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Nd isotopic constraints on sediment sources of the Ouachita-Marathon fold belt

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ABSTRACT

Nd isotopes for the overthrust deep-marine Ouachita-Marathon sedimentary assemblage of Arkansas-Oklahoma and west Texas, and associated Paleozoic shelf and foreland deposits, resolve into three distinct populations: (1) Lower to Middle Ordovician, $\varepsilon_{Nd} = -13$ to -16 (average $T_{DM} = 2.0$ Ga); (2) Upper Ordovician to Pennsylvanian, $\varepsilon_{Nd} = -6$ to -10 (average $T_{DM} = 1.6$ Ga); and (3) Mississippian tuffs, $\varepsilon_{Nd} = -1$ to -3 (average $T_{DM} = 1.1$ Ga). A rapid shift in ε_{Nd} from -15 (passive margin shales) to -7 (orogenic turbidites) in the Ouachita assemblage at ca. 450 Ma implies termination of craton-dominated sources and the emergence of the Appalachian orogen as the primary source of sediment for sea floor lying south of North America. This connection is reinforced by Nd isotopes in Ordovician-Silurian turbidites from both the Ouachita assemblage and the southern Appalachian Sevier-Martinsburg (Taconic) foredeep, which are identical ($\varepsilon_{Nd} = -7$ to -9). The post–450 Ma Ouachita assemblage falls along a single Nd isotopic trend that, significantly, is not deflected by onset of Carboniferous flysch ($\varepsilon_{Nd} = -7$ to -10) sedimentation nor by associated regional volcanism. The less negative ε_{Nd} (-2) of Mississippian ash-flow tuffs that erupted from arc(s) to the south probably resulted from isotopic mixing of old (Precambrian) crust with young, mantle-derived components within a continental margin arc. There is little isotopic, trace element, or petrographic evidence for any significant volcaniclastic detritus in the Carboniferous turbidites, indicating that volcanic arc sources were minimal.

Nd isotopes in fluvio-deltaic strata of the Ouachita-Appalachian foreland and continental interior, that is, Arkoma, Illinois, and Black Warrior basins ($\varepsilon_{Nd} = -7$ to -10), imply that continental margin pathways and interior basins received the same detritus as the Ouachita trough by Pennsylvanian time. These data are consistent with a composite Carboniferous Ouachita submarine fan complex built down the axis of a remnant ocean basin from varied mature/immature delivery systems tapping dominantly Appalachian fold-thrust belt sources to the east (Graham et al., 1975). Carboniferous turbidites from the Marathon fold belt (west Texas), which are isotopically similar ($\varepsilon_{Nd} = -8$ to -11) to Ouachita turbidites, may have been ultimately derived from similar sources; however, they probably do not represent merely distal turbidites of a Ouachita fan complex. It is suggested that dominantly Appalachian-derived detritus, augmented by uplifted plutonic and fold-thrust belt sources south of the Marathon basin, was swept up into subduction complexes on the north side of the approaching arc and recycled along the collision zone.

INTRODUCTION

Plate tectonic models for the late Paleozoic Ouachita (Hercynian) orogenic belt at the southern margin of North America generally place it in the context of a complete Wilson cycle (Viele and Thomas, 1989), but because most of it lies buried in the subsurface, many important tectonic relations are obscured. Recognition of the Ouachita orogenic belt in Mexico is important for delineating the limits of the Cordilleran miogeocline, the southern extension of the North American craton, and the subsequent tectonic assembly of Mexico (e.g., Stewart, 1988; Shurbet and Cebull, 1987; Handschy et al., 1987; Campa and Coney, 1983), but it has been hampered by extensive Cenozoic volcanic cover and, where exposed, by Mesozoic-Cenozoic metamorphism and deformation. Tectonic linkages with the Appalachian orogen and the Caribbean region are also obscured by Jurassic Gulf of Mexico rifting and subsequent burial of the continental margin (e.g., Thomas, 1989; Dickinson and Coney, 1980). The landmass(es) that collided with North America to produce the Ouachita orogenic belt may have included several tectonic elements presently distributed throughout the Gulf of Mexico–Caribbean region (e.g., Pindell, 1985; Campa and Coney, 1983; Yañez et al., 1991), but such speculations remain essentially without constraints; likewise, the landmass that separated from the Late Proterozoic/early Paleozoic Ouachita rifted margin is also unknown, though much importance has been affixed to its identity in the context of global tectonic reconstructions (e.g., Dalziel et al., 1994; Hoffman, 1991). Evidence suggests, however, that a long-lived proto-Atlantic ocean basin (Iapetus) resided south of North America through most of Paleozoic time (Scotese, 1984).

Despite these difficulties, a nearly complete Paleozoic stratigraphic record is preserved in the overthrust deep-marine Ouachita sedimentary assemblage, which documents the transition from a

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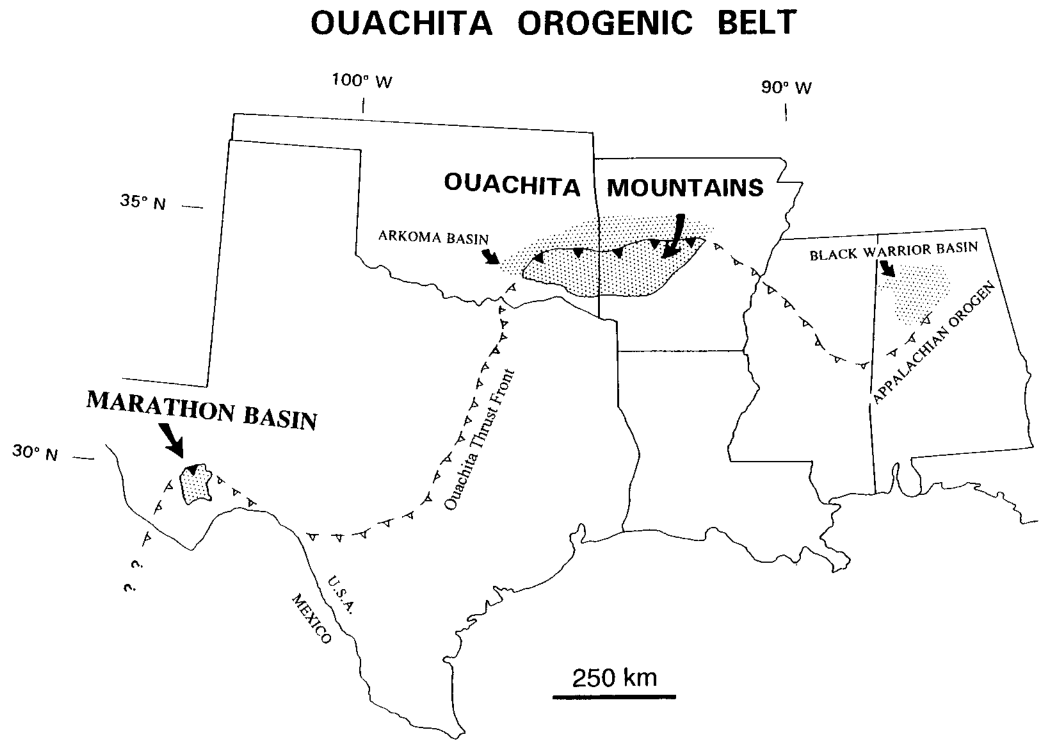

Figure 1. Ouachita orogenic belt and related tectonic elements discussed in this paper. Exposures of the mostly subsurface Ouachita-Marathon fold-thrust belt occur in the Ouachita Mountains (Arkansas-Oklahoma) and the Marathon basin (west Texas). Carboniferous rocks of the Arkoma and Black Warrior basins represent foreland deposits of the Appalachian-Ouachita orogen.

passive to a convergent margin in the Carboniferous (Viele and Thomas, 1989). The provenance of the Ouachita assemblage offers clues to the nature of the ocean basin that closed and the landmass(es) that collided with North America and places constraints on the paleogeography and tectonic setting of the Ouachita margin and adjacent regions during the Paleozoic. Much discussion has centered around the provenance of thick Carboniferous flysch deposits (Morris, 1989), which extend as far west as the Marathon basin in west Texas (McBride, 1989). Gleason et al. (1994) concluded, on the basis of Nd isotopic data, that most of the Ouachita assemblage was derived from Appalachian fold-thrust belt sources, implying an important long-lived relationship between Appalachian tectonics and sediment dispersal into the Ouachita region. In this paper, we document these results and extend the study to include the Marathon basin, and we supplement our database with new trace element, Rb-Sr isotopic, and petrographic data. We evaluate provenance models for Paleozoic Ouachita turbidites and place constraints on the regional tectonic and paleogeographic setting of southern Laurentia over a 200 m.y. period during which tectonic interaction between Laurentia and Gondwana culminated to produce the supercontinent of Pangea (e.g., Kent and Van der Voo, 1990; Dalziel et al., 1994).

OUACHITA-MARATHON FOLD BELT

The Ouachita-Marathon fold belt (Fig. 1) consists of a deep-marine Paleozoic clastic sedimentary succession that was thrust onto the southern margin of North America during the late Paleozoic Ouachita orogeny (Viele and Thomas, 1989; Ingersoll et al., 1995). The belt extends ~2000 km from the southern Appalachian region of the southeastern United States into northern Mexico, where its continuation is uncertain (Shurbet and Cebull, 1987; Stewart, 1988). Exposures in the Ouachita Mountains of Arkansas and Oklahoma, and the Marathon basin of west Texas, reveal a complex series of thrust sheets that carried deep-marine strata northward to their present position over platform and foreland basin facies (Lillie et al., 1983; Viele and Thomas, 1989). No depositional base to the Ouachita succession has been recognized, but it is inferred to have been deposited on oceanic crust (Viele and Thomas, 1989).

Closure of the Ouachita ocean basin is inferred to have begun by Mississippian time when turbidites, mixed with subaqueous ash-flow tuffs, were deposited conformably upon deep-marine cherts within the Ouachita-Marathon fold belt (Niem, 1977; Ethington et al., 1989; McBride, 1989). Carboniferous turbidite flysch reached total accumulations of 10–12 km (Morris, 1989) in the Ouachita region (thinning to <5 km westward toward the Marathon region) and is interpreted as the final filling stage of a remnant ocean basin separating Gondwana from North America (Graham et al., 1975). Regional tectonic relations suggest that the Ouachita Carboniferous flysch was deposited in front of a north-facing arc-trench system that approached the continent from the south-southeast, colliding in Pennsylvanian time to produce the Ouachita orogeny (Graham et al., 1975; Wickham et al., 1976; Viele and Thomas, 1989). Deformation in the Ouachita-Marathon fold belt continued into the Permian in the Marathon region, indicating diachronous collisional events from east to west along the Ouachita-Marathon suture (Graham et al., 1975; Viele and Thomas, 1989; McBride, 1989).

METHODS

McLennan et al. (1990) studied trace element and isotopic variations in modern turbidites from a variety of tectonic settings, work which forms a basis of comparison in this study. In general, certain trace elements, such as the rare earth elements (REE), Th, and Sc, are believed to be transported quantitatively from source rocks into sediments (e.g., McLennan, 1989); these elements are also the least prone to diagenetic redistribution, thus providing useful information on the composition of sediment sources (Taylor and McLennan, 1985; McLennan, 1989). For this study, trace element analyses were performed by inductively coupled plasma mass spectrometry (ICP-MS) at the University of Arizona. Samples were digested in HF/HNO_3 at 160 °C in sealed high-pressure bombs for one week, evaporated in $HClO_4$, and sealed again in high-pressure bombs overnight in HCl at 160 °C to ensure complete dissolution of all trace phases. All samples were run in dilute (2%) HNO_3. Oxide interference corrections for Sm, Eu, Gd, and Tb were made empirically based on early runs of pure Ba and REE solutions; corrections were largest (up to 50%) for high Ba samples and were probably the major source of error in rare earth determinations. All samples had concentrations well above the elemental detection limits (Hollocher et al., 1994). Analytical blanks were insignificant, typically between 0.1% and 0.01% of sample concentration.

Sedimentary provenance studies using Nd isotopes (see Gleason et al., 1994, and references therein) exploit the age sensitivity and general geochemical coherence of the Sm-Nd isotopic system; however, because large sedimentary systems potentially are composed of mixtures of sediment from several different source regions, Nd isotopic compositions must be interpreted as a weighted average of different source components, and not as unique provenance indicators. For this study, we emphasize initial ε_{Nd} values calculated for the stratigraphic age of samples; Nd model ages are also reported, but their importance is downplayed, as weathering and diagenesis can affect Sm/Nd ratios in sediments (e.g., McDaniel et al., 1994; Bock et al., 1994; Ohr et al., 1991), possibly resulting in spurious Nd model ages. This approach assumes that any diagenetic effects resulting in disturbance of Sm/Nd ratios would have occurred near the time of deposition; thus, calculated initial ε_{Nd} values should reflect true ε_{Nd} of the material at that time. In addition, some studies have demonstrated Nd isotopic and Sm/Nd unmixing between fine- and coarse-grained fractions in turbidites (McLennan et al., 1989; Frost and Coombs, 1989). These instances appear to be specific to turbidites deposited in active volcanic settings and probably reflect unmixing of volcanic and nonvolcanic components; however, we studied both coarse- and fine-grained samples to evaluate these effects.

Sm-Nd samples were digested in HF/HNO_3 at 160 °C in sealed high-pressure bombs for one week, evaporated in $HClO_4$, and sealed again in high-pressure bombs overnight in HCl at 160 °C. Solutions were then combined with a ^{149}Sm-^{150}Nd tracer and equilibrated in 20 mL 6M HCl solution over several hours during hotplate evaporation. Selected samples for Rb-Sr isotopic analysis were directly spiked with a ^{87}Rb-^{84}Sr tracer solution and dissolved in three steps with HF/HNO_3, HNO_3, and HCl in screw-top Savillex beakers. Sm, Nd, Rb, and Sr were separated by conventional ion exchange methods and run on a fully automated VG-354 multicollector mass spectrometer at Arizona following procedures described in Patchett and Ruiz (1987). During this study, the La Jolla Nd isotopic standard gave $^{143}\mathrm{Nd}/^{144}\mathrm{Nd} = 0.511\,867 \pm 12$, $\varepsilon_{Nd} = -15.0 \pm 0.23$ (2σ; $n = 28$); and the NBS-987 Sr isotopic standard gave $^{87}\mathrm{Sr}/^{86}\mathrm{Sr} = 0.710\,225 \pm 25$ (2σ; $n = 21$). Laboratory blanks averaged <100 pg Sm, <200 pg Nd, <300 pg Rb, and <900 pg Sr. Sr blanks were significantly higher than normally reported from this lab but were nevertheless insignificant (<0.01% of sample), requiring no blank correction. Nineteen duplicate Sm-Nd analyses from this study show that initial ε_{Nd} and T_{DM} values were always reproduced to within 0.5 ε_{Nd} and 0.05 Ga, respectively.

