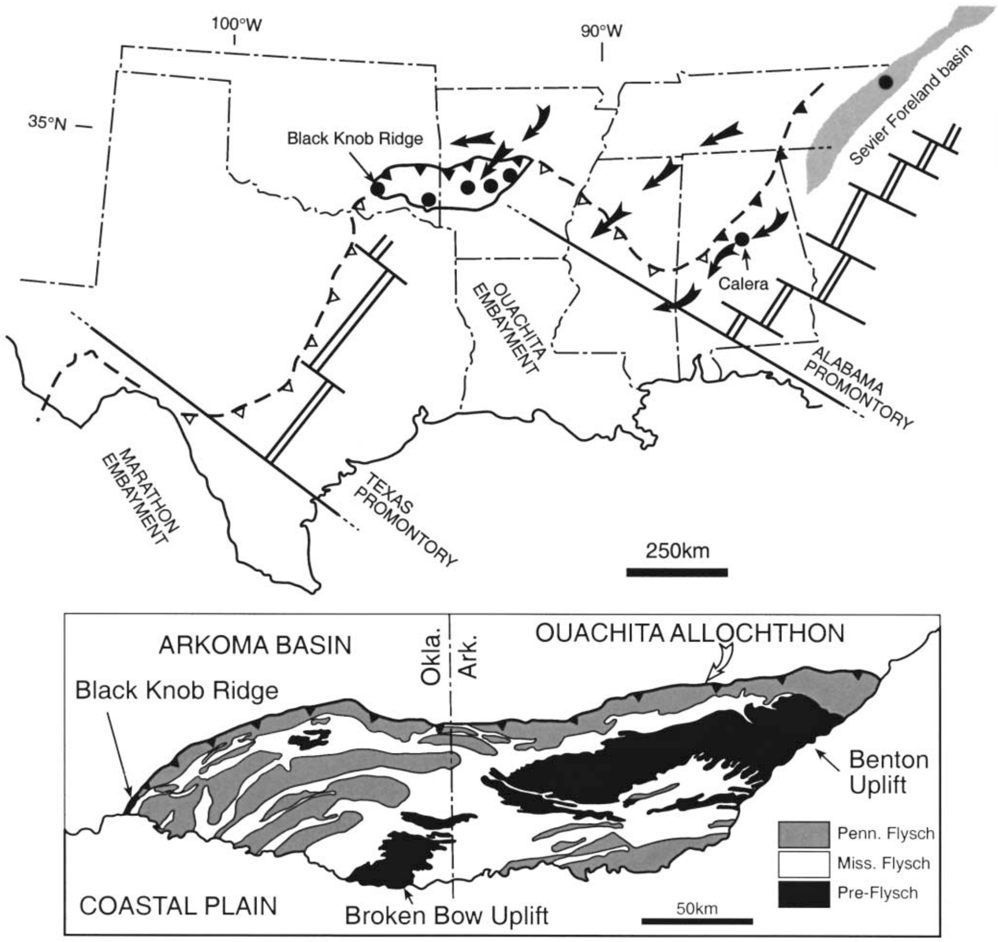


Figure 1. Early Paleozoic rifted margin of North America, showing Ouachita embayment, Marathon embayment, Texas promontory, and Alabama promontory (after Thomas 1991). Possible Ordovician (Taconian) sediment transport routes between Appalachian region and Ouachita embayment shown by curved arrows (modified from Thomas 1997). Mostly subsurface late Paleozoic Ouachita-Marathon thrust front also shown (solid teeth denote surface exposures). Sample localities, including Sevier basin and Calera/Vincent, Alabama, shown as solid circles. Inset map shows location of Black Knob Ridge and Benton and Broken Bow uplifts in the Ouachita Mountains.

shift was recognized (Gleason et al. 1994, 1995*a*, 1995*b*, 1997) and, as such, is among the best studied; however, it also presents a significant challenge because of the paucity of Ordovician outcrops and the significant structural dismemberment displayed by exposed lower Paleozoic rocks (Viele and Thomas 1989). In such cases, graptolite biostratigraphy can overcome the problem of precise placement within the stratigraphic section for rocks having abundant graptolites. We undertook this study in part to determine the extent to which graptolite-neodymium chemostratigraphy could be used for regional basin correlation. In addition, we hoped to gain more information on the nature of the isotopic shift, which has played a critical role in ongoing debates regarding the general question of provenance of Paleozoic sediments in the Ouachita fold belt (cf. Gleason et al. 1994, 1995*a*, 1995*b*, 1997; Thomas 1995, 1997). Finally, the current study is part of an ongoing attempt to characterize the isotopic signature and sources of sediments along the early North American Iapetus margin, from which the Argentine Precordillera terrane may have been derived (Thomas and Astini 1996, 1999; Dalziel 1997).

Below, we report data for 23 new neodymium analyses of the Middle and Upper Ordovician black shale assemblage, and 43 new single-grain U-Pb detrital zircon ages from two turbidite sandstone units that bracket the ca. 450 Ma isotopic shift in the Ouachita Mountains. In addition to using these data to address some of the scientific issues described above, we also hope the new data will serve as a useful reference database for continuing global paleotectonic correlation efforts.

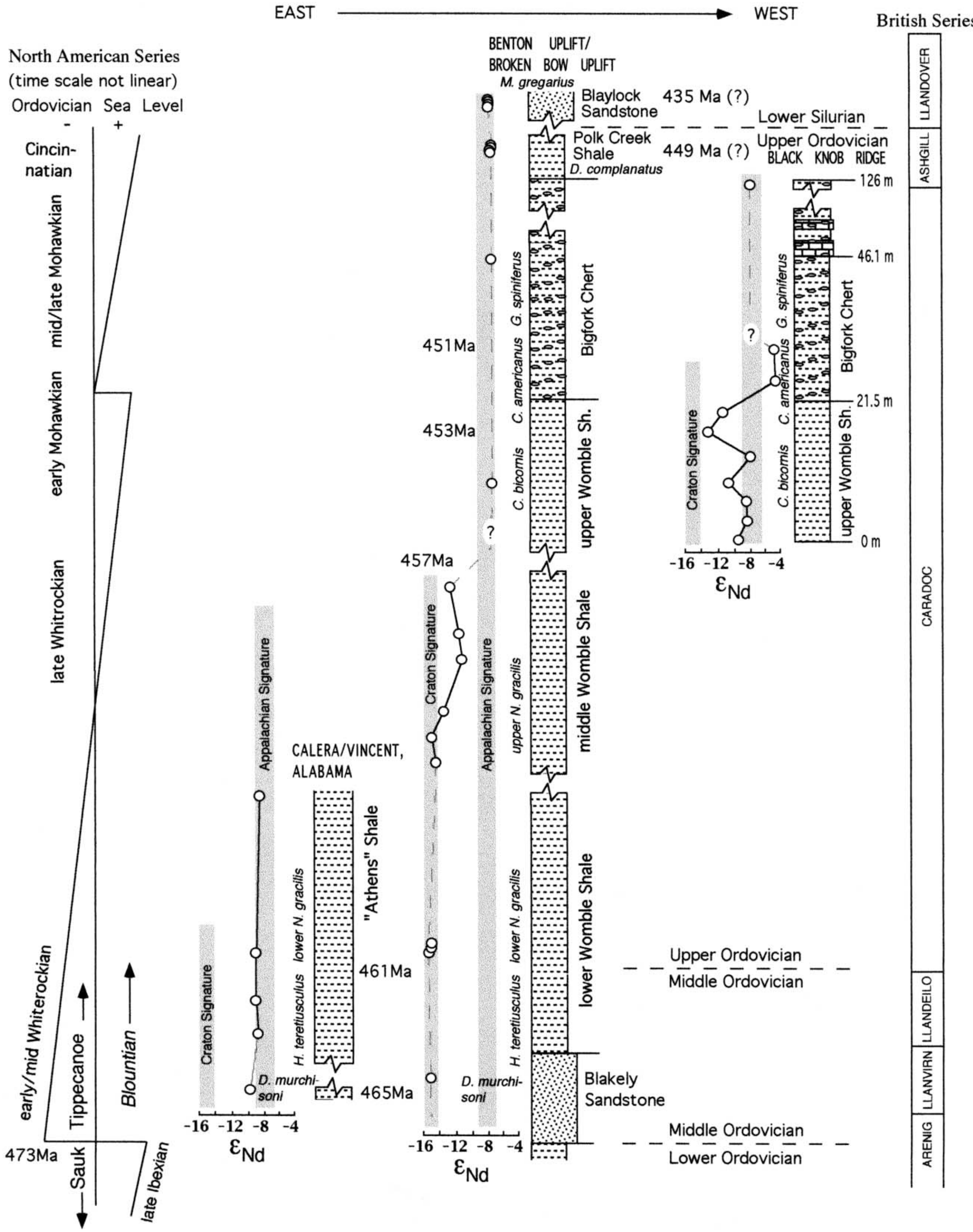
Geologic Setting, Stratigraphy, and Sampling

