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Nd isotopic constraints on sediment sources of the Ouachita-Marathon fold belt: Alternative Interpretation and Reply

Alternative Interpretation

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INTRODUCTION

Nd isotopes from Paleozoic sedimentary successions of the Ouachita and Marathon thrust belts and associated foreland and cratonic basins cluster into only three distinct populations: pre–450 Ma (Lower to Middle Ordovician) sedimentary rocks, post–450 Ma (Upper Ordovician to Pennsylvanian) sedimentary rocks, and Mississippian tuffs (Gleason et al., 1995). Gleason et al. (1995) conclude that an abrupt change in Nd isotopes at 450 Ma in the Ouachita succession reflects a change from a provenance in the cratonic interior to a provenance in the Appalachian (Taconic and Alleghanian) orogen, and that sediment from "Appalachian" sources spread to the Ouachita and Marathon regions along the southern margin of the continent. The remarkable uniformity of Nd isotopes after 450 Ma (Gleason et al., 1994, 1995) resolves neither the significant differences in lithotectonic composition between the Taconic (Ordovician) and Alleghanian (Mississippian-Pennsylvanian) orogens, nor variations along strike in both (several chapters in Hatcher et al., 1989). Similarly, additional provenance contributions indicated by other data are masked by the uniformity of Nd isotopes. The lack of resolution of provenance characteristics in Nd isotopes (as documented by Gleason et al., 1995) demonstrates the necessity for a more comprehensive approach to interpretations of regional sediment dispersal, diachroneity of orogenesis, lithotectonic composition of provenances, and location of orogenic uplifts.

REGIONAL TECTONICS AND SEDIMENT DISPERSAL PATTERNS

Preorogenic

Cambrian-Mississippian off-shelf passive-margin deposits in the Ouachita embayment (①, Fig. 1) include clastic sediment derived from the cratonic interior and transported over the shelf margin (Viele and Thomas, 1989). An upward transition from mud-rich units (Womble Shale and underlying strata, including craton-derived quartzose sandstones) to a chert-dominated succession (Bigfork Chert through Arkansas Novaculite, Fig. 2) signifies decrease to a very low sediment-accumulation rate (Viele and Thomas, 1989). An abrupt change in Nd isotopes at 450 Ma (Gleason et al., 1995, Fig. 7) coincides with the decrease in sediment-accumulation rate, suggesting a possible genetic association.

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Taconic Orogeny

Gleason et al. (1995) conclude that the change in Nd isotopes in the Ouachita succession at 450 Ma reflects sediment dispersal from the Taconic orogenic belt via the Sevier foreland basin (②, Fig. 1); the Blount clastic wedge (Thomas, 1977) in the Sevier basin, however, is older than the 450 Ma strata in the Ouachita succession (Fig. 2). The lower part of the Blount clastic wedge (Tellico Formation, Fig. 2) has an Nd-isotope signature like that of the post–450 Ma population of the Ouachita region (Gleason et al., 1995, Fig. 7B). The Blount clastic wedge shallows upward from turbidites to shallow-marine sandstones, and even the most widespread, upper part of the clastic wedge has limited cratonward (northwestward) extent (Walker et al., 1983). The black Athens Shale extends southwestward along the interior Appalachian thrust sheets in Georgia and Alabama, suggesting a possible sediment-transport route to the eastern part of the Ouachita embayment (③a, Fig. 1), but the Athens Shale is older than 450 Ma (Fig. 2). Synorogenic deposition in the Sevier foreland basin, as well as clastic sediment transport toward the Ouachita embayment, evidently terminated before the time of change in Nd isotopes in the Ouachita embayment, indicating that the change in Nd isotopes in the Ouachita embayment is not related to the Sevier foreland basin.