Sampling strategy in the Ouachita-Marathon fold belt was designed to maximize geographic coverage and lithologic variation for all major stratigraphic units. We collected fresh samples, mainly from well-known outcrops that are documented in field guides and that are stratigraphically well constrained. Complete descriptions of samples and collecting localities can be obtained from the GSA Data Repository.[1] Samples averaged about 1 kg (usually larger for sandstones and smaller for shales) and were carefully chosen to avoid veins, alteration, and weathering as much as possible. For sandstones, this usually meant sampling several different parts of the same bed at the outcrop, resulting in a larger, more representative sample. Sandstone-shale turbidite couplets were collected wherever possible in order to monitor isotopic fractionation effects between coarse- and fine-grained fractions. All samples were washed in deionized water, crushed in a steel jaw crusher, and powdered using an aluminum oxide mill prior to analysis. Additional samples of Mississippian tuffs and Paleozoic shales from Oklahoma were provided to us by B. Weaver and H. Blatt of the University of Oklahoma.

RESULTS

REE patterns (Fig. 2) and trace element ratios (Table 1, Figs. 3 and 4) for Paleozoic sandstones and shales of the Ouachita-Marathon fold belt are similar to average post-Archean upper continental crust throughout the sequence (e.g., Taylor and McLennan, 1985). REE patterns are characterized by light rare earth enrichment with fairly constant, modest negative Eu anomalies, and flat heavy rare earth (HREE) distributions (Fig. 2). Eu anomalies (Eu/Eu*) range from 0.57 to 0.69 for all but one sample and average 0.65 (Fig. 3), identical to the average upper crustal value of McLennan and Taylor (1985). Two samples (OUA-17 and OUA-24) have minor Ce anomalies (Table 1), possibly due to weathering effects of the type documented by McDaniel et al. (1994). Also, there is a strong tendency for sandstones to show relative enrichment in the heavy rare earth elements (HREE) compared to shales (Fig. 2), as reflected in La/Yb ratios (Table 1); this is correlated with Zr and Hf abundances (Table 1) and therefore probably due to concentration of zircon (Taylor and McLennan, 1995). The Mississippian tuffs have a greater range of Eu anomalies, some quite large (Figs. 2 and 3, Table 1), but otherwise have REE patterns similar to sediments (Fig. 2). La/Sc, Th/Sc, and La/Yb ratios for sediments do not depart significantly from average upper crustal values (Table 1, Fig. 4), whereas the tuffs show larger fractionations in these ratios, which, along with large Eu anomalies, suggest an origin in evolved magma chambers (Loomis et al., 1994).

Initial ε_{Nd} and Nd depleted mantle model ages (T_{DM}) for the Ouachita-Marathon assemblage (Table 2) show a large range (Figs. 5A and 5B) but define three distinct populations: (1) Missis-

[1]GSA Data Repository item 9538 is available on request from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301.

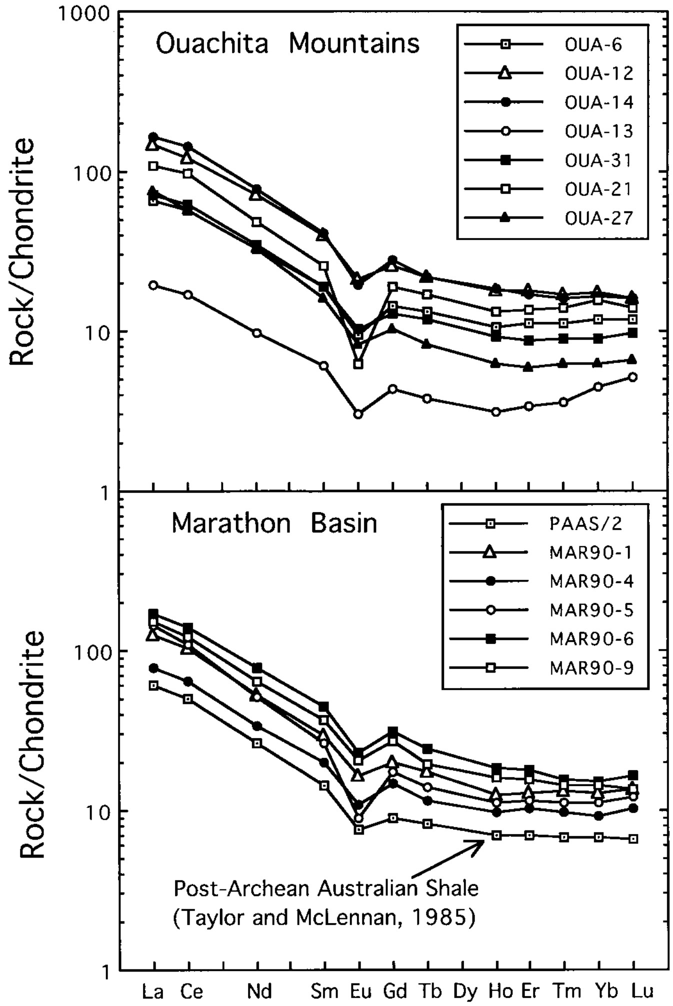

Figure 2. REE patterns of selected sandstones, shales, and tuffs from the Ouachita-Marathon fold belt (all data from Table 1). REE patterns for sediments are typical of average upper crust throughout the assemblage. The two Mississippian tuffs shown here (OUA-21 and MAR90-5) have larger Eu anomalies resulting from igneous processes but otherwise have patterns similar to the sediments. The HREE-enriched pattern for OUA-13 shows the effects of zircon concentration in quartzose sandstones (see text).

sippian tuffs (ε_{Nd} = −1 to −3, average T_{DM} = 1.1 Ga), (2) Lower to Middle Ordovician sediments (ε_{Nd} = −13 to −16, average T_{DM} = 2.0 Ga), and (3) Upper Ordovician to Pennsylvanian sediments (ε_{Nd} = −6 to −10, average T_{DM} = 1.6 Ga). Sm/Nd ratios range widely in the sediments (Fig. 5C), but most values fall near the average $^{147}Sm/^{144}Nd$ value for the entire Ouachita-Marathon sedimentary assemblage (0.115), which is typical of average upper continental crust (0.118; Jahn and Condie, 1995). There is some tendency for high and low Sm/Nd ratios to be correlated with low and high Nd model ages, respectively (Gleason, 1994), which suggests that some resetting could have occurred in a minor number of samples; however, initial ε_{Nd} values appear not to have been affected. Nine of ten sandstone-shale pairs have differences of 1 ε_{Nd} unit or less (Table 2), which suggests that our samples were not affected by any of the sorting or isotopic unmixing effects described by McLennan et al. (1990) for modern turbidites (Gleason et al., 1994). Nd-Sr isotopic relations for Carboniferous flysch of the Ouachita-Marathon sedimentary assemblage (Table 3, Fig. 6) are consistent with sediment sources dominated by old recycled upper continental crust, whereas the tuffs plot in a distinct Nd-Sr field closer to bulk earth values (see discussion below).

CONSTRAINTS ON SEDIMENT PROVENANCE

Part I

Ouachita Assemblage. *Lower to Middle Ordovician.* Strata from the Ouachita assemblage in the interval below the Bigfork Chert (see stratigraphic column of Fig. 7A, interval 1) include hemipelagites (Mazarn Shale and Womble Shale) with intercalated quartzose turbidite sandstones (Crystal Mountain Sandstone and Blakely Sandstone). Most workers interpret these units as continental slope and rise deposits along the southern flank of the rifted craton (Viele and Thomas, 1989). The two Ordovician sandstones we sampled are well sorted, medium- to coarse-grained orthoquartzites composed mainly of rounded to subrounded monocrystalline quartz grains (Table 4). The framework of OUA-25 is exclusively quartz grains, whereas OUA-28 contains a small amount of K-feldspar (2%), clastic siltstone grains (1%), and rare chert grains (Table 4). The compositions and textures of both sandstones are fully compatible with derivation as multicyclic sand from a deeply weathered craton (Dickinson, 1985). Paleocurrents suggest transport of sandstone turbidites from sources lying predominantly to the north of the Ouachita rifted margin (Viele and Thomas, 1989; Lowe, 1989), and carbonate debris and olistoliths, including 1.3–1.4 Ga granitic rocks (Bowring, 1984), are present throughout the interval, tying most of the Lower to Middle Ordovician sequence to sources on the North American shelf and craton (Viele and Thomas, 1989). Average ε_{Nd} (−14.6) and T_{DM} (1.97 Ga) for shales and orthoquartzites combined (n = 6, Table 2; Fig. 7A) are consistent with such sources and indicate a mixture of Archean and Proterozoic age crustal components. Dominant sediment sources, consistent with the supermature nature of the Blakely and Crystal Mountain Sandstone, were most likely the exposed early Paleozoic (Cambrian–Middle Ordovician) sedimentary cover of the North American craton (Dott and Batten, 1981), which would have contained crustal components recycled from North American Precambrian basement.

Middle Ordovician to Lower Mississippian. Strata in the interval bracketed by (and including) Bigfork Chert and Arkansas Novaculite (Fig. 7A, interval 2) consist of shales, cherts with interbedded argillites, and turbidites. Most workers interpret the massive cherts and argillites as pelagic and hemipelagic deep-marine deposits on a sea floor south of the passive continental margin (Ethington et al., 1989). The turbidites (Blaylock Sandstone), however, apparently mark a pulse of orogenic sedimentation within the lower part of the Ouachita sequence (Viele and Thomas, 1989). Two turbidite sandstone samples from the Blaylock Sandstone (Upper Ordovician/Lower Silurian) are quartz-rich lithic sandstones with closely similar compositions and textures (Table 4). Both are moderately sorted, very fine- to fine-grained sandstone with subangular to subrounded grains, minor detrital mica flakes (1%–2% of framework), and prominent interstitial phyllosilicate matrix (12% of whole rock), probably of detrital origin. Framework grains (in QFL percentages) are monocrystalline quartz (85%–89%), metasedimentary slate-phyllite grains composed of quartz-mica aggregates (5%), aggregate

TABLE 1. TRACE ELEMENT DATA FOR SANDSTONES, SHALES, AND TUFFS OF THE OUACHITA-MARATHON FOLD BELT

ppm	OUA-2 *sh*	OUA-6 *ss*	OUA-11 *sh*	OUA-12 *sh*	OUA-13 *ss*	OUA-14 *sh*	Duplicate analysis	OUA-15 *tuff*	OUA-16 *sh*	OUA17 *ss*	OUA-18 *sh*	OUA-20 *sh*	OUA-21 *tuff*	OUA-24 *sh*	OUA-27 *sh*
Hf	3.48	14.5	5.26	5.72	12.7	4.26	4.24	6.59	2.99	5.75	3.48	4.25	4.86	3.67	4.79
Nb	17.8	6.91	13.8	12.2	4.31	18.3	18.8	13.7	17.0	9.48	15.2	16.3	12.9	15.6	8.90
Ta	1.07	0.42	0.93	0.93	0.41	1.27	1.38	0.89	1.12	0.54	1.07	1.36	0.88	0.98	0.61
Y	21.6	19.8	28.1	15.0	6.44	29.2	25.8	16.6	29.5	27.9	29.1	24.6	22.2	20.2	10.5
Zr	129	558	201	206	477	162	157	288	108	234	126	148	175	143	183
Th	15.3	6.72	13.5	17.9	2.05	18.8	18.6	11.9	13.2	12.1	16.5	12.0	20.5	15.4	9.30
U									2.55			2.72			
Rb	137	24.8	151	192	2.08	163	178	105	177	20.1	347	121	149	148	102
Sr	93.1	33.2	90.9	105	12.9	71.4	79.6	156	23.3	44.5	56.8	71.8	61.4	46.5	21.0
Ba	402	123	665	244	16.6	710	603	596	626	61.4	909	334	841	310	336
Sc	18.3	5.49	14.6	18.72	2.43	16.3	17.5	10.1	14.7	4.83	21.5	13.3	6.12	21.6	10.1
Ni	61.7	21.5	36.6	32.8	4.44	33.3	39.9	10.5	31.9	13.0	26.8	33.2	3.83	35.6	23.3
Co	23.1	4.33	6.12	6.60	0.28	13.3	16.2	9.42	9.35	9.38	15.8	12.4	2.26	8.19	2.53
La	48.3	20.3	49.2	45.9	6.02	48.7	51.4	58.9	32.8	28.1	63.6	38.3	34.1	45.4	23.6
Ce	110	46.1	113	99.4	13.5	104	115	61.3	71.5	82.6	149	82.2	79.0	162	46.5
Nd	45.3	20.0	56.8	43.6	5.89	44.6	46.7	23.6	28.5	37.3	49.7	32.7	29.5	44.6	19.8
Sm	8.23	3.71	12.0	7.73	1.20	8.13	8.08	3.95	4.91	8.67	6.78	6.13	4.96	8.34	3.13
Eu	1.70	0.69	2.60	1.54	0.22	1.46	1.42	0.78	0.78	1.74	1.25	1.02	0.46	1.64	0.60
Gd	7.16	3.73	11.5	6.67	1.14	7.59	7.16	3.67	4.96	8.77	5.90	4.71	4.93	6.77	2.64
Tb	1.09	0.63	1.58	1.03	0.18	1.07	1.04	0.54	0.81	1.23	1.04	0.74	0.79	1.01	0.38
Ho	1.31	0.76	1.40	1.30	0.22	1.32	1.31	0.76	1.10	1.31	1.29	0.91	0.96	1.11	0.45
Er	3.67	2.37	3.57	3.71	0.71	3.90	3.55	2.18	3.22	3.33	4.06	2.63	2.87	3.31	1.25
Tm	0.57	0.36	0.58	0.56	0.11	0.58	0.52	0.32	0.49	0.47	0.65	0.41	0.45	0.49	0.20
Yb	0.34	2.49	3.58	3.69	0.94	3.67	3.47	2.55	2.59	3.00	4.30	2.55	3.30	3.61	1.29
Lu	0.48	0.37	0.50	0.51	0.16	0.50	0.52	0.33	0.47	0.39	0.61	0.37	0.45	0.54	0.21
Eu/Eu*	0.68	0.57	0.68	0.66	0.58	0.57	0.57	0.63	0.48	0.61	0.61	0.58	0.28	0.67	0.64
Ce/Ce*	1.06	1.04	1.00	1.01	1.03	1.06	1.06	1.04	1.04	1.22	0.99	1.04	1.11	1.64	0.96
$[La/Yb]_N$	8.51	4.94	8.33	7.53	3.88	8.98	8.98	6.87	7.67	5.67	8.96	9.10	6.26	7.62	11.1
Th/Sc	0.83	1.22	0.92	0.96	0.84	1.06	1.06	1.19	0.64	2.50	0.77	0.90	3.35	0.71	0.91
La/Sc	2.64	3.69	3.36	2.45	2.47	2.93	2.94	2.86	5.45	5.81	2.96	2.87	5.57	2.10	2.31

quartz grains derived mainly from fine-grained quartzites (3%–4%), polycrystalline mica aggregates of probable metasedimentary origin (1%), chert grains (<1%), rare volcanic rock fragments (trace amounts only), and minor feldspar grains (2%–4%), with roughly subequal proportions of plagioclase and K-feldspar. The quartzolithic character (Dickinson, 1985) of the Blaylock detritus is typical of distal turbidites derived from the fold-thrust belts of collisional orogens. Orogenic sources have also been proposed for the Blaylock turbidites based on sandstone composition, paleocurrent data, and facies distribution, all of which indicate they were part of a prograding submarine fan system derived from the east-southeast (Satterfield, 1982).