The Ouachita fold belt (fig. 1) comprises an off-shelf (slope, rise, and abyssal plain) assemblage of Cambrian through Pennsylvanian deep-marine shales and turbidites that was structurally emplaced along the southern margin of North America during the Hercynian age (Carboniferous-Permian) Ouachita orogeny (Viele and Thomas 1989). Carboniferous turbidite flysch (including Mississippian volcanic tuffs) is volumetrically dominant and least deformed within the assemblage, while lower Paleozoic rocks suffered variably intense structural deformation within an accretionary wedge/subduction complex that formed as the Ouachita remnant ocean basin closed between North America and Gondwana (Viele and Thomas 1989; Graham et al. 1975). Graptolite-rich Ordovician shales are exposed within the Ouachita fold belt at various localities (Lowe 1985, 1989; Finney 1988, 1997; Ethington et al. 1989), most notably the Benton uplift in central Arkansas (fig. 1), the Broken Bow uplift of eastern Oklahoma, and at Black Knob Ridge (Oklahoma), where the westernmost exposures of Ordovician rocks in the Ouachita system occur (Hendricks et al. 1937).

For this study, we sampled a composite stratigraphic section that traverses multiple graptolite zones from Middle through Upper Ordovician strata (fig. 2). The Middle Ordovician stratigraphic succession commences with the Blakely Sandstone (*Didymograptus murchisoni* zone to *Hustedograptus teretiusculus* zone), a thin turbiditic quartzite with interbedded shales that marks the early Whiterockian sea-level lowstand (fig. 2). Conformably overlying the Blakely Sandstone is the upper Middle to Upper Ordovician Womble Shale (*H. teretiusculus* zone to *Corynoides americanus* zone), a graptolite-rich, dominantly hemipelagic unit that extends through the Whiterockian into the early Mohawkian sea-level high stand (Finney 1986, 1997). The succession is capped by the Bigfork Chert (*C. americanus* zone to *Geniculograptus spiniferus* zone), the base of which is marked by a brief return to a sea-level lowstand in the early to middle Mohawkian. The Bigfork Chert is composed dominantly of interbedded chert and siliceous hemipelagite with some conglomerate at its base; however, siliceous (detrital) limestone is more prevalent westward within the belt (Finney 1986, 1988), in particular at Black Knob Ridge (Oklahoma). A return to starved-basin conditions is reflected in the overlying Polk Creek Shale (*D. complanatus* zone) (Cincinnatian), which is capped by the Upper Ordovician/Lower Silurian Blaylock Sandstone (*Monograptus gregarius* zone), a thick turbiditic unit best exposed in the Broken Bow uplift of eastern Oklahoma.

Sandstone compositions and paleocurrent indicators argue for a change in provenance of the Ouachita assemblage between deposition of the quartzitic, craton-derived Blakely Sandstone (Middle Ordovician), with dominantly south-directed paleocurrents (sources to the north), and the quartzolithic orogen (clastic wedge)–derived Blaylock Sandstone (Upper Ordovician), which thickens significantly to the south within the Ouachita belt and likely had sources to the east-southeast based on dominant paleocurrent directions (Satterfield 1982; Lowe 1985, 1989; Viele and Thomas 1989; Viele 1998). Originally, the timing of the Nd shift was placed at the Womble Shale/Bigfork Chert contact (ca. 450 Ma), though sampling resolution did not permit us to estimate the duration or timing of the shift to better than ± 10 Ma (Gleason et al. 1995, 1997). The Blakely Sandstone and Blaylock Sandstone, from which we extracted detrital zircons, were sampled from the same outcrop units in the Benton uplift (Arkansas) and Broken Bow uplift (Oklahoma), respectively, that were sampled for the original neodymium isotopic work of Gleason et al. (1995*b*) (see the appendix, available from *The Journal of Geology*'s Data Depository upon request).

Exposures of Ordovician strata in the Ouachita Mountains are limited in extent, and no continuous section of the Womble Shale exists. In the Benton uplift (Arkansas), the lower Womble Shale was sampled from a stream outcrop near Caddo Gap, Arkansas; the middle Womble Shale was sampled through a long section near the Crystal Springs Boat Landing locality; the upper Womble Shale was sampled from an outcrop of graptolite-rich strata at Crystal Springs, Arkansas (appendix). At Black Knob Ridge in Oklahoma (fig. 1), we sampled the westernmost outcrops of Ordovician strata in the Ouachita system (Hendricks et al. 1937). The uppermost Womble Shale, the Bigfork Chert, and the Polk Creek Shale are completely and continuously exposed in two places: the Stringtown Quarry section (Finney 1986, 1988, 1997), which, unfortunately, is no longer accessible, and a section on the west side of Black Knob Ridge 3 mi south of Stringtown, Oklahoma (appendix). This section allowed extensive isotopic sampling (with good time resolution) of the upper Womble Shale, the overlying


EAST
WEST
British Series
North American Series
(time scale not linear)
Ordovician Sea Level
BENTON UPLIFT/
BROKEN BOW UPLIFT
M. gregarius
Blaylock Sandstone
435 Ma (?)
Lower Silurian
Polk Creek Shale
449 Ma (?)
Upper Ordovician
BLACK KNOB RIDGE
D. complanatus
Cincin-natian
mid/late Mohawkian
early Mohawkian
late Whitrockian
early/mid Whiterockian
Tippecanoe
Blountian
Sauk
late Ibexian
473Ma
LLANDOVER
ASHGILL
CARADOC
LLANDEILO
LLANVIRN
ARENIG
126 m
46.1 m
21.5 m
0 m
Bigfork Chert
G. spiniferus
C. americanus
C. bicornis
upper Womble Sh.
Craton Signature
451Ma
453Ma
457Ma
upper Womble Sh.
middle Womble Shale
upper N. gracilis
lower Womble Shale
lower N. gracilis
H. teretiusculus
Appalachian Signature
Craton Signature
CALERA/VINCENT, ALABAMA
"Athens" Shale
461Ma
465Ma
D. murchi-soni
Blakely Sandstone
Upper Ordovician
Middle Ordovician
Middle Ordovician
Lower Ordovician
-16 -12 -8 -4
ε_{Nd}

Bigfork Chert, and their stratigraphic contact (fig. 2). Because the Womble/Bigfork formation boundary (previously taken to mark the location of the regional neodymium isotopic shift; Gleason et al. 1997) is exposed nowhere else in the Ouachita Mountains, this section was considered particularly important to our study. For samples of the upper Bigfork Chert, we used prior collections made at the Stringtown Quarry (Finney 1986, 1988).