Upper Ordovician shale within the carbonate-shelf succession of southern Laurentia (Sylvan Shale of the "Oklahoma shelf") has a post–450 Ma Nd signature; however, "sediments were not delivered from across the craton but instead represent detritus washed along, or *onto, the shelf edge from offshore muds*" [italics added] (Gleason et al., 1995, p. 1199–1200). Alternatively, extensive Upper Ordovician shale units (for example, Sylvan Shale, Cason Shale of northern Arkansas, Maquoketa Group of the Illinois basin, and unnamed discontinuous shale and sandstone in the Black Warrior basin, Fig. 2) suggest widespread dispersal across the craton (④ and ③b, Fig. 1) (Collinson et al., 1988; Johnson et al., 1988; Thomas, 1988). The Maquoketa Group (④, Fig. 1) is the distal detritus of the Queenston delta (Collinson et al., 1988), which marks maximum cratonward progradation of the Martinsburg-Shawangunk clastic wedge (Fig. 2) (Thomas, 1977) across the Taconic foreland in the Pennsylvania embayment (⑤, Fig. 1). The Martinsburg-Shawangunk clastic wedge has much greater cratonward extent than the Blount clastic wedge, and it overlaps the distal part of the Blount wedge in Tennessee (Thomas, 1977; Drake et al., 1989). Although the widespread Upper Ordovician shales may record sediment transport from the northern Appalachians to the Ouachita embayment (④ and ③b, Fig. 1), the most extensive shales are younger than 450 Ma and, therefore, are not the cause of the change in Nd isotopes.

The Lower Silurian Blaylock Sandstone (Fig. 2), above the stratigraphic

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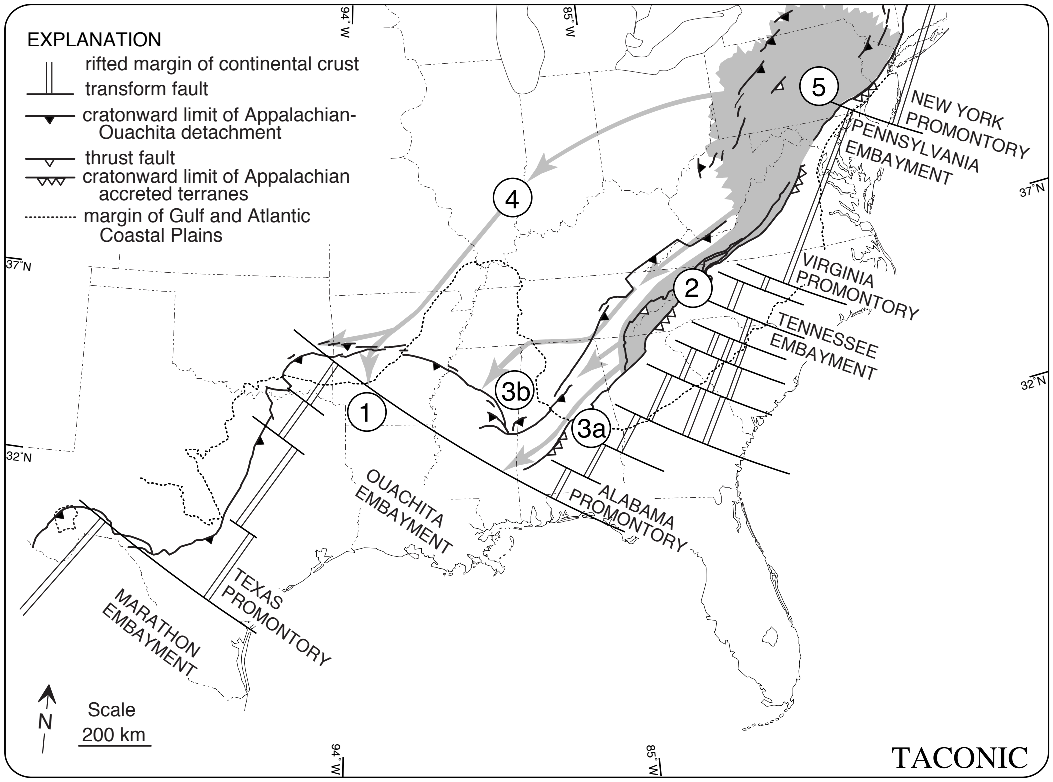