Four Blaylock samples have a narrow range of Nd isotopic compositions ($\varepsilon_{Nd} = -7.0$ to -8.7), but Nd model ages range widely from 1.35 Ga to 2.12 Ga (Table 2); these are positively correlated with $^{147}Sm/^{144}Nd$ ratios, suggesting disturbance in Sm/Nd at time of deposition. All samples (n = 14) from this interval combined have an average ε_{Nd} and T_{DM} of -7.6 and 1.65 Ga, respectively, and are isotopically distinct from the Lower to Middle Ordovician interval (Fig. 7A). The two intervals are bounded by a shift in ε_{Nd} of eight units (Fig. 7A), which occurs between the Womble Shale (-15) and the Bigfork Chert (-7.0) at 450 ± 10 Ma, suggesting a rapid change in the provenance of the Ouachita assemblage *before* Blaylock turbidites were deposited. Furthermore, the Nd isotopic signature does not revert back to pre–Bigfork Chert values, but instead remains at ε_{Nd} values between -6 and -10 through the remainder of the Ouachita sequence (Fig. 7A). The ε_{Nd} shift at 450 Ma could be interpreted as either (1) removal of an Archean component from pre-chert cratonal sources, (2) mixing between pre–Bigfork Chert sources and a newly introduced juvenile (e.g., island arc) component, or (3) a switch to an entirely new provenance that was also likely to be the source of Blaylock turbidites. We favor the latter alternative because (1) the quartzolithic sandstone composition of the Blaylock turbidites (Satterfield, 1982; Lowe, 1989; our point counts cited above) is consistent with dominantly recycled orogenic source materials, distinct from the craton-derived sandstones from the lower part of the sequence, and lacking in any volcanic lithic components suggestive of an arc-dominated source, and (2) the timing of the shift is coincident with Taconic (480–450 Ma) orogenic events in the southern Appalachians (Rast, 1989) and a global sea-level highstand (Dott and Batten, 1981) that would have submerged cratonal sources, leaving the Appalachian fold-thrust belt as the primary sediment source for sea floor lying south of North America. An Appalachian (Taconic) fold-thrust belt source was proposed by Satterfield (1982) for the Blaylock turbidites; however, the Nd isotopic data imply that detritus from this source was first deposited as hemipelagites interbedded with Bigfork Chert. We therefore suggest that the Bigfork Chert hemipelagites were the most distal deposits of a Blaylock submarine fan, which prograded gradually into the Ouachita region from southern Appalachian sources along the continental edge. If this is correct, Ordovician-Silurian detritus from Appalachian Taconic foreland basins (Rodgers, 1971; Thomas, 1977) should have the same isotopic signature as Blaylock turbidites, an inference that we test below.

Sevier-Martinsburg (Taconic) Clastic Wedge. Middle Ordovician turbidites of the Tellico Formation (Fig. 7B) were deposited in the Sevier foreland basin (eastern Tennessee) during rapid tectonic subsidence of the Appalachian carbonate shelf at onset of the Tac-

TABLE 1. *(Continued)*

ppm	OUA-29 *sh*	OUA-30 *ss*	OUA-31 *ss*	OUA-38 *sh*	MAR90-1 *sh*	MAR90-2 *sh*	MAR90-3 *sh*	MAR90-4 *ss*	MAR90-5 *tuff*	MAR90-6 *sh*	MAR90-7 *sh*	MAR90-8 *ss*	MAR90-9 *sh*	SDC-1 *(avg. of 3)*	*(rec.)*	Upper crust
Hf	5.11	7.20	5.67	3.91	2.96	2.97	5.63	11.1	4.50	3.84	4.00	7.90	3.82	7.69 ± 3%	8.3	5.8
Nb	11.7	11.5	8.74	14.9	13.7	15.3	7.47	9.65	12.4	17.8	17.0	7.21	18.1	20.4 ± 3%	18	25
Ta	0.74	0.87	0.52	0.81	0.62	1.39	0.49	0.81	0.77	1.11	0.94	0.45	1.37	1.39 ± 11%	1.21	2.2
Y	12.7	27.8	17.3	26.6	23.7	9.65	14.3	18.1	20.8	33.2	28.0	13.1	29.2	33.1 ± 8%	40	22
Zr	209	263	205	146	104	114	213	371	141	135	142	290	135	283 ± 2%	290	190
Th	11.0	9.18	6.94	10.1	10.7	9.36	4.70	7.45	23.3	17.2	12.8	4.67	14.8	11.9 ± 11%	12.1	10.7
U		2.74	1.85		2.95	3.10	1.47	2.07	6.56	3.37	3.60	1.42		3.2 (1)	3.1	2.8
Rb	155	73.4	69.1	91.7	158	130	38.6	16.6	93.1	180	185	38.6	132	127 ± 1%	127	112
Sr	9.91	109	71.5	72.7	185	360	67.9	77.6	96.8	90.8	144	46.7	95.2	159 ± 5%	183	350
Ba	475	626	272	284	501	517	231	77.4	381	561	507	185	634	578 ± 12%	630	550
Sc	11.8	8.80	6.70	8.34	17.1	15.5	4.33	5.16	6.31	16.6	18.8	4.75	16.6	15.6 ± 7%	17	11
Ni	28.1	19.7	15.4	27.8	60.4	9.14	7.42	12.3	10.5	42.7	50.7	10.6	38.4	36.2 ± 11%	38	20
Co	7.59	9.44	6.72	0.71	5.77	1.11	2.10	4.51	2.06	9.91	10.3	2.15	11.1	18.8 ± 11%	18	10
La	25.1	29.3	22.5	45.5	38.4	28.0	18.2	24.4	43.9	52.5	45.4	16.4	47.5	40.8 ± 5%	42	30
Ce	49.9	63.3	50.5	103	83.2	55.7	38.9	52.4	87.3	112	99.3	36.4	99.1	91.7 ± 5%	93	64
Nd	22.4	26.7	21.0	54.3	32.1	21.5	15.4	20.5	30.8	46.5	39.9	14.5	38.8	41.5 ± 4%	40	26
Sm	3.71	5.21	3.74	9.76	5.82	2.85	2.93	3.87	5.21	8.71	7.80	2.91	7.28	7.84 ± 1%	8.2	4.5
Eu	0.74	0.93	0.76	1.61	1.21	0.44	0.65	0.80	0.65	1.70	1.44	0.61	1.51	1.45 ± 8%	1.71	0.88
Gd	3.33	5.14	3.36	7.17	5.22	1.89	2.83	3.82	4.46	7.98	6.42	2.78	6.95	7.15 ± 5%	7.2	3.8
Tb	0.39	0.89	0.56	0.85	0.81	0.25	0.45	0.55	0.67	1.14	0.89	0.41	0.92	1.10 ± 3%	1.18	0.64
Ho	0.55	1.10	0.67	1.05	0.89	0.40	0.56	0.69	0.80	1.31	1.19	0.48	1.15	1.41 ± 7%	1.5	0.80
Er	1.58	2.98	1.82	3.15	2.66	1.35	1.51	2.15	2.43	3.78	3.58	1.50	3.29	4.14 ± 7%	4.1	2.3
Tm	0.23	0.45	0.29	0.45	0.43	2.64	0.27	0.31	0.36	0.51	0.48	0.23	0.47	0.71 ± 16%	0.65	0.33
Yb	1.89	2.71	1.85	3.15	2.66	1.81	1.54	1.92	2.32	3.21	2.97	1.40	2.98	4.05 ± 11%	4	2.2
Lu	0.28	0.43	0.31	0.42	0.44	0.61	0.27	0.33	0.39	0.53	0.49	0.25	0.44	0.66 ± 12%	0.53	0.32
Eu/Eu*	0.65	0.55	0.66	0.59	0.67	0.58	0.70	0.64	0.41	0.63	0.63	0.66	0.65	0.60	0.68	0.65
Ce/Ce*	0.94	1.01	1.05	0.98	1.05	0.99	1.03	1.04	1.02	1.02	1.04	1.06	1.02	1.02	1.03	1.03
$[La/Yb]_N$	8.04	6.55	7.37	8.75	8.75	9.37	7.16	7.70	11.4	9.91	9.26	7.09	9.66	6.18	6.28	8.3
Th/Sc	0.93	1.04	1.03	1.82	1.57	0.84	1.47	1.44	3.64	1.03	0.68	0.98	0.89	0.76	0.71	0.97
La/Sc	2.12	3.32	3.35	1.21	0.63	0.60	1.08	4.73	6.87	3.16	2.41	3.45	2.86	2.62	2.74	2.72

Note: Eu/Eu* = $Eu_N/(Sm_N \times Gd_N)^{1/2}$; Ce/Ce* = $Ce_N/(La_N^{2/3} \times Nd_N^{1/3})$, where N = chondrite-normalized value (normalizing values from Haskin et al.,1968). SDC-1 recommended *(rec.)* values from Govindaraju (1989). Average upper crustal values from Taylor and McLennan (1985). *ss* = sandstone; *sh* = shale.

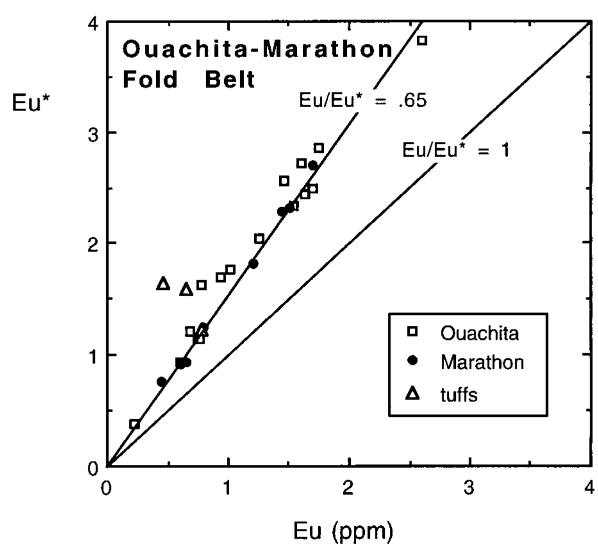

Figure 3. Eu* vs. Eu plot (see Table 1 for explanation of Eu*) for all sandstones, shales, and Mississippian tuffs of the Ouachita–Marathon fold belt analyzed in this study (Table 1). Eu anomalies (Eu/Eu*) in sandstones and shales are generally very close to the average upper crustal value of 0.65, implying dominantly recycled upper crustal sources for the entire sequence. Eu/Eu* for tuffs (0.63 to 0.28) is more variable (see text).

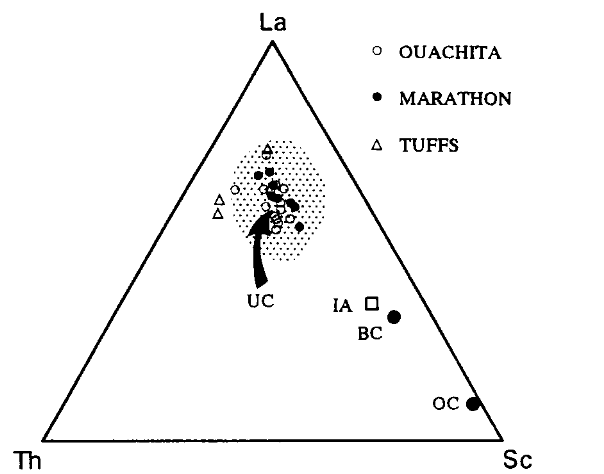

Figure 4. Ternary plot of La-Th-Sc for all sandstones, shales, and Mississippian tuffs from the Ouachita-Marathon fold belt analyzed in this study (Table 1). Sedimentary rocks plot within the fields for post-Archean Australian shales (dotted pattern) as well as modern turbidites from the Trailing Edge and Continental Collision tectonic settings of McLennan et al. (1990), indicating dominantly recycled upper crustal sources. Bulk crust (BC), oceanic crust (OC), average island arc (IA), and average upper crust (UC) are also shown for reference (from Taylor and McLennan, 1985). The tuffs plot toward higher La/Sc and Th/Sc values, indicating they are chemically somewhat more evolved than average upper continental crust (see text).

