GEOLOGICAL NOTES

Nd Isotopes of Atoka Formation (Pennsylvanian) Turbidites Displaying Anomalous East-Flowing Paleocurrents in the Frontal Ouachita Belt of Oklahoma: Implications for Regional Sediment Dispersal

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ABSTRACT

Within the Pennsylvanian Atoka Formation of Oklahoma, strata in the frontal Ouachita belt deposited by east-flowing turbidity currents yield the same ε_{Nd} values as strata in more interior parts of the Ouachita orogen deposited by west-flowing turbidity currents. The congruence of ε_{Nd} values throughout the Atoka Formation is consistent with widespread Paleozoic dispersal and recycling of detritus from the evolving Appalachian orogen across the surface of the Laurentian craton and along its margins. Sandstone in the olistostromal Johns Valley Shale underlying the Atoka Formation yields a similar ε_{Nd} value, reflective of reworking Appalachian-derived sediment from the Paleozoic Oklahoma shelf succession.

Introduction

Previous studies of Nd isotopes in clastic strata of the Ouachita system along the southern margin of Laurentia have shown that the detritus in turbidites emplaced by paleocurrents flowing westward along the floor of the Ouachita trough was derived ultimately from the evolving Appalachian orogen (Gleason et al. 1994, 1995). Note, however, that ultimate Appalachian sources for sediment in the Ouachita flysch does not preclude sediment recycling through sites of temporary storage in positions closer to the depositional basin.

The initial delivery of Appalachian-derived detritus to the Oklahoma segment of the Ouachita trough at ~450 Ma (Late Ordovician) is recorded by an abrupt upward shift in initial ε_{Nd} values ($\Delta\varepsilon_{Nd}$ ~7) for strata exposed within the Ouachita orogen (Gleason et al. 2002).

Past Nd isotope work did not sample Pennsylvanian (Atoka Formation) turbidites of the frontal Ouachita belt (southeast Oklahoma) emplaced by anomalous east-flowing (to northeast-flowing) paleocurrents (Ferguson and Suneson 1988), denoted here as east-flowing for simplicity. As noted by Ferguson and Suneson (1988), the clastic detritus in these strata may have been derived from uplands that formed during the initial phases of transpressive Pennsylvanian deformation (Donovan et al. 1989) in the Arbuckle uplift (southwest Oklahoma) that emerged from the southeastern (oceanward) end of the southern Oklahoma aulacogen (fig. 1). The uplift developed where the Ouachita orogenic belt along the Laurentian continental margin intersects the trend of the aulacogen at a high angle (Perry 1989). A transgressive wedge of Atoka Formation, later deformed by continuing deformation (Ham 1973), onlaps the northeastern flank of the