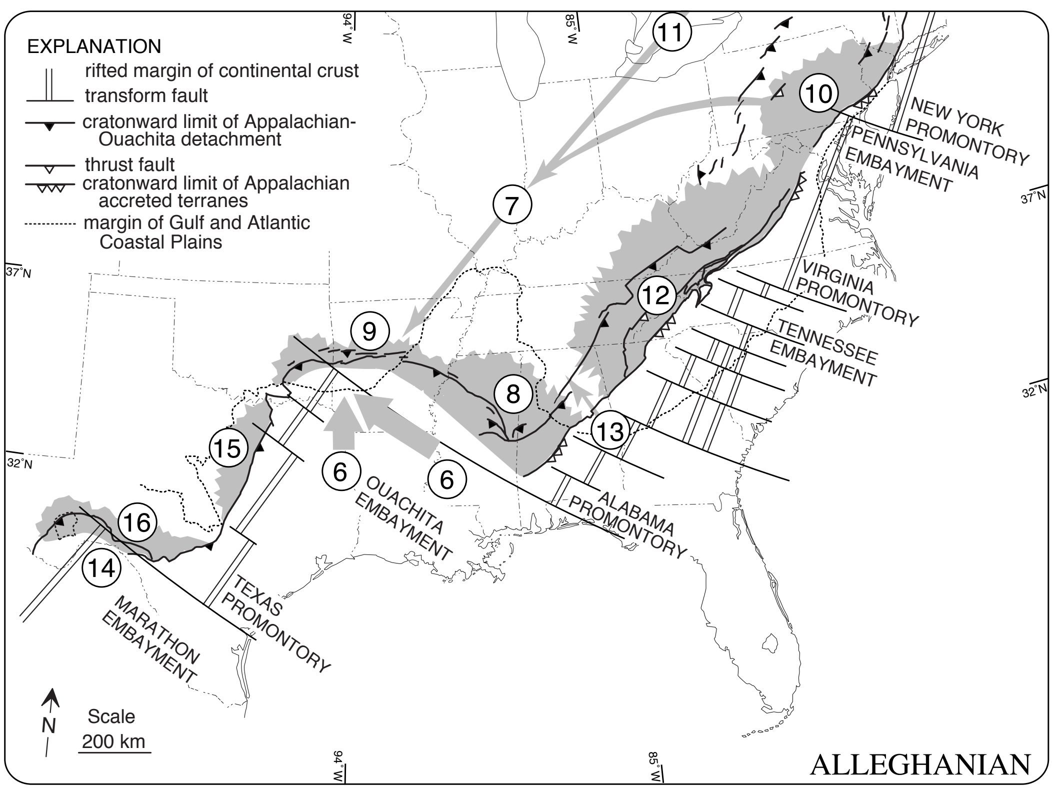

Figure 1. Map of Appalachian-Ouachita orogenic belt, showing distribution of synorogenic clastic wedges and sediment-dispersal patterns discussed in text; outline of early Paleozoic rifted margin of Laurentia from Thomas (1991). Circled numbers identify locations discussed in text.