In the southern Appalachian Mountains, samples from well-known graptolite localities in the upper Middle to lower Upper Ordovician (middle Whiterockian) Athens Shale were analyzed to establish a southern Appalachian reference for comparison with the Ouachita data. The Athens Shale was deposited during the earliest stages of the Taconian orogeny and is essentially time-equivalent to the Blount clastic wedge (Thomas 1977; Finney et al. 1996). In the Sevier basin (fig. 1), black graptolite shales and turbidites of the Blount clastic wedge were deposited during rapid subsidence of the Early to early Middle Ordovician carbonate platform (Hatcher 1989; Finney et al. 1996). Paleocurrent indicators within the Athens Shale are few, but turbidites from the Sevier basin of eastern Tennessee (neodymium data previously given in Gleason et al. 1994, 1995*b*; Andersen and Samson 1995) indicate that the Blount clastic wedge migrated cratonward toward the hinterland with time, dispersing both north and south along the foreland basin axis of the southern Appalachians (Finney et al. 1996). The sampling locality for the Athens Shale at Vincent, Alabama, and the Calera quarry section (fig. 2; appendix), both of which were described in Finney et al. (1996), expose the oldest Athens Shale in the southern Appalachians and, thus, the earliest sediment derived from the Taconic orogen.

Some of the shale samples in this study were collected from localities with well-established biostratigraphic controls (Finney 1986; Ethington et al. 1989; Finney et al. 1996), including the sections at Vincent and Calera, Alabama, and the Benton uplift, Arkansas. Others were from newly measured sections, such as at Black Knob Ridge, Oklahoma (south of the Stringtown Quarry section; Finney 1986, 1988). These outcrops required extensive collecting to construct a precise graptolite biostratigraphy. Graptolite specimens were identified initially in the field, and preliminary age determinations were then used to target stratigraphic intervals for isotopic sampling. In the laboratory, species identifications were further refined and precise biostratigraphy for the sampled intervals firmly established. Graptolite zones used for correlation generally follow the usage of Finney (1986) and Finney et al. (1996), with only slight modifications for some of the stratigraphic sections studied here. For this article, definitions of the Lower, Middle, and Upper Ordovician Series are those approved recently by the Subcommission on Ordovician Stratigraphy of the International Commission on Stratigraphy (Webby 1998). These are global series, and their definitions (and extent) differ substantially from those generally used in North America.

Methods

All samples for whole-rock neodymium isotopic analysis were prepared and analyzed by isotope dilution mass spectrometry at the University of Arizona on a VG 354 thermal ionization mass spectrometer. Procedures exactly followed those of Gleason et al. (1995*b*). For U-Pb single-grain detrital zircon analysis, two turbidite sandstone units were selected: the quartzose Blakely Sandstone (lower Middle Ordovician) and the quartzolithic Blaylock Sandstone (Upper Ordovician/Lower Silurian), from the Benton uplift (Arkansas) and Broken Bow uplift (Oklahoma), respectively (see Gleason et al. 1995*b*). Zircons were extracted from ~30-kg sam-

Figure 2. Stratigraphy and neodymium isotopic compositions of Ordovician shales from Ouachita and southern Appalachian Mountains (data from table 1 and Gleason et al. 1995). Ordovician sea-level curve is from Finney (1997), with modifications based on recent time-scale calibrations of Cooper (1999) and Subcommission on Ordovician Stratigraphy of the International Commission on Stratigraphy (Webby 1998). "Craton" signature defines shales from lower *Nemograptus gracilis* zone and older in the Ouachita assemblage (average ϵ_{Nd} of -15; see text). "Appalachian" signature (average ϵ_{Nd} of -8; see text) is carried by Middle Ordovician (Blountian) shales and turbidite sandstones of the Sevier foredeep assemblage (upper Blockhouse/Tellico assemblage of Tennessee; Gleason et al. 1994; Andersen and Samson 1995), Athens Shale (this article), Upper Ordovician/Lower Silurian Martinsburg-Juniata-Clinch shallow marine overlap assemblage (Gleason et al. 1995*b*; see text), and Upper Ordovician/Lower Silurian Polk Creek/Blaylock assemblage in the Ouachita Mountains (Gleason et al. 1995*b*). Transition from Craton to Appalachian-type signature occurs in the Ouachita assemblage between the upper *N. gracilis* zone and the upper *Climacograptus bicornis* zone in Arkansas and within the upper *C. bicornis* zone in Oklahoma.

ples representing a single turbidite sandstone unit. Detrital zircons were abundant in both samples, with yields of 0.54 g (Blakely) and 1.63 g (Blaylock). Zircons in the Blakely Sandstone are mainly well rounded and highly spherical, with subequal proportions of colorless and light pink grains. Additional grains include a small proportion of elongate rods that are also highly rounded and <1% euhedral grains that are colorless. Analyzed grains were between 125 and 145 μm in sieve size before abrasion, representing about 5% of the total size range. Grains in the Blaylock Sandstone are moderately rounded though not highly spherical, with subordinate euhedral crystals. Colorless grains are subordinate to light pink crystals. All of the grains analyzed were between 145 and 175 μm in sieve size before abrasion, representing about 5% of the total size range. Our strategy in selecting grains was to analyze grains from as many of the different color/morphology groups as possible to maximize the number of different sources represented (for an alternative viewpoint, see McLennan et al. 2001). The number of grains we analyzed from each color/morphology group was in general proportional to the group's abundance, and a minimum of at least two grains was analyzed from each group. All analyses were conducted by isotope dilution thermal ionization mass spectrometry at the University of Arizona using techniques outlined by Gehrels (2000). All of the analyses were of individual zircon grains abraded to approximately two-thirds of their original diameter using an air-abrasion device (Krogh 1982). This procedure has been demonstrated to improve the concordancy of individual detrital zircon U-Pb data (Gehrels 2000). Raw data were reduced using programs of Ludwig (1991*a*, 1991*b*).