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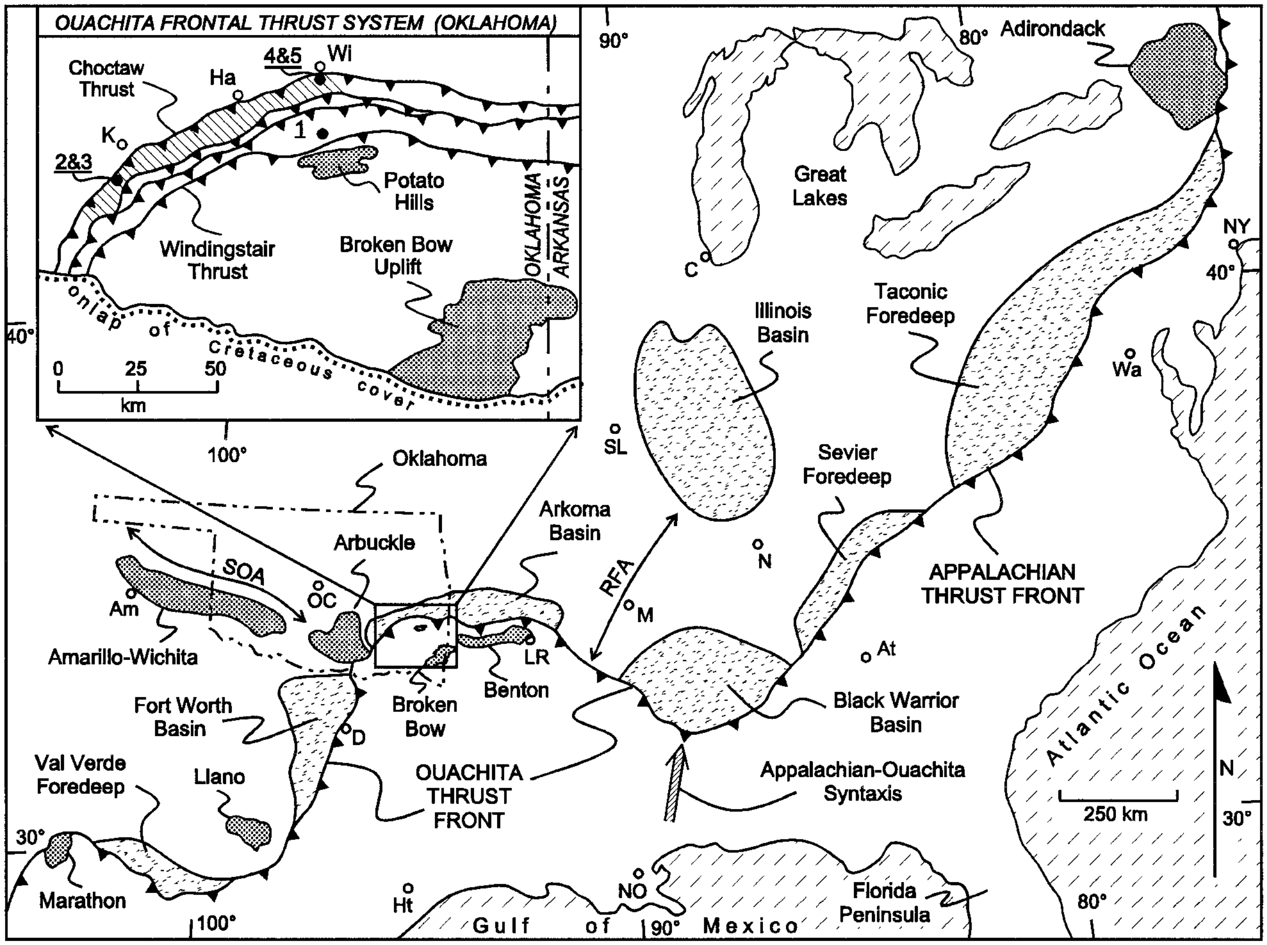

Figure 1. Location of sample sites (*solid circles* in inset) in relation to tectonic features (uplifts *shaded*; basins *stippled*) noted in text and tables. Zone of east-flowing (to northeast-flowing) Atoka paleocurrents ruled. Double-headed arrows denote trends of Early Paleozoic southern Oklahoma (*SOA*) and Reelfoot (*RFA*) aulacogens. Selected cities and towns (*open circles*): *Am* = Amarillo; *At* = Atlanta; *C* = Chicago; *D* = Dallas; *Ha* = Hartshorne; *Ht* = Houston; *K* = Kiowa; *LR* = Little Rock; *M* = Memphis; *N* = Nashville; *NO* = New Orleans; *NY* = New York; *OC* = Oklahoma City; *SL* = St. Louis; *Wa* = Washington; *Wi* = Wilburton.

Arbuckle uplift (Sutherland et al. 1982; Sutherland 1988).

This note discusses Nd isotopic values of Atoka turbidites that display sole marks recording east-flowing paleocurrents to test for a possible contrast in ε_{Nd} values between detritus transported toward the east and toward the west along the Ouachita trough and detritus from the older Johns Valley Shale not sampled during previous work.

Neodymium Isotopes

Neodymium (Nd) is a rare earth element (REE) present in trace amounts in clastic sedimentary rocks (note contents of <50 ppm in table 1). From its relative incompatibility with major rock-forming minerals, Nd in the crust resides principally in accessory minerals such as apatite or in products of weathering. Distinctly higher Nd contents in shales (e.g., 41–42 ppm in table 1) than in sandstones (e.g., 9–15 ppm in table 1) suggest that the main Nd sites in clastic sedimentary rocks are not accessory heavy minerals, but more likely clays within which the Nd is adsorbed.