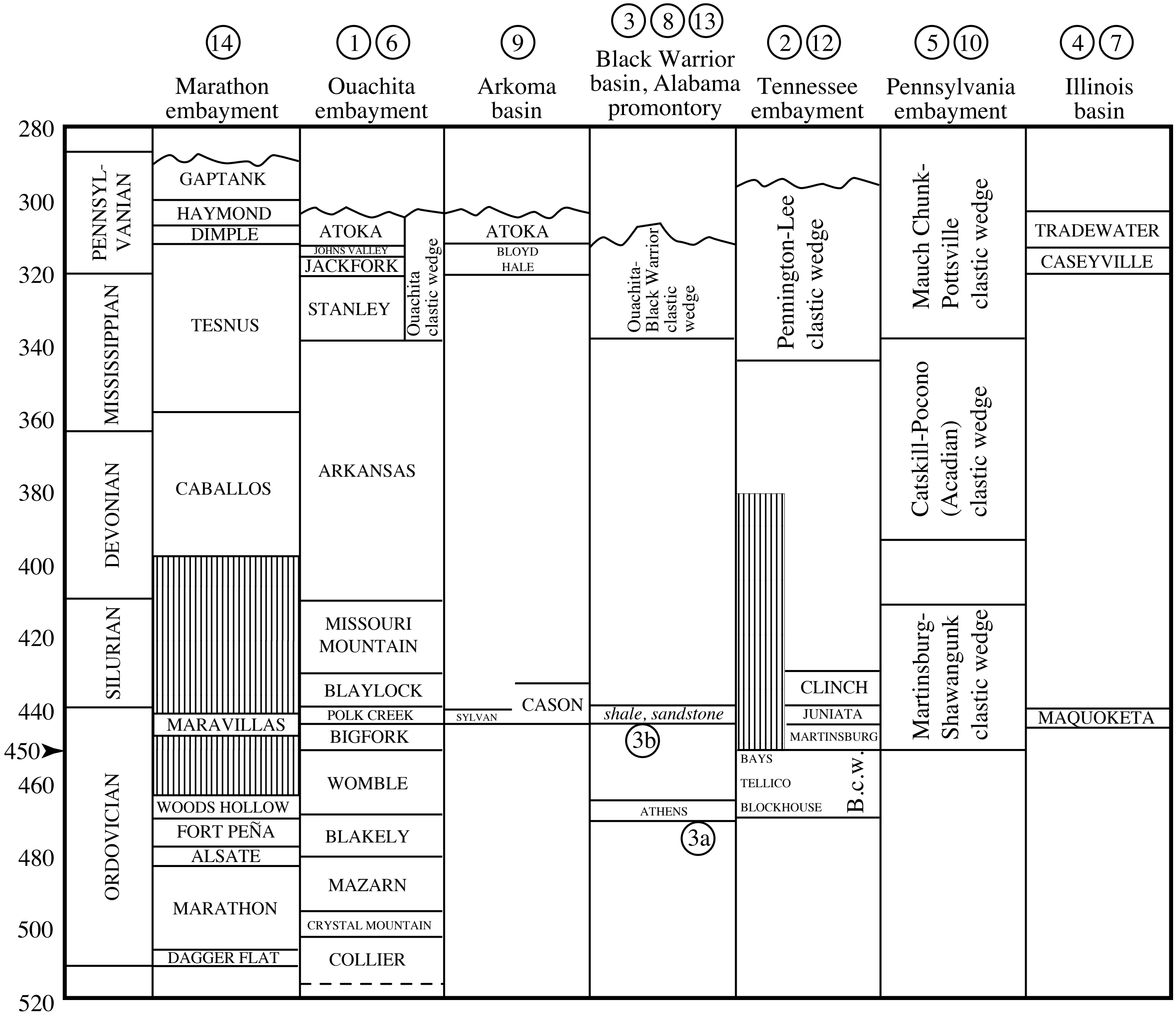

Figure 2. Correlation chart of stratigraphic units discussed in text. Locations of sections shown by circled numbers in Figure 1. B.c.w.—Blount clastic wedge. Correlations from Geological Society of America Geology of North America volumes D-2 and F-2, and from American Association of Petroleum Geologists Correlation of Stratigraphic Units in North America charts for Appalachian Region, Midwestern Basins and Arches Region, and Texas-Oklahoma Tectonic Region. Time scale from Harland et al. (1990). Vertical ruling indicates hiatus at unconformities. White space in columns includes stratigraphic units and unconformities that are not relevant to this discussion.

level of the change in Nd isotopes at 450 Ma, is the only thick clastic unit in the chert-dominated part of the Ouachita passive-margin succession (①, Fig. 1). The sandstone is restricted to the southern part of the Ouachita thrust belt and pinches out northward (Viele and Thomas, 1989). Blaylock lithic sandstones suggest an orogenic provenance, inferred to be the southern part of the Taconic orogen (Gleason et al., 1995). The Blaylock Sandstone is younger than any of the Blount clastic wedge and is equivalent in age to the middle part of the Martinsburg-Shawangunk clastic wedge (Fig. 2). Possible sediment-transport routes to the Ouachita embayment (Fig. 1) in Early Silurian time have not been identified or documented. Identification of the Blaylock provenance would contribute significantly to understanding of middle Paleozoic tectonics of southern Laurentia, but available data seem adequate only to characterize the provenance as orogenic.