Results

Neodymium isotopic results are tabulated in table 1, along with age-corrected epsilon Nd (initial ϵ_{Nd}) values and depleted model ages (T_{DM}), for 27 whole rock samples (data for four of these samples were previously published in Gleason et al. 1995*b*). As in previous studies (Gleason et al. 1994, 1995*b*), we choose to emphasize the age-corrected initial Nd isotopic values, rather than Nd model ages, which are susceptible to diagenetic effects (see references in Gleason et al. 1994). Initial ϵ_{Nd} range from −4.5 to −16.1, and model ages from 1.57 to 2.34 Ga, both comparable to (though slightly larger than) the range of values reported for a smaller subset of Ouachita Ordovician rocks by Gleason et al. (1995*b*). Age-corrected ϵ_{Nd} values for the current study are plotted in figure 2. ϵ_{Nd} values for four samples of the Athens Shale at Calera Quarry, Alabama (*Hustedograptus teretiusculus* and lower *Nemograptus gracilis* zones), are quite homogeneous, varying between −8.8 and −9.2 (essentially within analytical error of each other). A fifth sample, from the *Didymograptus murchisoni* zone at Vincent, Alabama, is slightly more negative (−9.9). These values are similar (though less variable) to those obtained for the lower (*H. teretiusculus* zone) Blockhouse Formation (−10.0 and −9.4) and upper (*N. gracilis* zone) Blockhouse Formation (−7 to −8) of the Sevier basin, Tennessee, by Andersen and Samson (1995). In the Benton uplift of Arkansas, ϵ_{Nd} varies little (−15 to −16) from the *H. teretiusculus* zone (Blakely Sandstone) through the lower part of the upper *N. gracilis* zone (lower middle Womble Shale) but begins to trend toward less negative values (−12) toward the top of the *N. gracilis* zone (fig. 2). The upper Womble Shale in the Benton uplift (*Climacograptus bicornis* zone) has an ϵ_{Nd} of −8. At Black Knob Ridge in Oklahoma, nine analyses through the upper *C. bicornis* zone into the *C. americanus* zone of the upper Womble Shale and lower Bigfork Chert show a large range of ϵ_{Nd} (−13 to −4.5). In both Arkansas and Oklahoma, further upsection in the Bigfork Chert (*G. spiniferus* zone), the overlying Polk Creek Shale (*D. complanatus* zone) and Blaylock Sandstone (*M. gregarius* zone), ϵ_{Nd} varies between −7 and −8, typical of the Upper Ordovician–Carboniferous Ouachita assemblage (Gleason et al. 1994, 1995*b*).

U-Pb data for individual detrital zircon grains from the Blakely Sandstone ($n = 21$) and Blaylock Sandstone ($n = 22$) are listed in table 2, and calculated apparent ages are shown on histograms in figure 3. The air-abrasion procedure resulted in mostly concordant ages for both samples (fig. 4). The age populations revealed by the zircons in these two samples are distinct. Single-grain $^{207}Pb/^{206}Pb$ zircon ages from the Blaylock Sandstone are, with one exception, concentrated between 980 and 1370 Ma, with peaks at ca. 1.03, 1.15, and 1.34 Ga. The exception is a single concordant grain with a $^{207}Pb/^{206}Pb$ age of 476 ± 22 Ma ($^{206}Pb/^{238}U$ age = 468 ± 7 Ma). The Blakely Sandstone, by contrast, has a significant population ($n = 5$; 24% of grains analyzed) of Archean-age zircons centered around 2.70 Ga (2680–2720 Ma). The remaining zircons are, with one exception, concentrated in age between 1000 and 1330 Ma, with a broad peak centered around 1.05–1.06 Ga. The exception is a single concordant grain with a $^{207}Pb/^{206}Pb$ age of 1744 ± 7 Ma. No correlation was observed between zircon grain morphology and age in either sample.

Table 1. Sm-Nd Isotopic Data for Middle and Upper Ordovician Shales, Ouachita and Southern Appalachian Mountains

Sample	Unit	Graptolite zone[a]	Height in section (m)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ measured	ϵ_{Nd} present	ϵ_{Nd} initial	T_{DM} (Ga)
Vincent, Ala.:										
V-1	Lower Athens	*D. murchisoni*	…	4.09	21.30	.1162	.511896 ± 9	−14.5	−9.9	1.79
Calera Quarry, Ala.:										
17-2	Middle Athens	*H. teretiusculus*	5.1	5.23	27.71	.1141	.511939 ± 9	−13.6	−8.9	1.69
26/28	Middle Athens	*H. teretiusculus*	11.8	4.67	24.26	.1163	.511932 ± 7	−13.8	−9.2	1.74
84/3	Upper Athens	Lower *N. gracilis*	22.5	5.16	27.38	.1139	.511921 ± 11	−14.0	−9.2	1.71
106-1	Upper Athens	Lower *N. gracilis*	57.0	6.20	33.08	.1134	.511941 ± 22	−13.6	−8.8	1.67
Benton uplift, Ark.:										
OUA-28[b]	Blakely SS	*H. teretiusculus*	…	.28	1.95	.0890	.511534 ± 9	−21.5	−14.9	1.84
OUA97-1	Lower Womble	Lower *N. gracilis*	…	5.10	25.98	.1186	.511584 ± 10	−20.6	−16.1	2.34
OUA-27[b]	Lower Womble	Lower *N. gracilis*	…	3.31	19.20	.1041	.511566 ± 9	−20.9	−15.5	2.05
OUA-29[b]	Lower Womble	Lower *N. gracilis*	…	4.22	23.69	.1077	.511583 ± 8	−20.6	−15.4	2.10
99SF-2	Middle Womble	Upper *N. gracilis*	24.0	3.41	21.48	.0961	.511553 ± 4	−21.2	−15.4	1.93
99SF-3	Middle Womble	Upper *N. gracilis*	29.0	2.47	16.68	.0895	.511509 ± 6	−22.0	−15.9	1.88
99SF-4	Middle Womble	Upper *N. gracilis*	34.5	3.29	20.37	.0977	.511610 ± 6	−20.1	−14.4	1.88
99SF-5	Middle Womble	Upper *N. gracilis*	43.5	2.41	14.27	.1021	.511736 ± 5	−17.6	−12.2	1.78
99SF-6	Middle Womble	Upper *N. gracilis*	48.5	2.30	12.46	.1117	.511741 ± 5	−17.5	−12.6	1.94
99SF-7	Middle Womble	Upper *N. gracilis*	58.0	1.45	9.32	.0939	.511631 ± 5	−19.6	−13.7	1.79
OUA97-2	Upper Womble	*C. bicornis*	…	4.65	20.86	.1346	.512034 ± 10	−11.8	−8.2	1.94
OUA-45[b]	Bigfork Chert	*G. spiniferus*(?)	…	1.85	9.45	.1185	.512050 ± 8	−11.5	−7.0	1.59
OUA-37[b]	Polk Creek	*D. complanatus*	…	6.22	29.60	.1271	.512074 ± 7	−11.5	−7.1	1.70
OUA-38[b]	Polk Creek	*D. complanatus*	…	11.17	58.70	.1150	.512086 ± 6	−11.0	−6.2	1.48
OUA-39[b]	Polk Creek	*D. complanatus*	…	7.49	42.29	.1135	.512047 ± 7	−10.7	−6.8	1.51
Broken Bow uplift, Okla.:										
OUA-17[b]	Blaylock SS	*M. gregarius*	…	9.06	38.50	.1422	.512126 ± 5	−10.0	−7.0	1.95
OUA-18[b]	Blaylock Sh	*M. gregarius*	…	6.67	44.32	.0909	.511958 ± 7	−13.3	−7.5	1.35
OUA-35[b]	Blaylock Sh	*M. gregarius*	…	6.49	39.22	.1000	.511921 ± 7	−14.0	−8.7	1.50
OUA-36[b]	Blaylock SS	*M. gregarius*	…	10.26	42.34	.1465	.512108 ± 7	−10.3	−7.6	2.12
Black Knob Ridge, Okla.:										
BKR97-22	Upper Womble	*C. bicornis*	1.0	3.87	19.95	.1175	.511951 ± 8	−14.0	−9.4	1.77
BKR97-23	Upper Womble	*C. bicornis*	4.0	3.13	15.03	.1257	.511987 ± 9	−12.7	−8.6	1.83
BKR97-24	Upper Womble	*C. bicornis*	7.0	2.94	14.90	.1193	.511979 ± 9	−12.9	−8.4	1.71
BKR97-25	Upper Womble	*C. bicornis*	10.0	5.37	25.16	.1289	.511894 ± 9	−14.5	−10.6	2.07
BKR97-1	Upper Womble	*C. bicornis*	14.0	3.18	15.25	.1259	.512023 ± 23	−12.0	−7.9	1.76
BKR97-5	Upper Womble	*C. bicornis*	18.0	3.89	21.53	.1093	.511708 ± 11	−18.2	−13.1	1.95
BKR97-5[c]				4.03	22.30	.1093	.511719 ± 7	−17.9	−12.9	1.93
BKR97-8	Upper Womble	*C. bicornis*	21.0	3.84	19.32	.1205	.511833 ± 8	−15.7	−11.3	1.98
BKR97-12	Lower Bigfork	*C. americanus*	26.0	3.91	17.20	.1374	.512218 ± 11	−8.2	−4.8	1.64
BKR97-15	Lower Bigfork	*C. americanus*	31.0	2.37	10.90	.1313	.512192 ± 9	−8.7	−4.5	1.57
SQ-126	Upper Bigfork	*G. spiniferus*	126.0	4.53	24.46	.1120	.511988 ± 10	−12.7	−7.8	1.58