The ratio $^{143}Nd/^{144}Nd$ (table 1) is controlled by radioactive decay of samarium (^{147}Sm) to neodymium (^{143}Nd). During crustal genesis, Nd is preferentially transferred into the crust relative to Sm, which is preferentially retained in the mantle. As a result, the Sm/Nd isotopic system evolves dif-

Table 1. New Sm-Nd Analytical Data[a] from Atoka Formation and a Sandstone in the Johns Valley Shale (OUA-01-1)

Sample	Lithology	Age (t) Ma	Sm ppm[b]	Nd ppm[b]	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$[c]	ε_{Nd} (t)[d]
OUA-01-1	Sandstone	310	3.67	15.18	.1463	.512044 ± 8	−9.60
OUA-01-2[e]	Sandstone	300	1.85	9.34	.1198	.512053 ± 7	−8.47
OUA-01-3[e]	Shale	300	7.48	40.53	.1116	.512006 ± 7	−9.07
OUA-01-4[e]	Sandstone	300	3.16	14.60	.1308	.512045 ± 7	−9.04
OUA-01-4[e,f]	Sandstone	300	3.16	14.60	.1307	.512045 ± 9	−9.04
OUA-01-5[e]	Shale	300	8.03	42.28	.1147	.512024 ± 6	−8.84

[a] Relative to average $^{143}Nd/^{144}Nd$ value of 0.511870 ± 7 for 14 analyses of La Jolla Nd isotopic standard using analytical methods described by Gleason et al. (1995, 2002).
[b] Two-sigma error <0.5%.
[c] Two standard errors of the mean from in-run statistics.
[d] Initial ε_{Nd} calculated for depositional age (t = 300 Ma).
[e] Samples OUA-01-2/OUA-01-3 and OUA-01-4/OUA-01-5 are sandstone/shale pairs from the same or closely spaced outcrops (app. A).
[f] Nd run only was duplicated.

ferently in crust and mantle along contrasting trends of ε_{Nd}, an expression comparing Nd isotopic ratios that is defined as 0 for the bulk earth as a whole. As crustal components were extracted from the mantle over time, the ε_{Nd} of residual Nd-depleted mantle evolved from 0 to a present value of +10 (fig. 2). Crustal materials derived from the progressively depleted mantle reservoir over time had intermediate values of 0 to +10 at the various times of crustal genesis.

During crustal residence of Sm and Nd, ε_{Nd} evolves to progressively more negative values over time, but projection of crustal evolution curves back to the mantle evolution curve provides a measure of the mean age of the crustal materials (fig. 2). Characteristic low mobility of REEs during metamorphism and diagenesis (Taylor and McLennan 1985) tends to preserve an Nd isotopic signature of ultimate provenance age through multiple cycles of weathering and erosion (neither of which alters Nd isotope ratios). Initial ε_{Nd} values [$\varepsilon_{Nd}(t)$ of table 1] can be calculated for times of sediment deposition from currently measured ε_{Nd} values and a knowledge of the present-day $^{147}Sm/^{144}Nd$ ratios (table 1) in the sedimentary rocks. Comparison of the Nd isotopic signatures of sediments deposited at different times can be achieved by calculating $\varepsilon_{Nd}(t)$ values for a common time in the past (table 2). In general, more negative values of ε_{Nd} are indicative of detritus derived from crust of older age.

Atoka Formation

To confirm analytical results with data from more than a single site, we sampled Atoka turbidite successions displaying indicators of east-flowing paleocurrents in two areas (see app. A, which is available from the *Journal of Geology* Data Depository free of charge upon request). To test for compatibility of ε_{Nd} values for interbedded sandstone and shale, and to control for diagenetic effects that might affect Nd isotopic signatures (Gleason et al. 1995), we collected closely associated sandstone and shale (sandstone/shale pair) from each locale (table 1). The overall congruence of ε_{Nd} values for the two sandstone-shale pairs implies derivation of both sandstone and shale from the same provenance and no diagenetic disturbance of the Nd isotopic system.