Alleghanian (Alleghanian-Ouachita) Orogeny

Gleason et al. (1995) infer three sources of Mississippian-Pennsylvanian synorogenic clastic sediment in the Ouachita embayment: a continental-margin arc south of a remnant ocean basin (⑥, Fig. 1), the northern Appalachians or southeastern Canadian shield with transport via the Illinois basin to the north side of the Ouachita remnant ocean basin (⑦, Fig. 1), and the southern Appalachians with transport via the Black Warrior basin (⑧,

Fig. 1) to the east end of the remnant ocean basin. The first two are compatible with interpretations of regional sediment dispersal derived from sedimentologic-stratigraphic data, but the third is not.

Mississippian-Pennsylvanian synorogenic turbidites in the Ouachita embayment reflect progressive closing of a remnant ocean basin between an arc complex and southern Laurentia (Graham et al., 1975; Thomas, 1976; Viele and Thomas, 1989). Initial arc-continent collision along the southwest side of the Alabama promontory (⑥, Fig. 1) was accompanied by northeastward progradation of synorogenic deltaic sediment into the Black Warrior peripheral foreland basin (⑧, Fig. 1) (Mack et al., 1983; Thomas, 1988). The same collision orogen supplied synorogenic turbidites westward to the remnant ocean basin in the Ouachita embayment (Thomas, 1976, 1989). Collision progressed northwestward along the continental margin to close the remnant ocean basin, as reflected in subsidence and filling of the Arkoma foreland basin (⑨, Fig. 1) (Houseknecht, 1986; Viele and Thomas, 1989). Mississippian tuffs from the volcanic arc (Niem, 1977) are isotopically distinct from the enclosing sedimentary succession, and Gleason et al. (1995) infer that the clastic sediment represents an orogenic provenance different from the volcanic arc. Distributions of turbidite fans, however, indicate a southerly source (Niem, 1976), presumably the volcanic arc (⑥, Fig. 1).

Facies distribution patterns and paleocurrent data indicate transport of clastic sediment southwestward across the Illinois basin (⑦, Fig. 1) (Potter and Pryor, 1961; Pryor and Sable, 1974); the provenance has been interpreted to be the northern Appalachians (distal fringe of the Mauch Chunk–Pottsville clastic wedge of the Pennsylvania embayment, ⑩, Figs. 1 and 2) and the southeastern Canadian shield (⑪, Fig. 1). In Pennsylvanian time, clastic sediment was transported through the Illinois basin (⑦, Fig. 1) to the Arkoma foreland basin (⑨, Fig. 1) and Ouachita remnant ocean (Sutherland, *in* Johnson et al., 1988). Nd isotopes in Pennsylvanian clastic rocks of the Illinois basin, Arkoma foreland basin and adjacent shelves, and the Ouachita remnant ocean all belong to the post–450 Ma population (Gleason et al., 1995).