TABLE 2. Sm-Nd ISOTOPIC DATA

Sample	Formation	Lith-ology	Age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ measured	ϵ_{Nd} present	ϵ_{Nd} initial	T_{DM} (Ga)
OUACHITA ASSEMBLAGE (Arkansas-Oklahoma)										
Lower to Middle Ordovician										
OUA-25	Crystal Mt	ss *(q)*	500	0.213	1.35	0.0959	0.511676 ± 7	-18.7	-12.3	1.77
duplicate				0.236	1.48	0.0964	0.511651 ± 6	-19.2	-12.8	1.81
OUA-19	Mazarn	sh	490	1.59	8.79	0.1095	0.511689 ± 5	-18.5	-13.1	1.98
duplicate				1.60	8.80	0.1096	0.511712 ± 6	-18.1	-12.6	1.94
OUA-26	Mazarn	sh	490	4.62	28.21	0.0990	0.511495 ± 8	-22.3	-16.2	2.05
duplicate				4.62	28.19	0.0991	0.511507 ± 7	-22.1	-16.0	2.04
OUA-28	Blakely	ss *(q)*	480	0.287	1.95	0.0890	0.511534 ± 9	-21.5	-14.9	1.84
duplicate				0.290	1.96	0.0894	0.511543 ± 8	-21.4	-14.8	1.84
OUA-27	Womble	sh	460	3.31	19.20	0.1041	0.511566 ± 9	-20.9	-15.5	2.05
OUA-29	Womble	sh	460	4.22	23.69	0.1077	0.511583 ± 8	-20.6	-15.4	2.10
duplicate				4.21	23.53	0.1081	0.511605 ± 5	-20.1	-14.9	2.07
Upper Ordovician to Lower Mississippian										
OUA-45	Bigfork	sh	450	1.85	9.45	0.1185	0.512050 ± 8	-11.5	-7.0	1.59
OUA-37	Polk Creek	sh	440	6.22	29.60	0.1271	0.512074 ± 7	-11.0	-7.1	1.70
OUA-38	Polk Creek	sh	440	11.17	58.70	0.1150	0.512086 ± 6	-10.7	-6.2	1.48
OUA-39	Polk Creek	sh	440	7.49	42.29	0.1135	0.512047 ± 7	-11.5	-6.8	1.51
OUA-17*	Blaylock	ss *(l)*	430	9.06	38.50	0.1422	0.512126 ± 5	-10.0	-7.0	1.95
duplicate				9.14	39.00	0.1417	0.512116 ± 6	-10.2	-7.2	1.96
OUA-18*	Blaylock	sh	430	6.67	44.32	0.0909	0.511958 ± 7	-13.3	-7.5	1.35
duplicate				6.78	45.58	0.0900	0.511952 ± 6	-13.4	-7.5	1.34
OUA-35*	Blaylock	sh	430	6.49	39.22	0.1000	0.511921 ± 7	-14.0	-8.7	1.50
OUA-36*	Blaylock	ss *(l)*	430	10.26	42.34	0.1465	0.512108 ± 7	-10.3	-7.6	2.12
duplicate				10.34	42.64	0.1466	0.512132 ± 6	-9.9	-7.1	2.07
OUA-43	Missouri Mt	sh	410	5.35	23.53	0.1374	0.511993 ± 7	-12.6	-9.5	2.10
duplicate				5.41	23.60	0.1387	0.512006 ± 6	-12.3	-9.3	2.11
OUA-44	Missouri Mt	sh	410	4.65	25.42	0.1005	0.511917 ± 6	-14.1	-9.6	1.65
OUA-24	Novaculite	sh	400	8.45	41.89	0.1219	0.512042 ± 7	-11.6	-8.0	1.66
OUA-40	Novaculite	sh	400	7.41	36.65	0.1222	0.512050 ± 5	-11.5	-7.7	1.65
OUA-34	Novaculite	sh	380	12.97	64.70	0.1212	0.512066 ± 6	-11.2	-7.5	1.61
OUA-46	Novaculite	sh	380	4.29	23.39	0.1109	0.512106 ± 6	-10.4	-6.2	1.40
Lower to Upper Mississippian										
OUA-14	Stanley	sh	340	8.63	45.60	0.1143	0.511964 ± 7	-13.1	-9.6	1.65
OUA-16	Stanley	sh	340	6.24	32.86	0.1147	0.512117 ± 8	-10.1	-6.6	1.43
OUA-20	Stanley	sh	340	6.62	37.33	0.1071	0.511974 ± 7	-12.9	-9.1	1.53
OUA-30	Stanley	ss *(l)*	340	6.35	32.72	0.1174	0.512105 ± 7	-10.4	-7.0	1.48
OUA-31	Stanley	ss *(l)*	340	4.54	23.34	0.1175	0.512049 ± 6	-11.5	-8.1	1.57
duplicate				4.66	24.09	0.1171	0.512021 ± 7	-12.0	-8.6	1.61
OUA-15	Stanley	tf (mc)	340	4.73	25.44	0.1123	0.512335 ± 6	-5.9	-2.3	1.07
T-5	Stanley	tf (mc)	340	5.23	27.87	0.1135	0.512303 ± 7	-6.5	-2.9	1.13
T-33	Stanley	tf (bb)	340	5.37	27.72	0.1171	0.512310 ± 7	-6.4	-2.9	1.16
T-36	Stanley	tf (bb)	340	6.67	33.85	0.1192	0.512330 ± 5	-6.0	-2.6	1.15
duplicate				6.48	32.86	0.1193	0.512315 ± 6	-6.3	-2.9	1.18
T-39	Stanley	tf (h)	340	5.99	30.99	0.1168	0.512375 ± 6	-5.1	-1.7	1.06
duplicate				5.94	30.88	0.1167	0.512382 ± 6	-5.0	-1.5	1.04
T-42	Stanley	tf (h)	340	6.28	32.54	0.1169	0.512361 ± 7	-5.4	-2.0	1.08
OUA-21	Stanley	tf (h)	340	6.05	30.77	0.1188	0.512377 ± 6	-5.1	-1.7	1.07
Lower Pennsylvanian (Ouachita Mountains)										
OUA-7	Jackfork	ss *(q)*	320	1.31	6.65	0.1190	0.512030 ± 7	-11.9	-8.7	1.63
OUA-8*	Jackfork	ss *(l)*	320	4.63	23.94	0.1169	0.512072 ± 8	-11.0	-7.8	1.53
OUA-9*	Jackfork	sh	320	8.64	42.91	0.1218	0.512045 ± 7	-11.6	-8.5	1.65
OUA-12*	Jackfork	sh	320	9.32	49.21	0.1145	0.512023 ± 6	-12.0	-8.7	1.57
OUA-13*	Jackfork	ss *(q)*	320	1.11	5.47	0.1222	0.512027 ±10	-11.9	-8.9	1.69
duplicate				1.14	5.63	0.1230	0.512039 ± 7	-11.6	-8.6	1.69
OUA-22*	Jackfork	ss *(l)*	320	3.45	18.14	0.1151	0.512075 ± 8	-10.9	-7.6	1.49
duplicate				3.34	17.49	0.1156	0.512088 ± 5	-10.7	-7.4	1.48
OUA-23*	Jackfork	sh	320	8.97	46.32	0.1170	0.512034 ± 6	-11.7	-8.5	1.59
OUA-41*	Jackfork	sh	320	9.93	52.48	0.1143	0.512018 ± 7	-12.1	-8.7	1.57
OUA-42*	Jackfork	ss *(l)*	320	3.65	18.98	0.1162	0.512055 ± 5	-11.4	-8.1	1.54
OUA-6	Atoka	ss *(l)*	300	4.08	21.03	0.1172	0.512041 ± 6	-11.7	-8.6	1.58
duplicate				4.14	21.27	0.1178	0.512061 ± 7	-11.3	-8.2	1.56
OUA-10*	Atoka	ss *(q)*	300	1.55	7.91	0.1186	0.512074 ± 6	-11.0	-8.0	1.55
OUA-11*	Atoka	sh	300	12.90	56.53	0.1379	0.512134 ± 6	-9.8	-7.6	1.82
duplicate				13.73	59.86	0.1384	0.512121 ± 7	-10.1	-7.9	1.86
OUA-47*	Atoka	sh	300	10.14	54.49	0.1124	0.512008 ± 5	-12.3	-9.1	1.56
OUA-48*	Atoka	ss *(l)*	300	3.66	19.08	0.1160	0.512048 ± 6	-11.5	-8.4	1.55
Lower Pennsylvanian (Arkansas Valley/Arkoma Basin)										
NEA-1	Hale	ss *(l)*	320	5.12	23.87	0.1298	0.512109 ± 7	-10.3	-7.6	1.69
NEA-2	Bloyd	sh	320	9.09	48.12	0.1142	0.511994 ± 6	-12.6	-9.2	1.60
OUA-2	Atoka	sh	300	8.84	45.54	0.1173	0.511954 ± 10	-13.3	-10.3	1.72
duplicate				8.72	45.04	0.1170	0.511967 ± 8	-13.1	-10.0	1.69
OUA-4*	Atoka	sh	300	5.36	28.84	0.1123	0.511980 ± 8	-12.8	-9.6	1.60
OUA-5*	Atoka	ss *(l)*	300	3.75	18.47	0.1227	0.512024 ± 6	-12.0	-9.2	1.70
OUA-32*	Atoka	ss *(l)*	300	4.27	22.46	0.1149	0.512002 ± 6	-12.4	-8.6	1.60
OUA-33*	Atoka	sh	300	8.92	46.38	0.1163	0.512009 ± 7	-12.2	-9.2	1.61
OUA-1	Hartshorne	ss *(q)*	300	2.27	12.21	0.1123	0.512152 ± 9	-11.4	-8.2	1.49
OUA-3	McAlester	sh	300	8.11	42.09	0.1165	0.512017 ± 6	-12.1	-9.0	1.60

TABLE 2. *(Continued)*

Sample	Formation	Lith-ology	Age (Ma)	Sm (ppm)	Nd (ppm)	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$ measured	ϵ_{Nd} present	ϵ_{Nd} initial	T_{DM} (Ga)
MARATHON ASSEMBLAGE (West Texas) *Middle Ordovician to Lower Pennsylvanian*										
MAR91-4	Alsate	sh	480	2.10	11.34	0.1123	0.511617 ± 5	-19.9	-14.8	2.14
MAR90-9	Tesnus	sh	340	8.75	45.15	0.1171	0.511907 ± 8	-14.3	-10.8	1.80
MAR90-4	Tesnus	ss *(l)*	340	4.58	23.63	0.1171	0.511877 ± 7	-14.8	-11.4	1.84
duplicate				4.53	23.39	0.1170	0.511902 ± 5	-14.3	-10.9	1.79
MAR90-3	Tesnus	ss *(l)*	340	3.34	17.47	0.1156	0.511957 ± 7	-13.2	-9.7	1.68
MAR90-6	Tesnus	sh	340	10.20	51.57	0.1196	0.511989 ± 8	-12.7	-9.3	1.70
MAR90-5	Tesnus	tf	340	6.25	35.59	0.1062	0.512334 ± 7	-5.9	-2.0	1.01
duplicate				6.14	34.88	0.1064	0.512335 ± 6	-5.9	-2.0	1.01
MAR90-2	Tesnus	sh	340	3.74	24.95	0.0905	0.519930 ± 7	-12.6	-7.9	1.40
MAR90-1	Dimple	sh	320	6.64	35.74	0.1123	0.512022 ± 7	-12.0	-8.6	1.53
MAR90-7	Haymond	sh	300	8.66	44.46	0.1177	0.512045 ± 5	-11.5	-8.5	1.58
MAR90-8	Haymond	ss *(l)*	300	3.18	15.89	0.1209	0.512040 ± 6	-11.6	-8.7	1.65
MAR91-1*	Haymond	ss *(l)*	300	1.94	12.37	0.0951	0.512011 ± 7	-12.2	-8.4	1.33
MAR91-2*	Haymond	sh	300	4.40	26.97	0.0986	0.512019 ± 6	-12.1	-8.3	1.36
MAR91-3	Haymond	sh	300	7.26	38.34	0.1145	0.511988 ± 6	-12.7	-9.5	1.62
OKLAHOMA SHELF *Upper Ordovician to Lower Pennsylvanian*										
SYL-911	Sylvan	sh	445	5.80	32.56	0.1077	0.511975 ± 7	-12.9	-7.9	1.53
KAC-38	Woodford	sh	365	7.12	37.99	0.1133	0.511987 ± 6	-12.7	-8.8	1.60
CAN-14	Caney	sh	330	5.18	26.72	0.1172	0.512073 ± 8	-11.0	-7.7	1.53
SPR-50	Springer	sh	315	7.67	37.25	0.1244	0.512042 ± 9	-11.6	-8.7	1.71
ILLINOIS BASIN (Western Kentucky) *Lower Pennsylvanian*										
RC-4	Caseyville	ss *(q)*	320	2.64	14.53	0.1099	0.512009 ± 6	-12.3	-8.7	1.52
RC-3	Tradewater	sh	300	7.51	40.82	0.1111	0.512018 ± 7	-12.1	-8.8	1.52
BLACK WARRIOR BASIN (Alabama) *Lower Pennsylvanian*										
WB-1	Pottsville	ss *(l)*	300	4.25	22.49	0.1144	0.512111 ± 8	-10.3	-7.1	1.43
WB-2	Pottsville	ss *(q)*	300	1.72	9.33	0.1117	0.512023 ± 7	-12.0	-8.7	1.52
SEVIER-MARTINSBURG BASIN (Eastern Tennessee) *Middle Ordovician to Lower Silurian*										
HOL-1*	Tellico	sh	460	9.21	49.35	0.1127	0.512001 ± 8	-12.4	-7.5	1.57
HOL-2*	Tellico	ss (l)	460	6.30	33.43	0.1139	0.512028 ± 5	-11.9	-7.0	1.55
TH-2	Martinsburg	ss (l)	450	6.30	28.12	0.1355	0.512000 ± 7	-12.4	-8.9	2.03
TH-1	Juniata	ss (l)	445	9.17	41.45	0.1337	0.512095 ± 5	-10.6	-7.0	1.80
TH-5	Clinch	ss (q)	440	3.45	16.40	0.1272	0.512044 ± 7	-11.6	-7.7	1.76

Note: * Denotes turbidite shale/sandstone pair. ss = sandstone (*q* =quartzose; *l* = lithic), sh = shale, tf = tuff (mc = Mud Creek, h = Hatton, bb = Beavers Bend). $^{143}Nd/^{144}Nd$ ratios normalized to $^{146}Nd/^{144}Nd = 0.7219$ (errors in Nd isotopic ratios are two standard errors of the mean on 105 ratios, and reflect in-run precision only). $\epsilon_{Nd} = 10^4[(^{143}Nd/^{144}Nd_{(t)SAMPLE})/(^{143}Nd/^{144}Nd_{(t)CHUR}) - 1]$, using $^{143}Nd/^{144}Nd = 0.512638$ as present day CHUR (bulk earth) value and $^{147}Sm/^{144}Nd_{CHUR} = 0.1966$. $^{147}Sm/^{144}Nd$ ratios generally reproducible to within 0.5%, and initial ϵ_{Nd} to within 0.5 ϵ_{Nd} units. Nd depleted mantle model ages (T_{DM}) calculated using equation of DePaolo (1981).

onic orogeny (Shanmugam and Walker, 1980; Rodgers, 1971). Paleocurrents are consistent with a northwest-prograding submarine fan derived from Taconic highlands to the southeast (Shanmugam and Walker, 1980). West of the Sevier basin, Upper Ordovician (Martinsburg Formation and Juniata Formation) and Lower Silurian (Clinch Sandstone) strata represent a mostly shallow-marine sequence deposited during later stages of the southern Appalachian Taconic foredeep, with dominant sediment sources to the southeast (Walker, 1985). We analyzed a sandstone-shale pair representing mid-fan deposits of the Tellico Formation at Holston Dam (Walker, 1980), and three sandstone samples from the Martinsburg-Juniata-Clinch sequence at Thorn Hill (Walker, 1985). The Martinsburg-Juniata-Clinch samples yield ε_{Nd} values of −8.9, −7.0, and −7.7, respectively, and the two Tellico samples yield ε_{Nd} values of −7.5 and −7.0 (Fig. 7B, Table 2). Nd model ages for the Martinsburg-Juniata-Clinch sequence (1.76 to 2.03 Ga) are high and variable compared to Tellico turbidites (1.55 to 1.57 Ga) and are correlated with Sm/Nd ratios, indicating disturbance of the Sm-Nd isotopic system in the shallow-water facies samples. However, the range of ε_{Nd} values (−7.0 to −8.9; average = −7.6) is identical (within analytical uncertainties) to the ε_{Nd} range for Ouachita Blaylock turbidites (−7.0 to −8.7; average = −7.7), and similar to the range of ε_{Nd} values for the combined Upper Ordovician to Lower Silurian Ouachita Bigfork–Polk Creek–Blaylock sequence (−6.2 to −8.7; average = −7.2). These data are consistent with an Appalachian (Taconic) fold-thrust belt source for Blaylock turbidites, providing a simple explanation for the rapid shift in ε_{Nd} values within the Ouachita assemblage at 450 Ma.