Note. $^{147}Sm/^{144}Nd$ ratios reproducible to ±0.5%. $^{143}Nd/^{144}Nd$ ratios normalized for mass fractionation to $^{146}Nd/^{144}Nd = 0.7219$ (reported uncertainties in measured $^{143}Nd/^{144}Nd$ ratios are two SEs of the mean on 105 ratios). ϵ_{Nd} initials calculated for 450 Ma; ϵ_{Nd} calculated according to present-day chondritic ratio of $^{143}Nd/^{144}Nd = 0.512638$; and initial ϵ_{Nd} reproducible to ±0.25. T_{DM} reproducible to ±0.05 Ga (calculated from DePaolo 1981). Total Nd and Sm laboratory acid blanks at the time of this study were 93 and 24 pg, respectively. The LaJolla Nd standard gave $^{143}Nd/^{144}Nd = 0.511867 \pm 13$ (2 SD of population; $n = 15$).

[a] The full names of the graptolite species listed are *Didymograptus murchisoni*, *Hustedograptus teretiusculus*, *Nemograptus gracilis*, *Climacograptus bicornis*, and *Dicellograptus companatus*.

[b] Data previously published in Gleason et al. (1995*b*).

[c] Duplicate.

Discussion

Nd Data. Gleason et al. (1994, 1995*b*) defined an "Appalachian type" signature (fig. 2) as the neodymium isotopic composition carried by post–Middle Ordovician rocks of the Ouachita sedimentary assemblage (i.e., those deposited after the ca. 450 Ma isotopic shift). This signature is generally characterized by ϵ_{Nd} between −7 and −9, averaging about −8 (Gleason et al. 1994, 1995*b*). Gleason et al. (1994, 1995*b*) proposed that rocks having the Appalachian-type signature carried a significant component of North American Grenvillian-age crust (T_{DM} = 1.4–1.7 Ga), supplied mainly from re-

Table 2. U-Pb Isotopic Data and Ages

Grain type and shape	Grain wt. (μg)	Pb (pg)	U (ppm)	$^{206}Pb/^{204}Pb$	$^{206}Pb/^{208}Pb$	Apparent ages (Ma)[a] $^{206}Pb/^{238}U$	$^{207}Pb/^{235}U$	$^{207}Pb/^{206}Pb$	Projected age (Ma)
Blakely:									
PR	23	6	145	6200	36.7	1002 ± 5	1003 ± 7	1003 ± 8	1003 ± 10
CR	12	7	104	1980	13.4	1031 ± 9	1032 ± 10	1035 ± 8	1036 ± 10
CR	12	15	55	468	4.5	1038 ± 14	1041 ± 18	1047 ± 23	1050 ± 29
PR	19	9	419	10,300	4.4	1053 ± 4	1052 ± 5	1051 ± 5	1051 ± 10
CRr	16	7	269	6510	57.6	1052 ± 5	1052 ± 6	1053 ± 7	1053 ± 10
PR	17	11	248	4280	6.6	1056 ± 5	1056 ± 6	1056 ± 6	1056 ± 10
CRr	11	8	74	1110	9.6	1043 ± 13	1047 ± 14	1057 ± 14	1061 ± 18
CRr	15	7	38	860	3.5	1062 ± 17	1062 ± 19	1062 ± 16	1062 ± 20
CR	15	18	126	1155	4.1	1061 ± 6	1061 ± 9	1062 ± 13	1062 ± 16
CE	6	7	193	1910	10.9	1088 ± 9	1088 ± 9	1088 ± 10	1088 ± 12
CR	16	13	167	2310	11.8	1092 ± 6	1092 ± 8	1092 ± 7	1092 ± 10
CR	13	4	112	4060	9.3	1169 ± 6	1169 ± 8	1170 ± 8	1171 ± 10
CE	5	13	72	370	5.9	1179 ± 24	1182 ± 29	1186 ± 26	1188 ± 32
CRr	16	8	119	3350	6.8	1268 ± 7	1269 ± 8	1271 ± 7	1271 ± 10
PR	14	10	310	5800	11.8	1300 ± 7	1311 ± 8	1329 ± 6	1334 ± 10
CR	13	8	90	2960	6.9	1745 ± 12	1744 ± 14	1744 ± 7	1744 ± 10
PR	16	6	231	19,800	9.7	2677 ± 12	2678 ± 13	2679 ± 4	2679 ± 10
PR	14	8	84	4500	3.7	2684 ± 14	2691 ± 15	2696 ± 4	2696 ± 10
PR	17	9	94	5260	3.5	2670 ± 13	2685 ± 15	2696 ± 4	2698 ± 10
CR	17	12	74	3040	3.2	2570 ± 17	2640 ± 19	2694 ± 4	2700 ± 10
PR	16	5	59	5850	3.4	2718 ± 16	2720 ± 17	2722 ± 4	2722 ± 10
Blaylock:									
CE	8	7	183	970	9.2	468 ± 7	469 ± 8	476 ± 22	486 ± 51
PE	31	9	523	18,600	6.5	976 ± 6	977 ± 6	979 ± 4	980 ± 10
PE	13	8	42	720	6.9	1004 ± 16	1004 ± 19	1005 ± 20	1004 ± 25
PE	9	7	115	1580	7.6	996 ± 10	998 ± 11	1004 ± 11	1006 ± 14
CR	16	15	43	504	5.5	1003 ± 13	1008 ± 17	1019 ± 22	1023 ± 28
CR	15	8	51	1110	9.0	1025 ± 13	1025 ± 15	1026 ± 14	1027 ± 18
PR	8	11	89	675	8.0	1013 ± 13	1016 ± 17	1024 ± 21	1028 ± 27
PE	12	9	98	1320	7.6	1028 ± 8	1030 ± 11	1032 ± 12	1033 ± 16
CR	15	8	39	780	4.8	1042 ± 16	1045 ± 19	1052 ± 19	1055 ± 24
PE	19	20	131	1370	6.0	1063 ± 7	1062 ± 9	1062 ± 12	1062 ± 14
CE	9	22	48	209	3.2	974 ± 19	995 ± 34	1042 ± 52	1063 ± 66
PR	11	11	149	1690	6.8	1092 ± 7	1092 ± 10	1091 ± 13	1091 ± 16
CE	6	9	74	590	8.4	1098 ± 19	1099 ± 23	1101 ± 23	1101 ± 28
PR	13	10	60	945	7.7	1125 ± 13	1131 ± 16	1143 ± 15	1148 ± 18
PE	5	14	251	1060	9.6	1130 ± 9	1139 ± 14	1157 ± 19	1163 ± 22
PR	9	11	167	1690	6.7	1158 ± 8	1163 ± 9	1171 ± 10	1173 ± 12
CR	17	9	174	450	6.9	1170 ± 29	1174 ± 35	1181 ± 29	1184 ± 35
PE	14	9	230	490	3.5	1180 ± 26	1181 ± 32	1185 ± 26	1186 ± 32
PR	17	10	79	1780	11.1	1265 ± 9	1282 ± 11	1312 ± 9	1321 ± 12
PE	17	7	317	1050	4.5	1280 ± 17	1293 ± 19	1316 ± 13	1323 ± 16
PE	16	17	100	1410	5.3	1366 ± 7	1368 ± 11	1370 ± 10	1371 ± 12
PE	6	432	455	156	1.3	1178 ± 24	1247 ± 32	1370 ± 36	1409 ± 42