Table 2 shows that initial ε_{Nd} values from the Atoka Formation are statistically indistinguishable for deltaic strata in the Arkoma foreland basin north of the Ouachita overthrust system (table 2, A), turbidites deposited by east-flowing paleocurrents in the frontal Choctaw thrust sheet (fig. 1, inset) of the thrust belt (table 2, B), and turbidites deposited by west-flowing paleocurrents in higher thrust sheets farther south (table 2, C). As the Atoka Formation oversteps buried fault scarps facing south along syndepositional down-to-the-basin normal faults of the Ouachita foreland (Houseknecht 1986), our turbidite samples from the frontal Choctaw thrust sheet may be somewhat younger than those reported by Gleason et al. (1994, 1995) from more interior thrust sheets. The turbidites that display indicators of east-flowing paleocurrents were probably deposited within an elongate structural basin, delineated by strands of the normal fault system and perched as a paleotopographic furrow flanking but parallel to the main Ouachita trough to the south (Ferguson and Suneson 1988).

Comparable ε_{Nd} values are observed in somewhat older Pennsylvanian turbidites underlying the Atoka Formation within the overthrust Ouachita system (table 2, D) and in Carboniferous flysch of the Marathon uplift (fig. 1) within the Ouachita

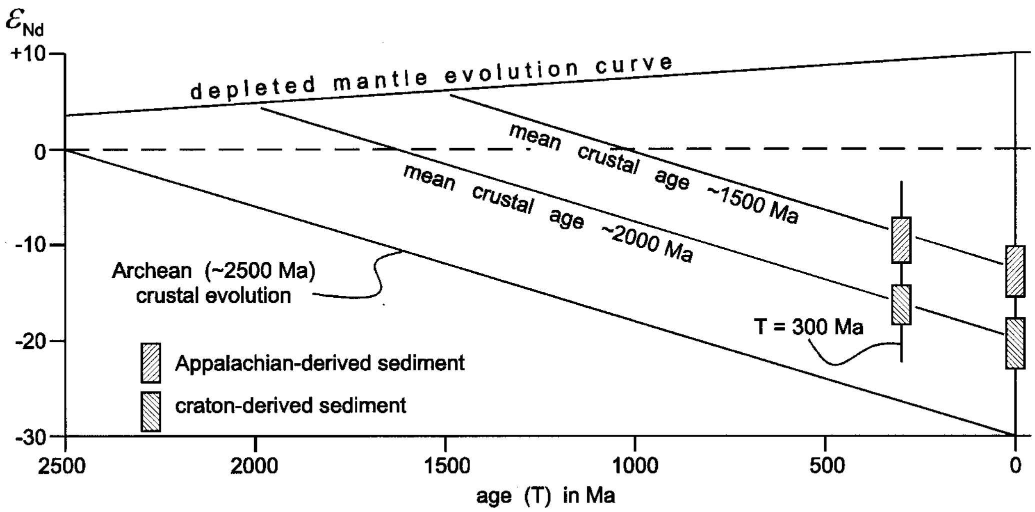

Figure 2. Evolution of ε_{Nd} values for mantle and crust. Ruled bars (see legend) at 0 Ma show ranges of observed ε_{Nd} values measured in Ouachita and comparative samples from this (table 1) and previous (table 2) work, while ruled bars along line marking $t = 300$ Ma show ranges of initial ε_{Nd} values (tables 1 and 2). Intersection of each crustal evolution curve with depleted mantle evolution curve indicates implied mean age of ultimate crustal provenance for the clastic sediment.

system ~1000 km along the tectonic strike to the southwest (table 2, E). The consistent range of ε_{Nd} values for Carboniferous flysch and molasse throughout the Ouachita system implies derivation of well-mixed sediment from a common ultimate provenance despite varied dispersal paths and probable sediment recycling along multiple transport routes (Gleason et al. 1994, 1995). Similar initial ε_{Nd} values, with overlap at one standard deviation, are reported from pre-Pennsylvanian but post-middle Ordovician strata of the Ouachita orogen (table 2, F) and from upper Ordovician to lower Silurian strata of the Taconic and Sevier foredeeps of the Appalachian foreland basin (table 2, H). The similar initial ε_{Nd} values from the Taconic-Sevier foreland (fig. 1) suggest that the evolving Appalachian orogen was the ultimate source of the well-mixed detritus in the Ouachita flysch.