Oklahoma Shelf (Pre-Carboniferous). Upper Ordovician (Sylvan Shale) and Upper Devonian (Woodford Shale) shales (Fig. 7A) deposited on the continental shelf north of the Ouachita trough were also analyzed in order to characterize the source(s) of sediment that may have been dispersed across the craton into the Ouachita region during this time. Nd isotopic signatures for two samples (ε_{Nd} = −7.9 and −8.8; T_{DM} = 1.53 and 1.60 Ga) show the same range as coeval strata in the Ouachita assemblage (Table 2; Fig. 7A). We suggest that Oklahoma shelf sediments were not delivered from across the craton but instead represent detritus washed along, or

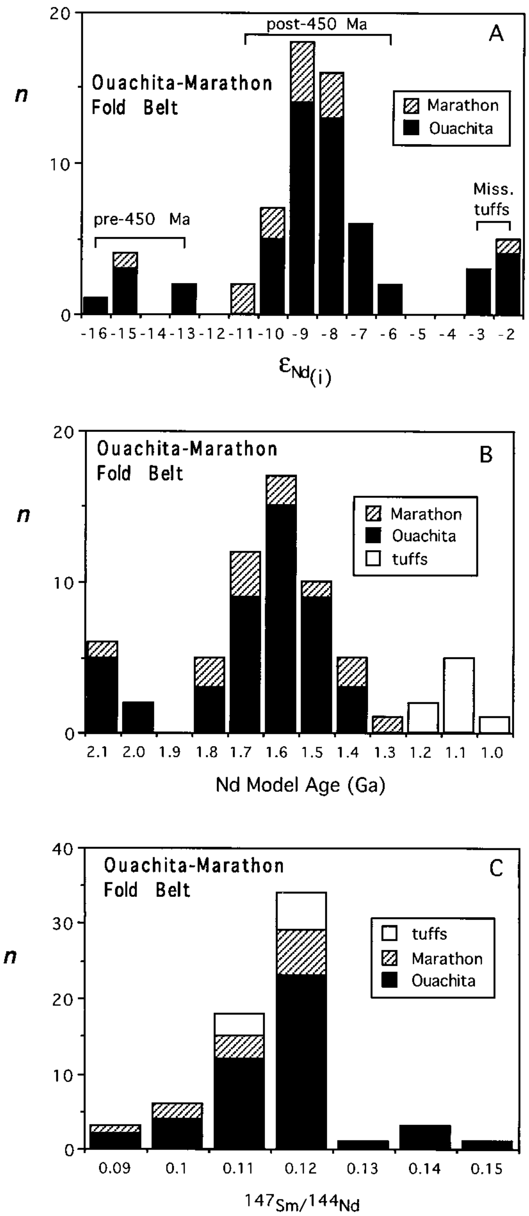

Figure 5. Histograms showing range of (A) initial ε_{Nd} values, (B) Nd model ages (T_{DM}), and (C) $^{147}Sm/^{144}Nd$ ratios for sandstones, shales, and Mississippian tuffs of the Ouachita-Marathon fold belt. Nd model ages do not define distinct groups, probably because of variable Sm/Nd ratios in sediments (see text), but initial ε_{Nd} values resolve three distinct populations in the Ouachita-Marathon assemblage consisting of (1) Mississippian tuffs, (2) pre–450 Ma sediments, and (3) post–450 Ma sediments.

onto, the shelf edge from offshore muds dispersed along the flank of the Ouachita trough.

Part II

Ouachita Assemblage. *Lower to Upper Mississippian.* The Mississippian Stanley Group (Fig. 7A, interval 3) is a dominantly shaly turbidite succession deposited conformably on deep marine cherts and argillites of the Arkansas Novaculite (Morris, 1989). It contains several major ash-flow tuff units near its base that were erupted from south of the Ouachita flysch basin (Niem, 1976, 1977). Paleocurrents in the lower to middle Stanley Group show dominantly north-northwest paleoflow in Arkansas, becoming more westerly toward Oklahoma (Morris, 1974a); upper Stanley paleocurrents show dominantly westerly paleoflow throughout the Ouachita fold belt (Morris, 1974a). The two Stanley graywacke samples we collected are quite poorly sorted, very fine- to fine-grained sandstones composed of subangular to subrounded grains separated by a foliated matrix (16%–17%), derived in large part from the deformation and alteration of framework grains (Table 4). Despite the likelihood that original detrital modes were modified during generation of secondary matrix, the QFL percentages of grain types are similar to those for the more lithic samples of overlying Pennsylvanian flysch (Table 4). Monocrystalline quartz grains (Qm = 64%) are accompanied by only minor feldspar (F = 5%–7%) and volcanic rock fragments (Lv = 2%), but by relatively abundant quartzose and pelitic sedimentary-metasedimentary lithic fragments (Qp = 12%–14%, Lsm = 11%–17%; Qp + Lsm = 25%–29%). As would thus be expected, Nd isotopic values for the Stanley graywackes ($\varepsilon_{Nd} = -7.0$ to -8.1; $n = 2$) and accompanying shales ($\varepsilon_{Nd} = -6.6$ to -9.6; $n = 3$) are distinct from Stanley tuffs ($\varepsilon_{Nd} = -1.7$ to -2.9; $n = 7$). Nd model ages for the tuffs (T_{DM} = 1.04 to 1.18 Ga) are also distinct from Stanley shales and graywackes (T_{DM} = 1.43 to 1.65 Ga). One shale sample (OUA-16) collected from a layer interbedded with tuff has a less negative ε_{Nd} (-6.6) than the other shales ($\varepsilon_{Nd} = -9.1$ to -9.6), suggesting this sample could contain a significant (>50%) component of tuffaceous material. The Stanley graywackes could also mask as much as 25% tuff component based on their Nd isotopic signature, if one assumes simple end-member isotopic mixing between tuffs and shales, both of which have similar Nd concentrations (Table 2). However, their quartzolithic composition (they are feldspar poor, with few volcanic lithic fragments) is not compatible with a significant tuff or related arc-volcanic component, unless the latter has been converted almost entirely to interstitial matrix.

Gleason et al. (1994) and Loomis et al. (1994) concluded that the tuffs were erupted from within a continental margin arc, based on Nd isotopes and trace elements, respectively. The Nd isotopic signature and model ages of the tuffs are best interpreted to reflect mixing between older Precambrian crust and younger mantle-derived material. We prefer this explanation because mixing of mantle and crustal components to produce hybrid isotopic signatures is documented to be a fundamental process in modern continental margin arcs (Hildreth and Moorbath, 1989). By this interpretation, the Carboniferous arc south of the Ouachita trough was constructed on an older continental substrate, possibly a reworked Proterozoic continental fragment.

Paleocurrent and regional facies relations imply that sedimentary sources of Stanley turbidites lay south-southeast of the Ouachita trough (Morris, 1974b, 1989; Niem, 1976). The average ε_{Nd} and T_{DM} for Stanley Group turbidites (-8.1 and 1.54 Ga, respectively) and the quartzolithic composition of Stanley graywackes suggest they had similar sources as Blaylock turbidites. We therefore suggest that Stanley Group turbidite flysch was supplied mainly from subduction complexes uplifted along a growing proto-Ouachita orogen to the south-southeast, but which was composed of sediment of dominantly Appalachian fold-thrust belt provenance. This view is similar to that of Mack et al. (1983), with the exception that the ultimate provenance of sediment thus recycled through subduction

TABLE 3. Rb-Sr ISOTOPIC DATA

Sample	Formation	Lithology	Age (Ma)	Rb (ppm)	Sr (ppm)	$^{87}Rb/^{86}Sr$	$^{87}Sr/^{86}Sr$ measured	$^{87}Sr/^{86}Sr$ initial
OUACHITA ASSEMBLAGE *(Carboniferous)*								
OUA-20	Stanley	sh	340	130	82.6	4.58	0.742569 ± 24	0.72042
OUA-30	Stanley	ss	340	75.2	121	1.80	0.722570 ± 17	0.71387
OUA-31	Stanley	ss	340	71.1	77.5	2.66	0.729512 ± 22	0.71665
duplicate				71.4	77.9	2.65	0.729489 ± 16	0.71664
OUA-15	Stanley	tf	340	104	180	1.68	0.717202 ± 17	0.70906
OUA-21	Stanley	tf	340	157	77.0	5.91	0.735319 ± 16	0.70673
duplicate				152	76.1	5.81	0.735329 ± 12	0.70773
OUA-22*	Jackfork	ss	320	21.8	34.7	1.83	0.723257 ± 17	0.71494
OUA-23*	Jackfork	sh	320	192	94.5	5.89	0.739824 ± 18	0.71300
OUA-41*	Jackfork	sh	320	256	102	7.33	0.748897 ± 12	0.71553
duplicate				251	101	7.23	0.748875 ± 17	0.71596
OUA-42*	Jackfork	ss	320	40.0	35.1	3.30	0.730822 ± 16	0.71579
OUA-6	Atoka	ss	300	22.8	37.3	1.77	0.724862 ± 19	0.71729
OUA-47*	Atoka	sh	300	247	130	5.50	0.741189 ± 16	0.71771
OUA-48*	Atoka	ss	300	36.6	33.6	3.16	0.731103 ± 16	0.71762
MARATHON ASSEMBLAGE *(Carboniferous)*								
MAR90-2	Tesnus	sh	340	139	452	0.89	0.717331 ± 19	0.71302
MAR90-3	Tesnus	ss	340	38.0	74.0	1.51	0.727809 ± 18	0.72050
MAR90-5	Tesnus	tf	340	96.0	105	2.64	0.720591 ± 17	0.70782
MAR90-1	Dimple	sh	320	167	210	2.31	0.721031 ± 16	0.71051
MAR90-7	Haymond	sh	300	198	172	3.34	0.728964 ± 18	0.71472
MAR90-8	Haymond	ss	300	39.5	51.0	2.24	0.728228 ± 18	0.71864
duplicate				38.9	50.9	2.21	0.728149 ± 19	0.71870

Note: $^{87}Sr/^{86}Sr$ ratios normalized to $^{86}Sr/^{86}Sr$ =0.1194 (errors in Sr isotopic ratios are two standard errors of the mean on 75 ratios, and reflect in-run precision only). Initial $^{87}Sr/^{86}Sr$ calculated for stratigraphic ages given. $^{87}Rb/^{86}Rb$ ratios are reproducible to within 1%, and initial $^{86}Sr/^{86}Sr$ to within 0.1%. All symbols and abbreviations are same as in Table 2.

complexes is here proposed to be the Appalachian orogen. Velbel (1985) and Kasper and Larue (1986) have documented the occurrence of modern subduction complexes composed of mainly recycled orogenic quartzolithic sands deposited by large river systems draining continental areas. We propose a similar origin for the provenance of Stanley Group turbidites, which would be consistent with their ultimate derivation from the same Appalachian sources that supplied Ordovician-Silurian Blaylock turbidites.

Lower Pennsylvanian. Pennsylvanian turbidite flysch (Fig. 7A, interval 4) was deposited on the Stanley Group as a complex series of overlapping deep-sea fans built down the basin axis from the east (Morris, 1974a, 1974b; Moiola and Shanmugam, 1984; Link and Roberts, 1986; Coleman et al., 1994). Paleocurrents are generally westerly in turbidites (Morris, 1974a, 1974b) but indicate more complex dispersal routes (Morris, 1974b; Houseknecht et al., 1993) in fluvio-deltaic facies of the Arkoma foreland basin to the north (Fig. 1). Sandstone samples of Pennsylvanian flysch turbidites (Jackfork Group and Atoka Formation) from the Ouachita Mountains (n = 8), as well as overlying deltaic sandstones (Atoka and Hartshorne Formations) from the Arkansas Valley to the north (n = 3), are generally moderately sorted, fine- to medium-grained sandstones composed of subangular to subrounded grains (Table 4). The grain size ranges downward to very fine sand or upward to coarse sand. Interstitial matrix, including both detrital and diagenetic components, varies from <1% up to 8%–12%. The lack of a reciprocal relationship between matrix content and framework percentage of lithic fragments, as well as textural criteria, indicates that little of the matrix was formed by deformation or alteration of detrital sand grains. Both turbidite and deltaic samples include quartzose and

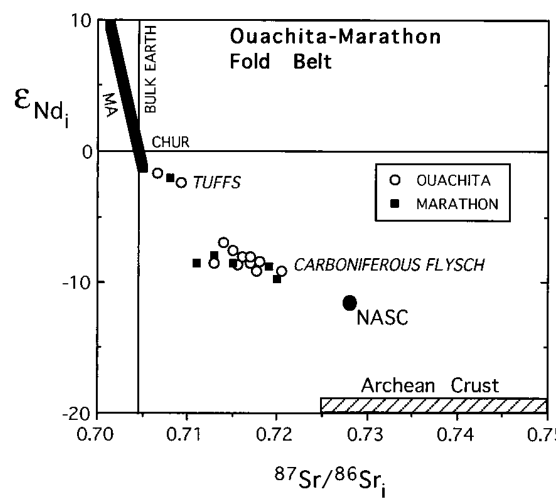

Figure 6. Initial ε_{Nd} vs. $^{87}Sr/^{86}Sr$ for Carboniferous rocks of the Ouachita-Marathon fold belt. Shales and sandstones plot between bulk earth and average Archean crust, consistent with inferred older recycled crustal sources. Mississippian tuffs plot close to bulk earth and may contain a significant juvenile (mantle-derived) component. NASC = North American shale composite (initial ratios calculated for 300 Ma from data of McCulloch and Wasserburg, 1978, using average upper crustal Sm/Nd and Rb/Sr ratios of Taylor and McLennan, 1985). Average Archean crust values are based on Archean Superior Province of McLennan et al. (1990), corrected for 300 Ma using average upper crustal values as above. CHUR = chondritic uniform reservoir (bulk earth); MA = mantle-array for oceanic basalts.