Note. Grain type: L = light pink, M = medium pink, C = colorless, P = pink. Grain shape: R = rounded, E = euhedral, Rr = rod-shaped grain. All grains are clear/translucent and abraded with an air abrador. $^{206}Pb/^{204}Pb$ is measured ratio, uncorrected for blank, spike, or fractionation. $^{206}Pb/^{208}Pb$ is corrected for blank, spike, and fractionation. Most concentrations have an uncertainty of up to 25% due to uncertainty in weight of grain. Constants used: $^{238}U/^{235}U = 137.88$. Decay constant for $^{235}U = 9.8485 \times 10^{-10}$. Decay constant for $^{238}U = 1.55125 \times 10^{-10}$. All uncertainties are at the 95% confidence level. Pb blank was 2–5 pg. U blank was consistently <1 pg. Projected ages are upper concordia intercepts projected from 280 ± 100 Ma.
[a] Radiogenic Pb.

cycled Appalachian foreland fold-thrust belt sources. Taconian-age (Middle and Upper Ordovician) sandstones and shales from the Sevier and Martinsburg basins of eastern Tennessee (Gleason et al. 1994, 1995*b*) also carry the same isotopic signature; however, the coincidence in timing of the isotopic shift in the Ouachita region and onset of orogenic (Taconian-age) sedimentation in the southern Appalachian region has remained poorly resolved (Gleason et al. 1994, 1995*a*, 1995*b*, 1997).

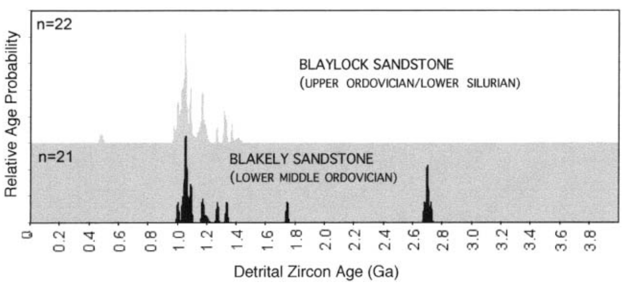


Figure 3. Relative age-probability plots (age histograms) showing the distribution of U-Pb ages for individual zircon grains in the Blaylock Sandstone (Upper Ordovician/Lower Silurian) and the Blakely Sandstone (Lower Middle Ordovician) from the Ouachita Mountains. Each age is plotted as a probability distribution (e.g., 1125 ± 12 Ma) rather than as a single point (e.g., 1125 Ma). Grains with high precision ages are enhanced graphically (*tall thin curves*) relative to grains with poor precision ages (*low broad curves*). This representation does not make any assumptions about whether analyses are representative of the whole zircon population (Stewart et al. 2001)

Thomas (1995, 1997) cast further doubt on this linkage, citing paleocurrent, sediment-dispersal, and facies arguments against it, noting also that Nd isotopes do not necessarily distinguish one Grenvillian terrane from another (but see Gleason et al. 1995*a*, 1997). A "craton type" signature (fig. 2) was defined as the "preshift" ϵ_{Nd} signature of the Lower to Middle Ordovician Ouachita assemblage, with values averaging about −15 (Gleason et al. 1994, 1995*b*). Gleason et al. (1994, 1995*b*) proposed that rocks with the craton-type signature carried a significant, though poorly defined, Archean component from the North American craton.

With the new data reported here, it appears that an Appalachian-type signature ($\epsilon_{Nd} = -8$ to -10) characterizes all analyzed Middle Ordovician sediments from the southern Appalachian Mountains 465 Ma and younger (fig. 2; table 3). This includes the Athens Shale (fig. 2), as well as shales and turbidites from the Sevier basin of eastern Tennessee (Blount clastic wedge) and the slightly younger Martinsburg-Shawangunk clastic wedge (Gleason et al. 1994, 1995*b*; Andersen and Samson 1995). The new neodymium data confirm that a homogeneous (Appalachian-type) signature of $\epsilon_{Nd} = -8$ to -9 was established in the middle Whiterockian (ca. 465 Ma) with deposition of earliest clastic sediment in the Sevier foreland basin, as represented by the Athens Shale of Alabama (this article), and the Blockhouse/Tellico trench foredeep assemblage of eastern Tennessee (Gleason et al. 1994, 1995*b*; Andersen and Samson 1995). However, not until after 457 Ma did this signature become well established in the eastern Ouachita Mountains (Benton uplift, Arkansas) and not until after 452 Ma was it well established in the westernmost Ouachitas at Black Knob Ridge, Oklahoma (fig. 2; table 3). It is interesting to note that Blountian sediments analyzed in both this study and Andersen and Samson (1995) show a slight increase in ϵ_{Nd} upsection (table 1) from the *Didymograptus murchisoni* through lower

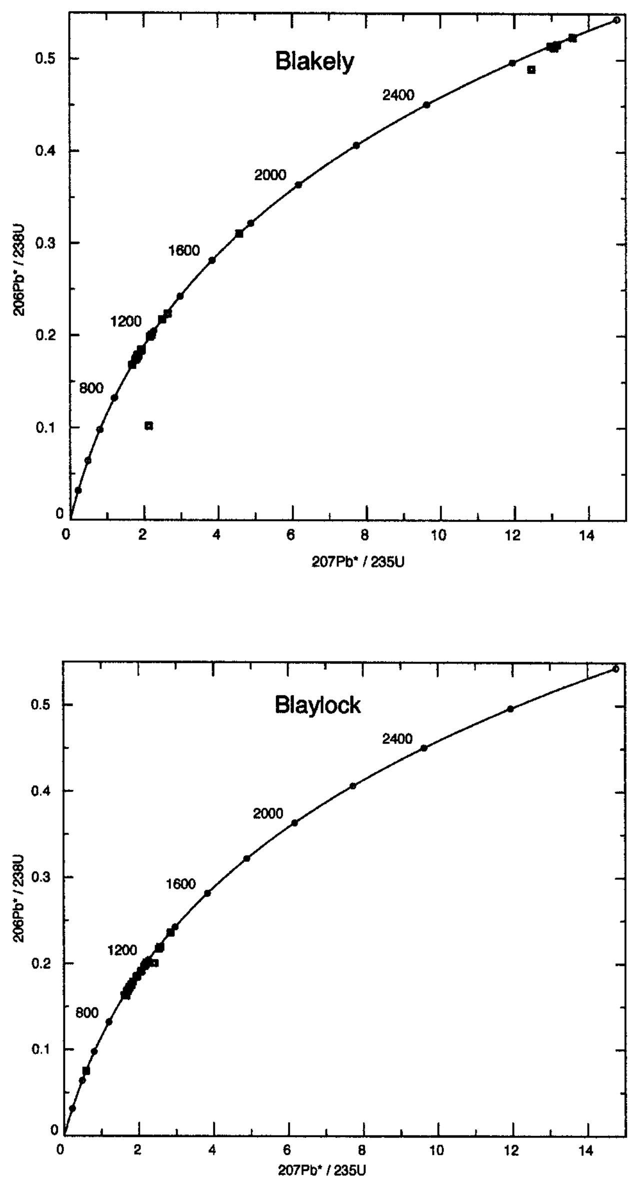


Figure 4. U-Pb concordia diagrams for zircons analyzed from the Blakely Sandstone and the Blaylock Sandstone (see text). Most of the zircons analyzed have concordant ages (all data from table 2).