The inference by Gleason et al. (1995) of sediment dispersal from the southern Appalachians westward across the Alabama promontory via the Black Warrior basin to the Ouachita embayment contrasts with sedimentologic-stratigraphic documentation of northeastward progradation of clastic sediment in the Black Warrior basin (⑧, Fig. 1) (summary and bibliography, Thomas, 1988). Synorogenic sediment dispersal in the Ouachita and southern Appalachian foreland reflects diachronous thrusting and foreland subsidence around the Alabama promontory (Thomas, 1988, 1995; Whiting and Thomas, 1994). Adjacent to the Black Warrior foreland basin, northwest-striking Ouachita thrust faults are truncated by younger northeast-striking Appalachian thrust faults (Fig. 1) (Thomas, 1989). In the Black Warrior basin, down-to-southwest foreland subsidence toward the Ouachita thrust front began in middle Mississippian time and was modified by down-to-southeast subsidence toward the Appalachian thrust front in Early Pennsylvanian time (Whiting and Thomas, 1994). Distributions of facies, thickness, and depositional systems document northeastward progradation of synorogenic clastic sediment into the Black Warrior foreland basin beginning in middle Mississippian (Meramecian) time (⑧, Fig. 1) (Thomas, 1988). Independently, westward progradation of clastic sediment into the southern part of the Appalachian foreland basin on the eastern side of the Alabama promontory also began in middle Mississippian time (⑫, Fig. 1) (Thomas and Schenk, 1988). Mississippian synorogenic clastic wedges prograding northeastward (Black Warrior basin) and westward (Appalachian basin) converged on a carbonate facies roughly centered on the Alabama promontory, effectively separating the two foreland basins (Thomas, 1974, 1988). Pennsylvanian clastic facies prograded over the Mississippian carbonate facies from both directions (Hobday, 1974; Thomas, 1974). Finally, in Early Pennsylvanian time, clastic sediment prograding northwestward into the Black Warrior foreland basin signaled northwest-directed Appalachian thrusting (⑬, Fig. 1) (Mack et al., 1983; Thomas, 1988; Pashin, 1994). Facies distribution like that in the Black Warrior basin persists in the Mississippian-Pennsylvanian strata in the Appalachian thrust belt in Alabama (⑧, Fig. 1), indicating that the rocks now in the Appalachian thrust belt were originally part of the "greater" Black Warrior basin in the Ouachita foreland and were subsequently imbricated in Appalachian thrust sheets (Thomas, 1995). In the upper part of the Lower Pennsylvanian succession, facies distribution and paleocurrent indicators document northwestward transport of coarse fan-delta sediment across the thrust belt (⑬, Fig. 1) (Osborne, 1991).

Without explaining disagreement with sediment-dispersal patterns documented by sedimentologic-stratigraphic data, Gleason et al. (1995) follow Graham et al. (1975) in inferring progressive westward recycling from the southern Appalachians via the Black Warrior basin to the Ouachita remnant ocean. In attempting to maintain the model of Graham et al. (1975), Gleason et al. (1995) cite only west-directed cross-bed orientations reported by Schlee (1963) as documentation for westward sediment transport. Most of Schlee's (1963) measurements are from westward-prograding facies in the southern part of the Appalachian basin (⑫, Fig. 1), but some are from the eastern part of the Black Warrior basin (east of the Gulf Coastal Plain cover, ⑧, Fig. 1). Before the recognition that cross-bed and ripple orientations must be interpreted in the context of depositional environments, especially shallow-marine environments, several workers (Schlee, 1963, and other references listed in Thomas, 1974) suggested west-directed paleocurrents across the eastern part of the Black Warrior basin; however, in barrier-island and marine-delta-front settings (Hobday, 1974; Thomas and Mack, 1982), paleocurrents are complex. Recent studies in the greater Black Warrior foreland basin have documented polymodal (commonly three or more modes) paleocurrents, reflecting tides, waves, longshore currents, and deltaic-fluvial currents (for example, Thomas and Mack, 1982; Osborne, 1985; Shadroui, 1986; Pashin et al., 1995). The inference by Graham et al. (1975) of westward progression of deformation along the Appalachian-Ouachita orogenic belt beginning east of the Black Warrior basin as a mechanism for repeated recycling and westward progradation of sediment from the southern (Georgia and Tennessee) Appalachians to the Ouachita and ultimately Marathon thrust belts is too simplistic to account for the well-documented history of diachronous thrusting and sediment dispersal around the Alabama promontory. The concept of progressive westward closure of a remnant ocean basin is applicable only from the western side of the Black Warrior basin to the Ouachita embayment (Thomas, 1988).