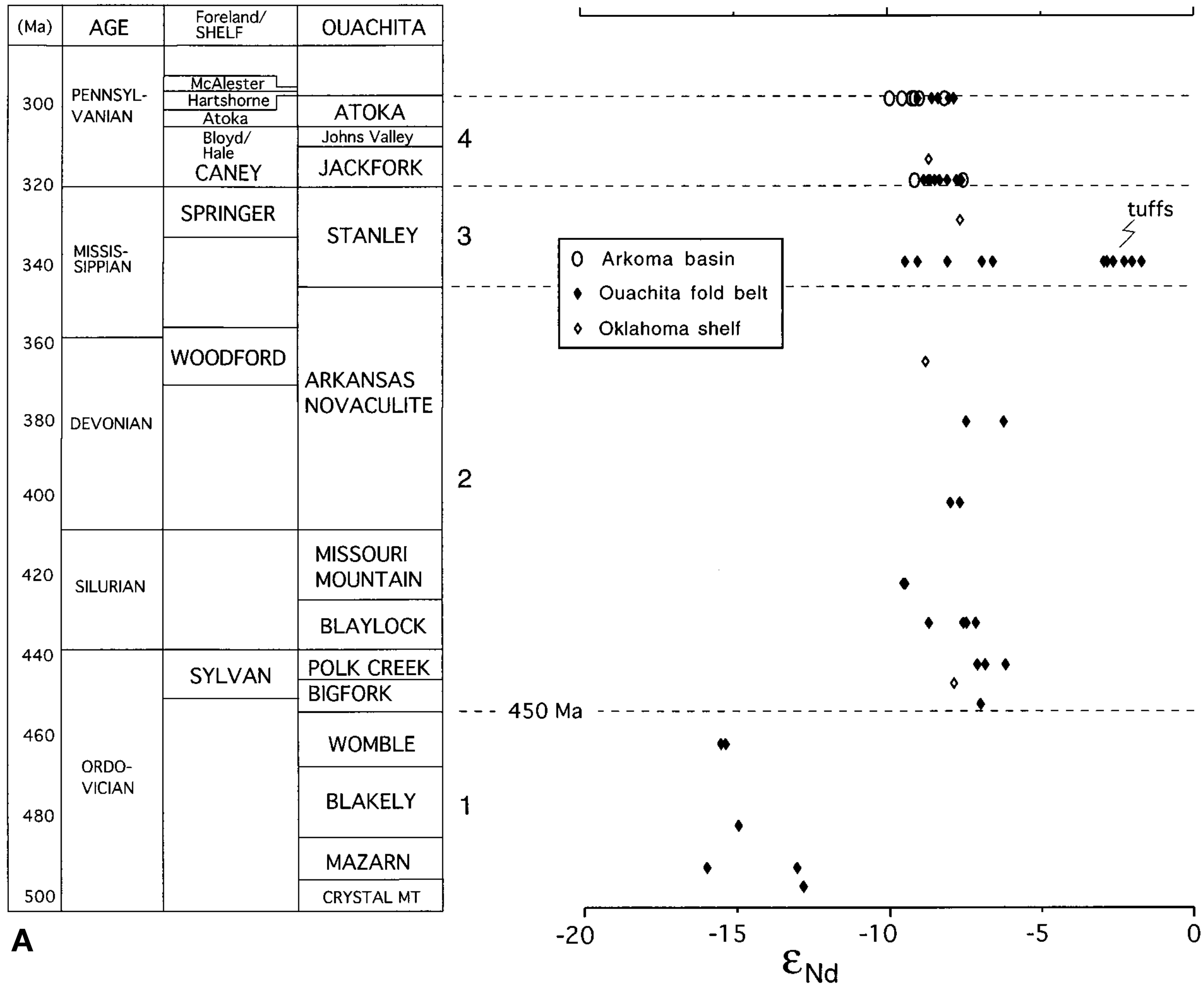

Figure 7. Initial Nd isotopic trends showing (A) Ouachita assemblage (Ouachita fold belt) and related foreland (Arkoma basin) and cratonal (Oklahoma shelf) deposits, (B) Carboniferous deposits of the Illinois and Black Warrior basins and Ordovician-Silurian deposits of the Appalachian Sevier-Martinsburg foredeep, and (C) Marathon assemblage. All data are keyed to stratigraphic ages based on DNAG time scale (Ethington et al., 1989). Numbered stratigraphic intervals for Ouachita assemblage refer to those discussed in text. In A, note shift of eight ε_{Nd} units between Womble and Bigfork Formations and constant post–450 Ma ε_{Nd} trend in Ouachita sedimentary assemblage and related foreland and shelf deposits. Implications for inferred 450 Ma provenance change are discussed in text.

quartzolithic sandstones in which QFL framework percentages of monocrystalline quartz grains (Qm) are 91%–96% (n = 4) and 66%–82% (n = 7), respectively (Table 4). Feldspar grains, with plagioclase and K-feldspar about equally abundant, form consistently <5% of the sand frameworks (most commonly only 1%–2%). Volcanic lithic fragments generally form <1% of the framework. The most common lithic fragments are (a) quartzose fragments (Qp), which include both aggregate quartz grains and chert or metachert grains of finer internal texture, and (b) polycrystalline fragments (Lsm) of pelitic sedimentary and metasedimentary rocks including murky argillite or shale grains, minor polycrystalline micas, and slate or phyllite grains, composed of quartz-mica aggregates and displaying variably developed internal foliation. As might be expected, quartzose lithic fragments dominate the population of lithic grains in the quartzose group of samples, and pelitic fragments, especially the slate-phyllite tectonites, are the dominant lithic grains in most of the quartzolithic samples. Detrital mica flakes are also present in most rocks and form as much as 1%–2% of the framework sand grains.

Graham et al. (1975, 1976) used petrographic and regional facies relations to infer a dominantly Appalachian fold-thrust belt source for Pennsylvanian turbidites, consistent with studies by Morris (1974a, 1974b), Moiola and Shanmugam (1984), and Link and Roberts (1986) demonstrating that a Ouachita Carboniferous (Pennsylvanian) turbidite fan complex was built down the basin axis from sources to the east. However, Mack et al. (1983) interpreted petrographic and subsurface data to indicate a dominantly volcanic arc provenance lying south of the continental margin, which supplied sediments to both the Black Warrior basin (Fig. 1) and Ouachita trough during the Carboniferous (see also Thomas, *in* Hatcher et al., 1989). Finally, other workers have proposed that Ouachita Pennsylvanian turbidites were derived in part from cratonal sources (or from across the craton) via the Illinois basin north of the Ouachita trough. Morris (1974b) reported dominantly southward paleoflow in

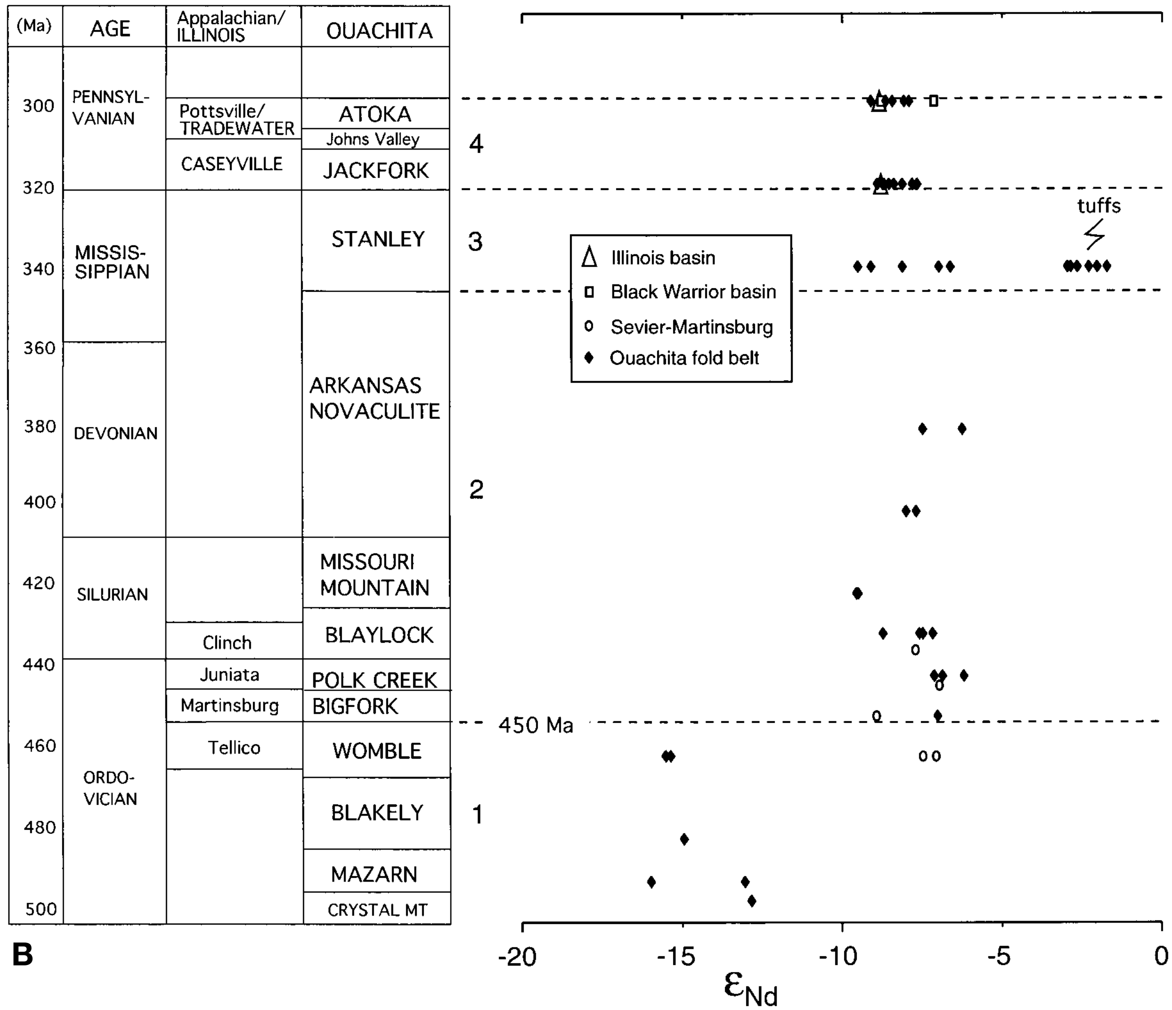

Figure 7B. Note similar ε_{Nd} between Ouachita and Appalachian Ordovician-Silurian deposits, with Carboniferous deposits of Ouachita fold belt and Illinois and Black Warrior basins falling along same isotopic trend (see text).

Pennsylvanian deltaic strata of the Arkoma basin (Fig. 1), suggesting non-Ouachita sources, and Houseknecht (1986) similarly concluded on the basis of petrographic studies that quartzose deltaic sandstones of the Atoka Formation ("Ozark petrofacies") were derived dominantly from northern sources off the Ozark dome and from the Illinois basin to the northeast. However, lithic sandstones ("Arkoma petrofacies") were interpreted to have sources in the Ouachita orogen to the south (Houseknecht, 1986). Subsequent work has demonstrated that the quartzose and lithic sandstones cannot be distinctly categorized by provenance (Houseknecht et al., 1993), and additional paleocurrent data demonstrate much greater complexity in sedimentary transport pathways within the Arkoma basin than originally implied by the work of Morris (1974b). Increasing contributions from Appalachian (via the Illinois basin) and Ouachita sources are, however, inferred from Morrowan through Desmoinesian time (Houseknecht et al., 1993).

Nd isotopic compositions for Pennsylvanian turbidite flysch ($\varepsilon_{Nd} = -7.4$ to -9.1; average $= -8.5$) and deltaic sediments ($\varepsilon_{Nd} = -7.6$ and -10.3; average $= -8.9$) are quite uniform (Table 2, Fig. 7A) and, with one exception (OUA-11), have constant $^{147}Sm/^{144}Nd$ ratios (0.11 to 0.12) and uniform Nd model ages ($T_{DM} = 1.49$ to 1.72 Ga; average = 1.61 Ga). Eight sandstone-shale pairs (including sample OUA-11) have differences of <1 ε_{Nd} unit (four have $\Delta\varepsilon_{Nd} < 0.5$), suggesting that sedimentary sorting had minimal effect on isotopic ratios. Previous work has suggested that the sandstones with higher quartz contents may contain important admixtures of cratonal quartz, in part because the average quartz content of Jackfork turbidites increases toward the north and east (Danielson et al., 1988), but the isotopic data suggest otherwise (see Fig. 8). The most quartzose sandstone samples ($n = 4$) and the most lithic sandstone samples ($n = 7$) display identical average ε_{Nd} values (-11.5 present and -8.4 initial). Variable quartz/lithic ratios probably stem from differences in dispersal history of detritus derived from similar sources. Either weathering or abrasion during transport could reduce the content of unstable lithic fragments in relation to quartz.

Two sandstone samples from the lowermost Pennsylvanian Bloyd and Hale Formations (Fig. 7A) along the south flank of the Ozark Dome (northern Arkoma basin) are particularly important because they represent orogenic detritus transported across the Illinois basin and into the Arkoma foreland basin from the northeast (Sutherland, 1988). ε_{Nd} values (-9.2 and -7.6) and Nd model ages (1.60 and 1.69 Ga) for these samples (Table 2) fall within the range

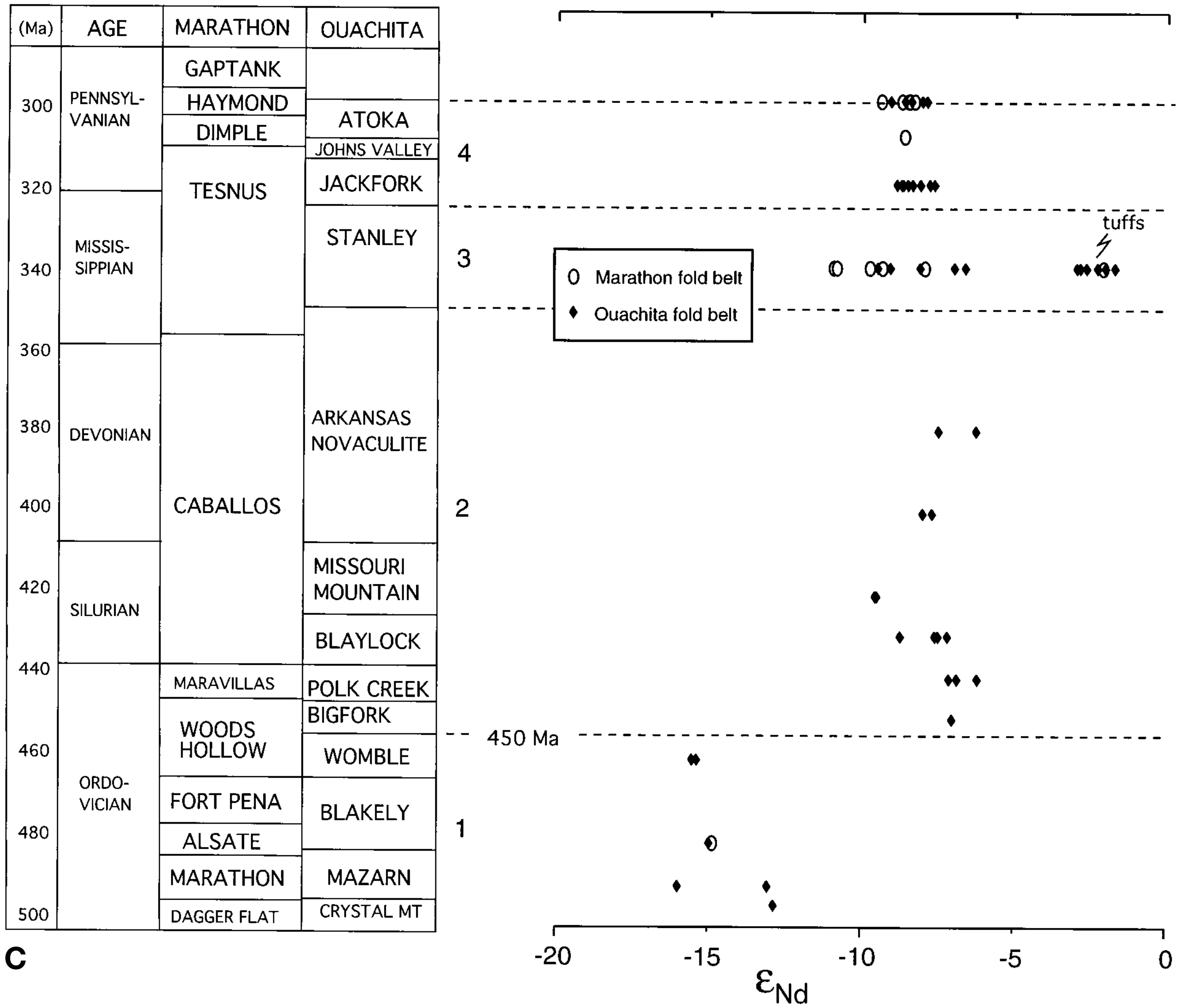

Figure 7C. Note similar isotopic trends in Marathon assemblage: The three isotopic populations (pre–450 Ma strata, post–450 Ma strata, and Mississippian tuffs) are the same as those identified in the Ouachita assemblage (see text).