Table 3. ϵ_{Nd} (Initial) for Sampled Middle to Upper Ordovician Shales, Ouachita and Southern Appalachian Mountains

Zone	Tennessee	Alabama	Arkansas	Oklahoma	Age (Ma)
Didymograptus murchisoni	...	−10	...	...	464
Hustedograptus teretiusculus	−10	−9	−15	...	461
Nemograptus gracilis	−8	−9	−15 to −12	...	459
Climacograptus bicornis	...	...	−8	−13 to −5	457
Corynoides americanus	...	...	−8	−8	453
Geniculograptus spiniferus	...	...	...	...	451
Dicellograptus complanatus	...	...	−8	...	449
Monograptus gregarius	−8	...	...	−8	440

Nemograptus gracilis zones (fig. 2; table 3). Andersen and Samson (1995) interpreted this trend to reflect gradually increasing proportions of Grenville basement-derived (or other "juvenile") material being shed into Blountian foredeeps as they evolved.

Gleason et al. (1994, 1995*b*) concluded that the neodymium isotopic shift in the Ouachita region marked a potentially rapid change from dominantly craton-derived sediments to dominantly Appalachian-derived sediments at about 450 Ma, initiated by the emergence of Taconic fold-thrust belts as a major sediment source beginning around 465 Ma. In Arkansas, the time-correlative (or Blountian equivalent) lower Womble Shale has a craton-dominated signature of −14 to −15, the same as turbidites of the Lower Ordovician Blakely Sandstone (table 1). Our detailed sampling of the middle Womble Shale (late Whiterockian) shows considerable fluctuation in the isotopic signature ($\epsilon_{Nd} = -12$ to -16), suggesting that craton-dominated sources were beginning to mix with those having a less negative (Appalachian-type) ϵ_{Nd} signature by about 458 Ma (fig. 2). The upper Womble Shale (early Mohawkian) is unfortunately not well exposed in Arkansas; however, a single confirmed sample from the Crystal Springs locality shows, along with samples previously analyzed by Gleason et al. (1995*b*) from the overlying Bigfork Chert and Polk Creek Shale in the Benton uplift, that an ϵ_{Nd} signature of −8 was apparently well established by late Whiterockian to early Mohawkian time (ca. 455 Ma). With the new data, it is now apparent that the isotopic shift in the Arkansas Ouachitas occurred during a period of gradual sea-level rise (fig. 2). Although the base of the Bigfork Chert (early Mohawkian) does in fact mark a brief departure from the post–Sauk Ordovician sea-level high stand (fig. 2) (Finney 1986, 1997), an Appalachian-type signature had already been firmly established by this time in the Benton uplift. Sampling of the Bigfork Chert of Arkansas is sparse (one sample from Gleason et al. [1995*b*] has an ϵ_{Nd} of −8), but the signature of $\epsilon_{Nd} = -8$ from the upper Bigfork Chert in Oklahoma (middle to late Mohawkian) also suggests the persistence (by 450 Ma) of the postshift signature across a broad region at a time of extremely reduced sediment flux (fig. 2). The persistence of the postshift signature through this condensed sequence, and its continuation within the overlying Polk Creek Shale and Blaylock Sandstone turbidites, argues against a previously masked minor component (becoming unmasked during times of reduced sediment flux) as a cause of the isotopic shift (Thomas 1997). Rather, we believe it argues for the arrival of material from a new, tectonically emergent source.

At Black Knob Ridge in Oklahoma (approximately 300 km from the Crystal Springs sample localities in the Benton uplift of Arkansas), the uppermost Womble Shale (early Mohawkian) shows large fluctuations in its Nd isotopic signature ($\epsilon_{Nd} = -13$ to -8). The boundary across the upper Womble Shale (*Climacograptus bicornis* zone) and lower Bigfork (*C. americanus* zone), where we had originally placed the location of the isotopic shift, also shows a large Nd isotopic excursion (from −11 to −5). A value of −5 is unusual for Ouachita clastic rocks, and we speculate that it may reflect an additional component, perhaps volcanic (one potential bentonite layer has been identified by us in the uppermost Womble Shale at Black Knob Ridge). Sampling in the Bigfork Chert is sparse because of the lack of suitable clastic material to analyze within the silica-rich and calcitic units that compose most of the formation. Nevertheless, it is clear that a homogeneous, Appalachian-type isotopic signature is probably not well established at this locality until after early Mohawkian time (ca. 452 Ma).

U-Pb Data. U-Pb dating of detrital zircons in sandstones provides more direct information on the age distribution of crystalline (igneous and metamorphic) rocks from geologic terranes that have been sampled by the sedimentary system over time (Gehrels and Dickinson 1995; Gehrels et al. 1995; McLennan et al. 2001). In many cases, zircons have been multiply recycled, so the information supplied is of a different, but complementary, nature to that provided by whole rock Nd isotopic analysis. The U-Pb single-grain detrital zircon ages from the Blakely Sandstone and Blaylock Sandstone reveal a distinct provenance change within the Ouachita assemblage, thereby placing some loose time limits on the Middle Ordovician Nd isotopic shift. The preshift, lower Middle Ordovician Blakely Sandstone in Arkansas ($\epsilon_{Nd} = -15$; ~25% Archean zircons) is coeval with the earliest Blountian clastic sediment in the southern Appalachians (*D. murchisoni* zone; ca. 465 Ma), while the postshift, Upper Ordovician/Lower Silurian Blaylock Sandstone (*M. gregarius* zone) in eastern Oklahoma ($\epsilon_{Nd} = -8$; no Archean zircons) represents the first large influx of orogenic sediment (combined Polk Creek/Blaylock assemblage) into the Ouachita region at about 440–435 Ma. The sandy facies alone therefore place only a 25–30 m.yr. time limit on the duration of the isotopic shift. However, the age population of the zircons reveals additional information on the composition of source terranes supplying sediment to the Ouachita region, information that the neodymium data can only imply.