Progressive recycling from Appalachian sources through the Ouachita embayment to the Marathon embayment (Gleason et al., 1995) requires transport of sediment more than 1000 km around the Texas promontory to the Marathon embayment (Fig. 1); however, deposition of Tesnus deep-water muddy turbidites began in the Marathon embayment (⑭, Figs. 1 and 2) before deposition of Stanley turbidites began in the Ouachita embayment (Ethington et al., 1989; Gleason et al., 1995, Fig. 7C). Between the Ouachita and Marathon embayments, the Ouachita orogen is linked to the Fort Worth (⑮, Fig. 1) and Kerr–Val Verde (⑯, Fig. 1) foreland basins, indicating thrusting and sediment dispersal into foreland basins at approximately the same time all along the margins of the Texas promontory (Viele and Thomas, 1989).

TECTONIC COMPOSITION OF OROGENIC BELTS

The Taconic and Alleghanian-Ouachita-Marathon orogenic belts vary significantly along strike in lithotectonic composition (tectonic origin, composition, and age of rocks in the orogen); however, sediments inferred to have been derived from various locations and at various times along the "Appalachian orogen" are indistinguishable on the basis of Nd isotopes (Gleason et al., 1995). Some examples will illustrate the range of compositions.

Taconic Orogen

Clasts in the Blount clastic wedge (②, Fig. 1) (Kellberg and Grant, 1956) represent the entire pre–Middle Ordovician passive-margin shelf succession of eastern Laurentia. In addition to sedimentary rocks, sandstone petrography indicates crystalline basement rocks in the provenance (Mack, 1985).

Locally on the New York promontory (⑤, Fig. 1), Silurian conglomerate (equivalent to Shawangunk and Clinch) rests unconformably on Grenville-age basement rocks (Finks, 1968), indicating that the entire shelf succession, as well as basement, was part of the provenance of the Martinsburg-Shawangunk clastic wedge. Sandstone petrography confirms that provenance composition and also indicates volcanic components (McBride, 1962; Mack, 1985).

Alleghanian Orogen

From the New York promontory southward to the Alabama promontory, the Alleghanian orogen represents continent-continent collision, accompanied by extensive cratonward thrusting of metamorphic terranes (summary in Hatcher, 1989), but north of the New York promontory, Alleghanian deformation is manifest in a system of strike-slip pull-apart basins involving Taconic and Acadian accreted terranes (Thomas and Schenk, 1988). Along-strike contrasts in the Appalachian orogen from Alabama to New York are particularly significant, because Nd isotopes are indistinguishable in sediment inferred by Gleason et al. (1995) to represent different routes of sediment dispersal that converged in the Ouachita embayment from the northern Appalachians via the Illinois basin and from the southern Appalachians via the Black Warrior basin. Gleason et al. (1994) emphasize a provenance of Grenville-age basement rocks, and Gleason et al. (1995, p. 1208) conclude that the ultimate source of synorogenic recycled sediment was "predominantly Grenville basement-derived Late Proterozoic Appalachian rift deposits." Grenville basement rocks and basement-derived synrift successions are distributed discontinuously along the hinterland side of the Appalachian thrust belt (Thomas, 1977), and the internides of the Appalachian orogen consist mostly of accreted terranes of various lithotectonic compositions and ages (Horton et al., 1989). Thick synrift sedimentary accumulations are widespread in the Tennessee embayment, and thinner and more locally distributed synrift accumulations are scattered along part of the Virginia promontory and in the Pennsylvania embayment (summary in Thomas, 1991). Across the New York promontory, the base of the postrift passive-margin succession rests on Grenville-age basement rocks, and no synrift sedimentary rocks are present. A wide expanse of synrift rocks and Grenville basement separates the foreland in Tennessee from accreted terranes, but accreted terranes in Pennsylvania are proximal to the foreland (Fig. 1) (Horton et al., 1989). Therefore, the provenance of sediment from the "northern Appalachians" or the "southeastern Canadian shield" differed substantially from the provenance of sediment from the "southern Appalachians."