Analysis of Nd-isotope data from Paleozoic sedimentary assemblages around the periphery of Laurentia indicates that the onset of Caledonian-Appalachian orogenesis at ~450 Ma triggered dispersal of voluminous orogenic detritus across the craton and along its margins throughout the remainder of Paleozoic time (Patchett et al. 1999). The effect of the persistent sediment flood is reflected by the same characteristic and statistically indistinguishable ε_{Nd} values from both nonmarine and marine strata (table 2, G) of upper Ordovician through Pennsylvanian age in the Black Warrior basin lying within the Appalachian-Ouachita syntaxis, the Illinois basin of the continental interior, and the Oklahoma shelf north of the Ouachita thrust belt, as well as within the Ouachita system and the Taconic-Sevier foredeeps (fig.1). Pre-upper Ordovician clastic strata of the Ouachita system yield much different initial ε_{Nd} values (table 2, I), ~7 ε_{Nd} units lower, reflective of derivation from the craton to the north (Gleason et al. 1994, 1995).

The contrasting Nd isotopic signatures of craton-derived and Appalachian-derived clastic detritus in the Ouachita system reflect distinct differences in the average crustal ages of source rocks (fig. 2). For the Appalachian detritus, ε_{Nd} reflects dominant sources in crust having an average age indistinguishable from the Grenville province (<1500 Ma), which was deformed together with overlying Grenville-derived sediment cover along the flank of the Appalachian orogen. For the cratonic detritus, reflecting a mean crustal age of ~2000 Ma (fig. 2), ε_{Nd} reflects sources in a mix of pre-Grenville Proterozoic (>1600 Ma) and Archean crust forming the interior of the Laurentian craton. The ability to distinguish between Appalachian-derived and craton-derived detritus is a serendipitous function of the geographic distribution of Precambrian age provinces in North America (Hoffman 1988). No mix of sediment derived ultimately from the pre-Grenville age provinces that jointly form all of the Laurentian craton

Table 2. Comparative Initial ε_{Nd} Values

Sample suites	n[a]	Initial ε_{Nd} (t)[b]	Source(s) of data
A. Atoka Formation and associated strata of Arkoma basin in Ouachita foreland (Arkansas-Oklahoma)	9	−8.9 ± 1.1	Gleason et al. 1995
B. Atoka Formation (easterly flowing paleocurrents) of frontal Ouachita Mountains (Oklahoma)	4	−8.9 ± .3	Table 1
C. Atoka Formation (westerly flowing paleocurrents) of interior Ouachita orogen (Arkansas-Oklahoma)	5	−8.3 ± .5	Gleason et al. 1995
D. Pre-Atoka Pennsylvanian flysch (Jackfork Group) of interior Ouachita orogen (Arkansas-Oklahoma)	9	−8.6 ± .5	Gleason et al. 1995
E. Carboniferous flysch of Marathon uplift of Ouachita orogen (west Texas)	11	−9.5 ± 1.1	Gleason et al. 1995
F. Upper Ordovician to Mississippian strata of Ouachita orogen (Arkansas-Oklahoma)	26	−9.0 ± 1.2	Gleason et al. 1995, 2002
G. Upper Ordovician to Pennsylvanian strata of Oklahoma shelf and Illinois and Black Warrior basins	8	−8.8 ± .7	Gleason et al. 1995
H. Ordovician-Silurian strata of Taconic and Sevier foredeeps in Appalachian foreland	60	−10.1 ± 1.4	Gleason et al. 1995, 2002; Andersen and Samson 1995; Bock et al. 1998
I. Pre-upper Ordovician strata, Benton (Arkansas), Broken Bow (Oklahoma), and Marathon (Texas) uplifts of Ouachita orogen	15	−16.3 ± 1.4	Gleason et al. 1995, 2002