The cluster of ages between 980 and 1186 Ma in the Blaylock Sandstone is consistent with U-Pb igneous ages from many parts of the Grenville orogenic belt in North America, including Appalachian basement (of which it is a major component), as well as localities in Texas and Mexico (Hoffman 1989; Patchett and Ruiz 1989; Rainbird et al. 1997). The age cluster between 1320 and 1370 Ma is consistent with zircon sources in the Granite-Rhyolite Terranes of the North American midcontinent (Bickford et al. 1986; Patchett and Ruiz 1989; Van Schmus et al. 1996). The single Paleozoic age zircon (468 ± 7 Ma) is consistent with ca. 480–460 Ma pluton ages from the southern Appalachian Taconic orogen (e.g., Hatcher et al. 1989; Miller et al. 2000). These data do not supply direct information on sediment dispersal paths (e.g., zircons derived ultimately from the midcontinent could have been recycled through Appalachian terranes etc.), but this age spectrum does appear to attest to a strongly Laurentian/Appalachian signature for the Blaylock Sandstone. Its presumed derivation from unknown orogenic sources east-southeast of the Ouachita embayment (Viele 1998) is consistent with this interpretation.

Zircons in the Blakely Sandstone are also dominantly Grenvillian in age (1003–1188 Ma), with a slightly older subpopulation (1271–1334 Ma) that could either be Grenvillian or (as with the Blaylock Sandstone) derived from the North American midcontinent (fig. 3). Archean-age zircons (2696–2722 Ma), lacking in the Blaylock Sandstone, are also abundant and consistent with the Blakely's more negative ϵ_{Nd} (-15 vs. -8). A large number of ca. 2.7 Ga zircons could imply sources in the Superior Province of North America (Hoffman 1989) consistent with a cratonic provenance for the Blakely Sandstone (Lowe 1985, 1989). A large number of Grenvillian-age zircons may, on the other hand, seem unusual for a unit thought to have a dominantly cratonic provenance, unless one considers that Grenvillian-age zircons were probably widely distributed and recycled on a continent-wide scale between ca. 1.0 and 0.5 Ga. This is attested to by the dominance of Grenvillian-age zircons in, for example, Neoproterozoic fluvial units in northwestern Canada (Rainbird et al. 1997). Two grains from the Blakely Sandstone with ages of 1271 and 1334 Ma were likely derived from nearby exposed basement sources. Both ages are consistent with U-Pb zircon ages obtained by Bowring (1984) from granite boulders in the Blakely Sandstone (1284 ± 12 to 1407 ± 13 Ma), indicating close proximity of these basement sources to the Ouachita embayment. Bowring (1984) concluded that these proximal sources represented a basement terrane of 1.3–1.4-Ga epizonal granites and rhyolites, stretching from present-day eastern Oklahoma to the Texas Panhandle, and possibly into the subsurface of Arkansas (Bickford et al. 1986). A single grain with an age of 1744 Ma was most likely derived from Paleoproterozoic (1780–1720 Ma) basement beneath the Great Plains region of the United States (Bickford et al. 1986).

The highly rounded, spherical zircon grains in the Blakely Sandstone suggest repeated episodes of recycling within the sedimentary system and, therefore, little should be inferred from the zircon ages regarding specific dispersal pathways. Zircon morphology combined with the pure quartz sandstone lithology of the Blakely Sandstone indicates very mature sedimentary sources, however, consistent with a North American cratonal provenance. This is reinforced by neodymium isotopes ($\epsilon_{Nd} = -15$), paleocurrents (from the north), and olistoliths (1.3–1.4-Ga granites), the latter indicating that Blakely turbidites were delivered to Ouachita seafloor from the North American shelf. The less rounded, less spherical zircon grains in the Blaylock Sandstone suggest only minor recycling, in line with the less mature sources that have been inferred for these turbidites. Gleason et al. (1995*b*) suggested that the primary source of the Blaylock Sandstone (as well as younger Ouachita turbidites) was the voluminous, dominantly Grenville basement-derived material that filled Neoproterozoic Appalachian rift basins (Rankin et al. 1989), which we find to be consistent with the new zircon data. As suggested by Thomas (1997), Appalachian-derived sediment could have been transported across the craton to the Ouachita region in the late Ordovician by known dispersal routes from more northerly points along the Taconic orogen (e.g., Martinsburg-Shawaungunk clastic wedge), although this material would have arrived too late to have produced the isotopic shift in the Ouachita assemblage. Nonetheless, it is interesting to note that the age distribution of zircons in the Upper Ordovician/Lower Silurian Blaylock Sandstone and detrital zircons from the central Appalachian Martinsburg-Shawangunk clastic wedge of the same age are very similar (Gray and Zeitler 1997; McLennan et al. 2001). The well-documented southeasterly sources for the Ouachita Blaylock clastic wedge would require large-scale transport of such material via Taconic foreland basins to points southeast of the Ouachita embayment (Alabama promontory?). Identification of such a tectonic source for the Blaylock turbidites has proved elusive (Thomas 1997; Viele 1998). We conclude from the new data, however, that the Blaylock Sandstone had a dominantly Laurentian provenance like the rest of the Ouachita assemblage (Gleason et al. 2001).

Conclusions

We revise our original estimate for the age of the isotopic shift in the Ouachitas from ca. 450 Ma to a time range spanning some 5 m.yr., from ca. 457 Ma in the eastern Ouachitas to about 452 Ma in the westernmost Ouachita fold belt. However, complexities introduced by fluctuating sediment sources over periods of as much as a few million years are also resolved by these data. A considerable time lag is also revealed between the onset of the Blountian phase of the Taconian orogeny in the southern Appalachian Mountains (ca. 465 Ma) and the Nd isotopic shift ($\Delta\epsilon_{Nd} =\sim 7$) signaling arrival of orogenic clastic sediment in the Ouachita region (ca. 455 Ma). This interval (465–455 Ma) coincides with rising Ordovician sea level. We conclude that this, combined with the tectonic emergence of Appalachian-Taconian thrust belts, produced a large reservoir of isotopically homogeneous sediment that eventually served as the primary source of clastic sediment for this part of the North American continent (Gleason et al. 1994, 1995*b*; Patchett et al. 1999). Two stratigraphic sections, one at Black Knob Ridge, Oklahoma, in the westernmost Ouachita fold belt, and another in the central Benton uplift of Arkansas, show fluctuating sources over a several-million-year period that predate establishment of a stabilized, primarily Appalachian-type isotopic signature in this region. We therefore conclude that, superimposed on the general westward geographic shift in the isotopic composition of sediments, there were also complicated localized effects reflecting varied proportions of different provenance types. By 450 Ma, however, the entire southern margin of North America (and the seafloor south of it) was apparently being supplied by well-mixed sediment derived in large part from the Appalachian orogen.

Ordovician shale sequences around the periphery of North America record a similar changeover in isotopic composition (Patchett et al. 1999), strongly suggesting that the Ouachita region was recording part of a continent-wide phenomenon. U-Pb ages of single detrital zircons from two sandstone units bracketing the isotopic shift in the Ouachitas indicate, along with Nd isotopes, that the preshift "craton" signature ($\epsilon_{Nd} = -15$) essentially consists of two components: Archean Superior Province and Grenville Province (with minor Granite-Rhyolite Terrane and Great Plains orogen), while the postshift "Appalachian" signature ($\epsilon_{Nd} = -8$) is dominated by the Grenville component (with minor Granite-Rhyolite Terrane and Taconian orogen). We conclude that the lag time between the emergence of mountain ranges and delivery of sediments into distant basins can be precisely traced by use of neodymium isotopes as a proxy for sediment source, in concert with precise, high-resolution graptolite biostratigraphy. However, the ability to trace sediment dispersal paths over long distances is seriously compromised when adequate stratigraphic sections are few. More precise knowledge of Ordovician paleodrainage and sediment transport between the Appalachian and Ouachita regions (e.g., Gleason et al. 1997; Thomas 1997; Viele 1998) awaits more detailed work.

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