of values for the combined Ouachita flysch-deltaic sedimentary assemblage (Fig. 7A), consistent with other provenance information suggesting that Appalachian-derived sediments were transported across the Illinois basin into the Ouachita region during this time (Pryor and Sable, 1974; Sutherland, 1988; Houseknecht et al., 1993). Our data thus imply that the Appalachian fold-thrust belt, which apparently supplied isotopically well-mixed detritus across the craton into the northern Arkoma basin, also supplied isotopically similar detritus to the Ouachita trough and Arkoma basin from sources to the east. If that is correct, then Pennsylvanian deltaic strata from the Illinois and Black Warrior basins should be isotopically similar, an implication that we test below.

Illinois Basin. Lower Pennsylvanian fluvio-deltaic strata of the Caseyville Sandstone and the Tradewater Formation from the eastern Illinois basin (Fig. 7B) were deposited in a series of prograding deltas that drained dominantly northern Appalachian sources, with possibly some sediment being derived from the southeastern Canadian Shield as well (Pryor and Sable, 1974). The dominant direction of sediment transport into and across the Illinois basin during Pennsylvanian time was to the west-southwest (Potter and Pryor, 1961). Rivers that drained through the Illinois basin probably connected with dispersal systems in the Arkoma basin of the Ouachita foreland to the southwest (Sutherland, 1988). Documenting the Nd isotopic composition of Pennsylvanian strata from the Illinois basin is thus important for establishing whether a midcontinental link between Appalachian and Ouachita dispersal systems existed during the Carboniferous (Sutherland, 1988; Houseknecht et al., 1993; Dickinson, 1988). Samples of Caseyville Sandstone and Tradewater Shale yield ε_{Nd} values of -8.8 and -8.7, respectively, and Nd model ages of 1.52 Ga each (Table 2). The ε_{Nd} values are identical to the average value for the Ouachita turbidite-deltaic assemblage, consistent with proposed links between the Illinois and Arkoma basins during Early Pennsylvanian time (Pryor and Sable, 1974).

Black Warrior Basin. The Black Warrior basin lies at the southern end of the Appalachian Carboniferous foreland basin (Fig. 1) and may have been a primary conduit for delivery of sediments from the Appalachian region into the Ouachita trough during Pennsylvanian time (Graham et al., 1975, 1976; Dickinson, 1988). Paleocurrent indicators measured by Schlee (1963) show dominantly west-to-southwest sediment transport throughout the Pennsylvanian

Pottsville Formation in Alabama. We sampled fluvio-deltaic strata of the Lower Pennsylvanian Pottsville Formation, consisting of marginal-marine lagoonal and barrier-island quartzose sandstone and shale in the lower part, and overbank shale, coal, and lithic channel sandstone, representing a channelized deltaic complex, in the upper part (Rheams and Benson, 1986; Thomas, 1988). One of our Pottsville sandstones (Boyles Sandstone Member, basal Pottsville) is similar to the quartzose variants of the Ouachita flysch suite, but the other sample has a quartzolithic framework more lithic than any of the flysch samples (Table 4). Various types of lithic fragments are present, however, in comparable proportions. Quartzose (Qp) and sedimentary-metasedimentary (Lsm) lithic fragments are approximately equal in abundance, but together are approximately an order of magnitude more abundant than volcanic lithic fragments. The similarity of populations of lithic fragments in Pennsylvanian sandstones from the Ouachita Mountains and the Black Warrior basin was documented previously by Graham et al. (1976).

The lithic and quartzose sandstones yield ε_{Nd} of -7.1 and -8.7, respectively (Fig. 7B), and Nd model ages of 1.43 Ga and 1.52 Ga. There is thus a suggestion, based on just two samples, that, unlike the Ouachita flysch, lithic and quartzose sands of the Black Warrior basin are isotopically slightly different. The lithic-rich Pottsville sample (WB-1) is texturally and isotopically more similar to one of the Mississippian (Stanley Group) graywackes we sampled (OUA-30) than the Pennsylvanian turbidites from the Ouachita Mountains, which may suggest that the most poorly sorted sandstones also represent more poorly isotopically mixed sediment than the mature sandstones (presumably a larger data set for lithic-rich sandstones would reveal an average isotopic composition the same as quartzose sands in the Black Warrior basin). These ε_{Nd} values fall within the same range of values as Ouachita Carboniferous flysch (Fig. 7B), reinforcing petrographic evidence for similar provenance of Black Warrior and Ouachita sandstones (Graham et al., 1976). The isotopic data are also consistent with recent studies that document an Appalachian provenance for upper Pottsville sediments in the Black Warrior basin (Liu and Gastaldo, 1992; Pashin et al., 1990). We note that the quartzose Pottsville sample (WB-2) is identical in Nd isotopic composition to the quartzose Caseyville Sandstone of the same age from the Illinois Basin, consistent with Appalachian fold-thrust belt sources supplying detritus both across the craton and along the continental margin to the Ouachita region by Pennsylvanian time.

Oklahoma Shelf (Carboniferous). We also analyzed Carboniferous shales deposited on the continental shelf north of the Ouachita trough in order to further characterize the source(s) of sediment that may have been dispersed across the craton into the Ouachita region. Nd isotopic data for the Caney (Upper Mississippian) and Springer (Lower Pennsylvanian) shales ($\varepsilon_{Nd} = -7.7$ and -8.7; $T_{DM} = 1.53$ and 1.71 Ga) are close to the average values for Ouachita Mississippian (-8.1; 1.53 Ga) and Pennsylvanian (-8.7; 1.68 Ga) samples, respectively (Table 2, Fig. 7A), and similar to values for Carboniferous strata of the Illinois basin (Fig. 7B). These samples are also isotopically similar to the Ordovician and Devonian Oklahoma shelf samples (Fig. 7A), suggesting that sediment sources supplying the Ouachita trough and continental shelf were the same from Middle Ordovician time onward, but may have included a component dispersed across the craton from these same sources during Carboniferous time, as well.

Part III

Marathon Assemblage. *Lower to Middle Ordovician.* Pre-Carboniferous strata of the Marathon sedimentary assemblage (see stratigraphic column in Fig. 7C) consist of dominantly deep-sea chert and shelf-derived carbonate with minor shale and turbidites. Sources of turbidites and associated olistoliths were probably the North American shelf and craton (McBride, 1989). The only sample collected from this interval, the Lower Ordovician Alsate Shale (Fig. 7C), is roughly coeval with Mazarn Shale and Blakely Sandstone of the Ouachita assemblage (Fig. 7C) and yields a similar ε_{Nd} value (-14.8; $T_{DM} = 2.14$ Ga). This is consistent with dominantly cratonal sources inferred from other provenance indicators for this interval and suggests that similar sources supplied detritus along the length of the Ouachita-Marathon rifted margin during this time.

Carboniferous. Marathon Carboniferous flysch (Tesnus, Dimple, and Haymond Formations) has an estimated total thickness of 4 to 5 km (McBride, 1989) and is approximately coeval with Ouachita Carboniferous flysch. The Mississippian (to Lower Pennsylvanian?) Tesnus Formation conformably overlies the Devonian Caballos Novaculite (Fig. 7C), thickening from a thin shale unit (~100 m) in the northeast part of the Marathon basin to nearly 2000 m of alternating shale and sandstone turbidite beds in the southeast (King, 1980; McBride, 1989). Tesnus paleocurrents show consistent northwesterly paleoflow toward the continental margin, in the direction of inferred submarine fan progradation (McBride, 1970; Ross, 1986). Sources are inferred to have been an island (?) arc southeast of the Marathon basin, based mainly on direction of sediment transport, the presence of tuff beds in the Tesnus Formation (Imoto and McBride, 1990), and the occurrence of igneous clasts within overlying Pennsylvanian strata (see below), which have Devonian ages inconsistent with proximal North American sources (Denison et al., 1969; McBride, 1989). Pennsylvanian (Morrowan to Atokan) carbonate turbidites of the Dimple Formation (Fig. 7C) were derived from sources northwest of the present Marathon basin along the North American shelf (McBride, 1989). The basinal facies we sampled reaches at least 275 m in thickness but grades northwestward to shelf facies only 100 m thick (Thomson and Thomasson, 1969). The Haymond Formation (Atokan/Desmoinesian) is composed of turbidites (King, 1980; McBride, 1989) shallowing upward into fan-delta facies (Flores, 1972). Haymond turbidites display sedimentological features characteristic of foredelta submarine-ramp deposits (Heller and Dickinson, 1985). The Haymond Formation reaches a total composite thickness of perhaps 1500 m and displays both transverse (northwesterly) and longitudinal (southwesterly) paleocurrent indicators (McBride, 1970). It also contains a mega-conglomeratic unit with large (>10 m) clasts derived from the lower part of the Marathon sequence, as well as exotic Cambrian carbonate blocks, and metamorphic and igneous cobbles, some of which have yielded Devonian (400 Ma) Rb-Sr isotopic ages (Palmer et al., 1984; Denison et al., 1969).

Although our Tesnus and Haymond turbidite samples ($n = 3$) are very fine- to fine-grained sandstones, whereas the one sample of Haymond deltaic sandstone is fine to medium grained with less interstitial matrix, all four samples are moderately sorted quartzolithic sandstones composed of subangular to subrounded grains (Table 4). Their framework percentage of feldspar (5%–11%) is generally higher than for correlative strata in the Ouachita Mountains (1%–7%), but in all other respects, the compositions of Carboniferous sandstone samples from the Marathon region are similar to

TABLE 4. MODAL COMPOSITIONS OF SANDSTONES

	Ouachita Mountains-Arkansas Valley (Carboniferous)												
Grain Types	OUA-13 Jack.	OUA-7 Jack.	OUA-1 Hart.	OUA-10 Atoka	OUA-5 Atoka	OUA-42 Jack.	OUA-32 Atoka	OUA-48 Atoka	OUA-22 Jack.	OUA-6 Atoka	OUA-8 Jack.	OUA-30 Stan.	OUA-31 Stan.
Monocrystalline quartz (Qm)	96	95	92	91	82	76	76	75	74	73	66	64	64
Feldspar mineral grains (F)	tr	tr	1	1	2	3	1	1	2	3	5	5	7
Quartzose lithic fragments (Qp)													
aggregate quartz/quartzite	2	3	2	3	3	6	7	7	14	5	13	9	12
chert or metachert	2	2	tr	2	tr	1	1	2	1	1	1	3	4
(total Qp)	(4)	(5)	(2)	(5)	(3)	(7)	(8)	(9)	(15)	(6)	(14)	(12)	(14)
Volcanic lithic fragments (Lv)	0	0	tr	tr	tr	tr	tr	tr	1	1	3	2	2
Sedimentary/metasedimentary Lithic fragments (Lsm)													
quartz-mica aggregates (slate-phyllite grains)	0	0	4	2	10	11	12	13	6	12	7	14	10
polycrystalline mica (slate-phyllite grains)	0	0	1	tr	2	2	3	2	1	2	1	2	1
shale-argillite grains	tr	tr	tr	1	1	1	0	tr	1	3	4	1	0
(total Lsm)	(tr)	(tr)	(5)	(3)	(13)	(14)	(15)	(15)	(8)	(17)	(12)	(17)	(11)
Q-F-L Composition (Sum)	100-0-0	100-0-0	94-1-5	96-1-3	85-2-13	83-3-14	84-1-15	84-1-15	89-2-9	79-3-18	80-5-15	76-5-19	80-7-13
Qm-F-Lt Composition (Sum)	96-0-4	95-0-5	92-1-7	91-1-8	82-2-16	76-3-21	76-1-23	75-1-24	74-2-24	73-3-24	66-5-29	64-5-31	64-7-29
Mica flakes (% framework)	0	0	1	0	1	2	1	2	2	1	2	2	3
Interstitial matrix (% wr)	0	1	0	8	0	6	1	8	4	12	8	16	17
Calcite cement (% wr)	0	0	0	0	0	0	0	0	0	0	0	0	0

counterparts in the Ouachita Mountains (Fig. 9). The larger component of igneous detritus presumably indicated by the enhanced feldspar content is not reflected by Nd isotopic ratios, which are generally comparable for the two sets of rocks (Figs. 7C and 8). Eleven samples of the Marathon Carboniferous sedimentary assemblage yield initial ε_{Nd} between −7.9 and −11.4 (average = −9.2), similar to the Ouachita Carboniferous assemblage (−6.6 to −10.0; average = −8.5), but shifted by 1.3 ε_{Nd} units toward more negative ε_{Nd} values (Fig. 7C). Nd model ages (1.33 to 1.84 Ga) are somewhat more variable than in the Ouachita Carboniferous assemblage (1.43–1.82 Ga) but average the same (1.60 Ga). Fine- and coarse-grained components from two Haymond Formation sandstone-shale pairs (one turbidite-flysch, the other shallow deltaic) yield identical ε_{Nd} values (Table 2), implying minimal sedimentary sorting effects on isotopic composition. One sample from a tuff horizon (Imoto and McBride, 1990) within the Tesnus Formation (MAR90-5) yields ε_{Nd} of −2 (T_{DM} = 1.01 Ga), the same as Mississippian tuffs in the Ouachita Stanley Group (Table 2, Fig. 7C). One shale sample interbedded in carbonate turbidites of the Dimple Formation has an ε_{Nd} of −8.6 (T_{DM} = 1.53 Ga), similar to upper Tesnus and Haymond turbidites. It is likely, based on these data, that shales in the Dimple Formation represent a continuation of Tesnus depositional systems, which delivered sediment from the southeast, although a somewhat different provenance for Dimple shales is indicated by the Pb isotopic data of Cameron et al. (1992). Regardless, ε_{Nd} values for Marathon Carboniferous flysch from our study match closely those for Tesnus, Dimple, and Haymond shales (−8.8 to −10.1; average = −9.6) analyzed by Cameron et al. (1992) and indicate that Marathon Carboniferous flysch is broadly homogeneous with respect to Nd isotopes. There is an increase in ε_{Nd} upsection within the Tesnus Formation, from ε_{Nd} values of −11 near the base to −8 toward the top (Table 2); also, ε_{Nd} values of overlying Haymond turbidites (ε_{Nd} = −8.5 to −9.5; average = −8.7) are less negative compared to Tesnus turbidites (average ε_{Nd} = −9.8), suggesting a possibly significant increase in ε_{Nd} values upward within the Marathon Carboniferous flysch.