Note. The table shows comparative initial ε_{Nd} values for selected subsets of siliciclastic sedimentary rocks from the Ouachita-Marathon orogen and foreland, Appalachian (Taconic-Sevier) foreland, and associated midcontinent region.
[a] Number of samples.
[b] Mean ± standard deviation for $t = 300$ Ma.

lying to the northwest of the Grenville province—on the exposed Canadian shield, across the midcontinent region buried by Phanerozoic sediment cover, and in Rocky Mountains uplifts—could yield ε_{Nd} values similar to those measured from the Ouachita depositional systems for which an ultimately Appalachian provenance is inferred. Derivation of sediment from igneous and metamorphic basement rocks of the craton would uniformly produce more negative ε_{Nd} values for the clastic detritus.

Sediment Recycling

The presence of detritus of ultimate Appalachian provenance in Atoka turbidites of the frontal Ouachita thrust belt (table 2, B) can be attributed to sediment recycling, on a subregional scale, back toward the ultimate Appalachian sources of the detritus. Nd isotopes cannot distinguish, however, between derivation of the recycled detritus from Paleozoic strata of the Oklahoma shelf exposed in the Arbuckle uplift on the edge of Laurentia, as opposed to deformed turbidites of Appalachian provenance accreted as a subduction complex to the flank of the Gondwanan continent as it approached Laurentia by consuming oceanic crust lying to the south (Graham et al. 1975; Ingersoll et al. 1995).

Pre-upper Ordovician strata of the Arbuckle uplift that might otherwise contain siliclastic detritus of cratonic derivation are dominantly carbonate rocks (Ham 1973), from which little or no clastic sediment could be derived. Upper Ordovician to lower Pennsylvanian clastic units of the Oklahoma shelf succession extending westward into the Arbuckle uplift, and from which clastic detritus could be recycled, yield $\varepsilon_{Nd}(t = 300$ Ma) values ($n = 4$) of −8.6 to −9.5 (recalculated from Gleason et al. 1995), compatible with derivation from Appalachian sources and statistically indistinguishable from the $\varepsilon_{Nd}(t = 300$ Ma) values of −8.5 to −9.1 for frontal Ouachita turbidites (table 1). Chert pebbles associated locally with finer detritus in the Atoka Formation (Ferguson and Suneson 1988) were apparently derived from nodules in the dominantly carbonate strata of the Oklahoma shelf succession and seemingly support an Arbuckle source for the recycled detritus.

Because sand-rich strata are subordinate in the Oklahoma shelf succession, recycling of sand from deformed Appalachian-derived turbidites of the evolving Ouachita system is a potential alternative to erosion of an incipient Arbuckle uplift. At present, however, there is no independent evidence for sufficient topographic relief along the evolving Ouachita suture belt to provide an adequate source of recycled sediment during Atoka deposition (Sutherland 1988).

Johns Valley Shale

The Pennsylvanian Johns Valley Shale (formal stratigraphic name) separates the overlying Atoka Formation from the underlying Jackfork Group (table 2, D) in multiple thrust sheets along the northwest flank of the Ouachita Mountains in Oklahoma. The unit forms a stratigraphic interval typically 125–250 m thick over which olistostromal intervals are interbedded with turbidites lithologically indistinguishable from Atoka Formation. Lithic constituents of its olistostromes are in part disrupted and deformed Carboniferous flysch but also include extrabasinal limestone and sandstone blocks and boulders, deformed shale enclaves, and polylithologic megaclasts or raft-like displaced stratal successions derived from the wide range of Paleozoic formations forming the Oklahoma shelf succession exposed to the northwest (Shideler 1970). The Johns Valley Shale was not sampled during previous Nd-isotope work on the Ouachita system (Gleason et al. 1994, 1995) because analysis of either reworked blocks or flysch of uncertain depositional age seems fruitless. Our sample (OUA-01-1 of table 1) of Johns Valley Shale was collected, however, from an undeformed sandstone bed (app. A) lithologically unlike sandstones in the overlying Atoka Formation or the underlying Jackfork Group.

By analogy with the Maumelle chaotic zone along approximate tectonic strike in Arkansas to the east, Viele and Thomas (1989) concluded that the Johns Valley Shale is a folded band of tectonic mélange, structurally interleaved within the Pennsylvanian flysch succession. They inferred that the irregular domains and discrete clasts of shelf strata were incorporated structurally into the Ouachita system as thrust sheets overrode the shelf edge now buried beneath the overthrust assemblage (Lillie et al. 1985; Keller et al. 1989). The internal lithology of the Johns Valley Shale denies this interpretation, however, because the commonly rounded exotic blocks dispersed in a shaley matrix include not only discrete limestone clasts but also abundant clasts of matrix-supported limestone-clast conglomerate composed of subrounded limestone pebbles and cobbles. The latter lithology implies initial deposition before reworking into Johns Valley olistostromes as debris-flow deposits of submarine slopes and channels or alluvial fans and fan deltas and is unknown from the Oklahoma shelf succession.

We accordingly interpret olistostromes of the Johns Valley Shale as the depositional record of a steep submarine slope into which submarine canyons and associated channels were incised along the northern flank of the Ouachita trough at the passive southern margin of Paleozoic Laurentia. Present exposures in Ouachita thrust sheets have been transported tectonically northward from initial sites of deposition along or near the high-relief continental margin later overridden by the thrust sheets. The varied lithology and protolith age of displaced blocks and domains within Johns Valley Shale implies the existence of submarine canyons or escarpments, with 1000–2000 m of bathymetric relief incised into the Oklahoma shelf succession (Link and Roberts 1986). Reworked fossiliferous blocks in the Johns Valley Shale display inverted clast stratigraphy, with blocks most commonly of Mississippian age near the base grading through intermediate stratigraphic levels to blocks most commonly of Ordovician age near the top. Blocks decrease progressively in size southward through successive stacked thrust sheets. The large megaclasts and internally deformed enclaves of shelf strata characteristic of northern thrust sheets are interpreted as the products of submarine landslides on a steep continental slope or the walls of submarine canyons. The reduced clast sizes in more southerly thrust sheets reflect progressive southward disaggregation of the slide masses into submarine debris flows that were emplaced either farther downslope or within submarine-fan channels extending beyond the mouths of submarine canyons.

The sampled bed of sandstone in the Johns Valley Shale is interpreted as a deposit emplaced by a throughgoing turbidity current that traveled along the thalweg of a canyon or channel into which penecontemporaneous shelf deposits and turbidites calved or slumped to form submarine landslides and debris flows. Local outcrop relations are inadequate, however, to interpret the sedimentary environment of its final deposition. The sandstone bed yields an initial ε_{Nd} value of −9.6 (table 1), slightly more negative than the overlying Atoka Formation or the underlying Jackfork Group (table 2, A–D), but compatible with recycling of Oklahoma shelf sediment having an ultimate provenance within the Appalachian orogen. The contrast with initial ε_{Nd} values for craton-derived pre-upper Ordovician strata (table 2, I) of the Ouachita region is nearly as great for the sandstone bed in the Johns Valley Shale as for associated Pennsylvanian flysch and molasse units. A minor component of craton-derived detritus may have influenced ε_{Nd} for the Johns Valley Shale, but Appalachian-derived upper Ordovician to Pennsylvanian sedimentary suites in the Appalachian foreland basin and across the southern Laurentian craton (table 2, F–2, H) include samples with initial ε_{Nd} values as negative as the Johns Valley Shale sample.

The ε_{Nd} value for sandstone in the Johns Valley Shale, which clearly seems to have been derived in large part from reworking of Oklahoma shelf strata, is compatible with the interpretation that Atoka turbidites displaying indicators of anomalous east-flowing paleocurrents contain Appalachian-derived detritus recycled through Oklahoma shelf deposits of the Arbuckle uplift.

Conclusions

Nd isotope analysis of previously unsampled components of the Ouachita system is supportive of previous inferences (Gleason et al. 1994, 1995; Archer and Greb 1995; Patchett et al. 1999) that the Paleozoic Appalachian orogen was the dominant regional provenance for sedimentary detritus transported across and around the margins of the Laurentian block into the Ouachita trough. Varied recycling of the Appalachian-derived sediment through intermediary depositional sites did not alter its fundamental isotopic signature.

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