The average ε_{Nd} (−9.2) of Marathon Carboniferous flysch is only ~0.5 ε_{Nd} units different from the Ouachita Carboniferous flysch (−8.6), suggesting the same ultimate provenance; however, we prefer not to view the Marathon flysch as simply distal deposits of Ouachita turbidite fans, as that would be inconsistent with paleocur-

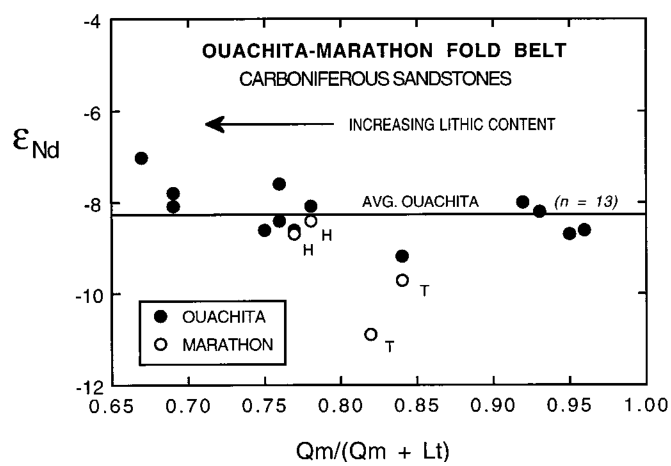

Figure 8. Initial ε_{Nd} vs. percentage of lithic content (Qm/[Qm + Lt]) for Carboniferous sandstones of the Ouachita-Marathon fold belt. There is no isotopic difference between lithic and quartzose sandstones for the Ouachita assemblage, implying no difference in provenance for these two distinct petrographic groups as some have suggested (see text). Marathon Tesnus sandstone falls off main Ouachita trend, possibly indicating a more complex provenance (see text). T = Tesnus; H = Haymond; *N* = total number of samples.

TABLE 4. *(Continued)*

	Arkoma		*Marathon*				*Ouachita (pre-Carboniferous)*				*Black Warrior*	
Grain Types	NEA-1 Hale	NEA-3 Bloyd	MAR90-3 Tes.	MAR90-4 Tes.	MAR90-8 Hay.	MAR91-1 Hay.	OUA-25 Cryst.	OUA-28 Blak.	OUA-17 Blay.	OUA-36 Blay.	WB-1 Potts.	WB-2 Potts.
Monocrystalline quartz (Qm)	80	84	75	75	70	74	97	100	89	85	52	91
Feldspar mineral grains (F)	3	2	11	8	9	5	2	tr	2	4	5	tr
Quartzose lithic fragments (Qp)												
aggregate quartz/quartzite	9	5	6	9	5	4	tr	tr	3	4	18	5
chert or metachert	2	1	1	1	2	3	tr	tr	tr	1	3	tr
(total Qp)	(11)	(6)	(7)	(10)	(7)	(7)	(tr)	(tr)	(3)	(5)	(21)	(5)
Volcanic lithic fragments (Lv)	tr	1	1	1	1	2	0	0	tr	tr	3	0
Sedimentary/metasedimentary Lithic fragments (Lsm)												
quartz-mica aggregates (slate-phyllite grains)	2	4	3	4	7	7	0	0	5	5	16	3
polycrystalline mica (slate-phyllite grains)	2	1	1	0	2	1	0	0	1	1	3	tr
shale-argillite grains	2	2	2	2	4	4	1	tr	tr	tr	tr	1
(total Lsm)	(6)	(7)	(6)	(6)	(13)	(12)	(1)	(tr)	(6)	(6)	(19)	(4)
Q-F-L Composition (Sum)	91-3-6	90-2-8	82-11-7	85-8-7	77-9-14	81-5-14	97-2-1	100-0-0	92-2-6	90-4-6	73-5-22	96-0-4
Qm-F-Lt Composition (Sum)	80-3-17	84-2-14	75-11-14	75-8-17	70-9-21	74-5-21	97-2-1	100-0-0	89-2-9	85-4-11	52-5-43	91-0-9
Mica flakes (% framework)	4	1	1	tr	2	tr	0	0	1	2	2	tr
Interstitial matrix (% wr)	1	5	5	10	7	2	0	0	12	12	3	2
Calcite cement (% wr)	5	0	1	2	0	0	0	0	0	0	0	0

Note: All reported modal compositions of sandstones are based on point counts of 400 grains in the QFL (quartz-feldspar-lithic) population, with variable numbers of additional points counted where detrital mica flakes, interstitial matrix, or diagenetic cement is present. Lithic grain types were classified as described by Graham et al. (1976). Qm = monocrystalline quartz; Qp = poly-crystalline quartz; F = feldspar; L = lithic fragments (Lv + Lsm); Lv = lithic volcanic fragments; Lsm = lithic sedimentary or meta-sedimentary fragments; Lt = total lithic fragments (Lsm + Lv + Qp); Q = total quartz (Qm + Qp). Jack. = Jackfork; Hart. = Hartshorne; Stan. = Stanley; Tes. = Tesnus; Hay. = Haymond; Cryst. = Crystal Mountain; Blak. = Blakely; Blay. = Blaylock; Potts. = Pottsville. Localities for Jackfork Sandstone are: OUA-7, OUA-8 = Rich Mountain, OK, and OUA-13 = Kiamichi Mountain, OK (all northern belt); OUA-22 = Dierks Lake, AR, and OUA-42 = DeGray Lake, AR (all southern belt).

rents, olistoliths, and the more feldspathic composition of Marathon turbidites. The prevalence of microcline and unzoned plagioclase in the Marathon flysch may imply the significant role of an uplifted basement source not recognized in Ouachita flysch, perhaps the same source that supplied Devonian-age plutonic and metamorphic clasts to the Marathon basin during Pennsylvanian time. Although the origin of these clasts and the enhanced feldspar content of the Marathon flysch remains unresolved, the isotopic data are consistent, for the bulk of the sediment, with sources similar to those proposed for the Ouachita Carboniferous flysch. An uplifted subduction complex along the flanks of an approaching arc system may have supplied Tesnus turbidites with detritus analogous to Ouachita flysch derived from Appalachian fold-thrust belt sources, perhaps augmented by detritus from older recycled sea-floor strata of the Marathon assemblage, which would impart a slightly more negative ε_{Nd} isotopic signature to Tesnus turbidites. Additional plutonic feldspar may have also been supplied from uplifted arc basement sources to the south, which apparently were near enough to supply whole clasts by Pennsylvanian time. We thus envision multiple tectonic recycling of Appalachian-derived detritus along the Ouachita-Marathon suture as it closed from east to west, much as proposed by Graham et al. (1975). Depositional facies and megaclasts within the Haymond Formation reflect shoaling of the Marathon basin and deformation and uplift of Marathon strata along the suture by Haymond time. The slightly more positive ε_{Nd} isotopic signature of Haymond turbidites, in comparison to Tesnus turbidites, presumably reflects the increasing dominance of recycled Appalachian detritus as sea-floor strata were incorporated into the suture belt and eroded to supply the collapsing Marathon depositional basin.

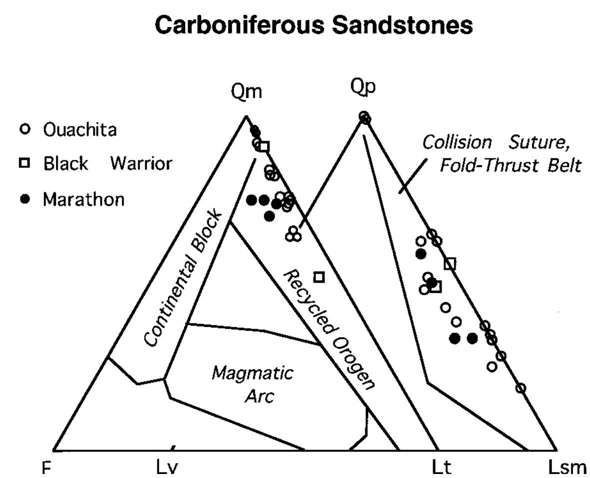

Figure 9. Qm-F-Lt and Qp-Lv-Lsm ternary plots of modal sandstone grain compositions determined from this study for Carboniferous sandstones of the Ouachita-Marathon fold belt and the Black Warrior basin (see Table 4 for explanation of symbols). All samples plot within the QFL recycled orogen field of Dickinson (1985), with lithic proportions indicating dominantly fold-thrust belt sedimentary and metasedimentary sources (provenance associations from Dickinson, 1985). Marathon samples contain a larger feldspar component than Ouachita samples (see text).

TECTONIC AND PALEOGEOGRAPHIC IMPLICATIONS

The widespread dispersal of Appalachian-derived orogenic detritus into a wide variety of sedimentary basins within and adjacent to the North American continent underscores the potential for major collisional orogens to serve as dominant sediment sources over large segments of the globe. The main Carboniferous entry points for flysch sediments of the Ouachita trough are inferred to have been the Black Warrior basin to the east (Graham et al., 1975), the Illinois basin to the northeast (Houseknecht et al., 1993), and a proto-Ouachita subduction complex to the southeast (Mack et al., 1983). The same isotopic patterns revealed in the Marathon sequence 800 km to the southwest of the Ouachita region suggest, in combination with petrographic, paleocurrent, and regional tectonic relations, that Appalachian-derived detritus was transported westward to the Marathon region by a complex multistep process involving tectonic uplift and sedimentary recycling in Carboniferous subduction zones along the Ouachita-Marathon suture. Sm-Nd isotopic data for Mississippian tuffs confirm that the southern plate consisted in part of an older continental fragment or fragments (e.g., Loomis et al., 1994; Gleason et al., 1994) but do not define limits for its identity. Some detritus derived from arc basement is apparently present in Marathon Carboniferous flysch, but volcanic components are virtually absent in Carboniferous flysch of the Ouachita-Marathon fold belt, suggesting that southern sources were primarily subduction complexes composed of recycled sediment derived from the Appalachian orogen.

Turbidite facies, regional tectonics, paleocurrents, sedimentary petrography, and isotopic data all point to the Appalachian fold-thrust belt as the dominant sediment source for the Ouachita sedimentary assemblage after Middle Ordovician time. Two orogenic pulses, the Ordovician Taconic orogeny (ca. 480 to 450 Ma) and the Carboniferous Alleghanian orogeny (ca. 330 to 285 Ma), appear to be directly represented by derivative turbidites in the Ouachita assemblage. No Acadian-age (Devonian) turbidites are present in the Ouachita assemblage, and so the persistence of the post–450 Ma Nd isotopic signature through the Silurian and Devonian cannot be directly tied to Appalachian or any other specific orogenic sources. Detritus supplied by Taconic clastic wedges (Rodgers, 1971) may have blanketed a significant part of the eastern North American craton and been available for recycling along the Ouachita margin, thus maintaining a fundamentally Appalachian isotopic signature through this time period. Nd isotopes, however, cannot distinguish sediments transported in multiple steps from those supplied directly from the source, for example, by large river systems draining the Acadian Appalachian highlands. High sea level during Ordovician time may have contributed to cessation of craton-supplied detritus to the Ouachita margin and the emergence of the Appalachian orogen as the primary sediment source for sea floor lying south of North America. Fine-grained detritus deposited on the Ouachita sea floor and on the Oklahoma shelf during mid-Paleozoic time has the same isotopic signature, and we suggest that longshore drift currents may have also transported mud along the continental margin from Appalachian sources into the Ouachita region, consistent with inferred paleo-wind directions and paleogeographic reconstructions that place the Ouachita margin south of the equator during most of Paleozoic time (Dott and Batten, 1981; Van der Voo, 1988).

Petrographic, trace-element, and Sm-Nd isotopic data confirm that the Ouachita-Marathon sedimentary assemblage is composed dominantly of old recycled continental crust. Post–450 Ma sediments probably are made up of a homogeneous mixture of mainly Proterozoic crustal components recycled through Appalachian fold-thrust belt sources. Our conclusions thus constitute a testable hypothesis, in that Middle Ordovician and younger turbidites from the Appalachian, Ouachita, and Marathon regions should contain detrital zircons from various Proterozoic orogenic belts and magmatic terranes of North America in roughly similar proportions, possibly with some admixture of Archean and Paleozoic arc-derived crustal components as well. Preliminary U-Pb detrital zircon data from Ouachita Carboniferous flysch (Hutson et al., 1993) are consistent with this but do not uniquely define sources because similar crustal age distributions may also have been characteristic of accreting continental fragments south of the Ouachita-Marathon suture (e.g., Yañez et al., 1991; Ruiz et al., 1988). Preliminary Sm-Nd data from Late Proterozoic–Carboniferous shales of the Appalachian fold-thrust belt (Krogstad et al., 1994) show uniform values for Taconic, Acadian, and Alleghanian clastic wedges ($\varepsilon_{Nd} = -6.5$ to -8.5) but more negative values for Cambrian passive margin shales ($\varepsilon_{Nd} = -10$ to -15). These patterns are the same as those observed in the Ouachita-Marathon assemblage; however, Late Proterozoic Appalachian syn-rift shales, though isotopically variable, have average ε_{Nd} values of -4 (Krogstad et al., 1994) at the time of sedimentation (ca. 650 Ma), which, corrected for Nd isotopic evolution, yields an average ε_{Nd} of -6.5 to -8.0 between 450 and 300 Ma. This suggests to us that thick (12–16 km), predominantly Grenville basement–derived Late Proterozoic Appalachian rift deposits (e.g., Rast and Kohles, 1986; Rodgers, 1972) could be the ultimate source of much of the sediment deposited in Appalachian foredeeps during the Taconic, Acadian and Alleghanian orogenies and hence the ultimate source of most post–450 Ma sediment in the Ouachita-Marathon fold belt.

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