Pennsylvanian clastic sediment transported northwestward across the Appalachian thrust belt and into the Black Warrior basin (⑬, Fig. 1) includes distinctive clasts. Conglomerate clasts in the Appalachian thrust belt include granitic gneiss, schist, granodiorite, unmetamorphosed volcanic rocks, and quartz, in addition to metasedimentary and sedimentary rocks (Osborne, 1991). Clasts of schist, gneiss, granodiorite, and sedimentary-metasedimentary rocks interpreted by Liu and Gastaldo (1992) as having been transported in floating logs into the upper part of the Lower Pennsylvanian succession in the eastern outcrops in the Black Warrior basin are evidently part of the northwest-directed sediment-dispersal system from the metamorphic accreted terranes of the Appalachian internides. (Although not formally acknowledged, I examined and identified the clasts for Yuejin Liu, and emphasized that they are unlike any known rocks of the Ouachita orogen but instead are like rocks of the Appalachian Piedmont in Alabama.) Gleason et al. (1995) conclude that Black Warrior basin Nd isotopes reflect the Appalachian sediment source identified by Liu and Gastaldo (1992), but the Nd isotopes from the Black Warrior basin are like all the others of the post–450 Ma population, indicating no distinction between accreted metamorphic terranes and other Appalachian provenances.

The Ouachita-Marathon orogenic belt is the product of late Paleozoic arc-continent collision (summary in Viele and Thomas, 1989), and accretion of an arc terrane contrasts with multiple terrane accretion of the Alleghanian orogen. Nd data indicate an Ouachita continental-margin arc (Gleason et al., 1994), and geophysical data show a fragment of continental crust south of the fore-arc complex (Mickus and Keller, 1992). An accretionary prism within the subduction complex consists of the lower Paleozoic off-shelf succession scraped up from slope-and-rise facies of the Laurentian passive margin (Viele and Thomas, 1989).

The Pennsylvanian Haymond Formation in the Marathon thrust belt (⑭, Fig. 1) includes large clasts of two types: granitic gneiss, metarhyolite, and schist having latest Silurian to Devonian ages (Denison et al., 1969), and Middle Cambrian carbonate rocks of outer-shelf facies (Palmer et al., 1984). Clearly, these clasts were not recycled from the Appalachians or Ouachitas, yet the associated finer grained sediment of the Haymond is indistinguishable in Nd isotopes from other post–450 Ma rocks.

COMPREHENSIVE INTERPRETATIONS

The change in Nd isotopes at 450 Ma in the Ouachita succession suggests a change in the nature of sediment supplied to the slope off the Laurentian passive margin. The change in Nd isotopes coincides temporally with a large-magnitude change in sediment-accumulation rate (Viele and Thomas, 1989), implying a substantial decrease in supply of fine-grained clastic sediment across the craton to the passive margin. Much of the cratonic interior was covered by shallow-marine environments and sediments in Early Ordovician time (maximum Sauk transgression of Sloss, 1963), and presumably that "event" reduced the supply of clastic sediment from the cratonic interior. Maximum transgression, however, was reached at approximately 476 Ma (end of Early Ordovician) and does not correspond temporally to the change in isotopes. Possibly, the sediment supply was so reduced that the minor shale beds in the chert-dominated succession record only limited reworking of older muddy slope deposits in the nearly complete absence of extrabasinal sediment. The change in Nd isotopes occurred >10 m.y. earlier in the Blount clastic wedge than in the Ouachita succession. Although Gleason et al. (1995) repeatedly assert that change in Nd isotopes at 450 Ma in the Ouachita succession marks initiation of an "Appalachian source" for clastic sediment, timing and sediment-dispersal patterns do not support that simple interpretation.

The Blaylock Sandstone continues to pose a problem. The Taconic (Blount) orogeny and possible sediment-transport routes from the Sevier foreland basin are older than the Blaylock Sandstone. Sediment-dispersal patterns suggested by facies distribution of Silurian rocks on the shelf adjacent to the Ouachita embayment show no indication of sediment transport from an Appalachian source. The northward pinch-out across the Ouachita thrust belt, the limited volume of sand, and sandstone composition suggest the possibility of a distal orogenic source directly south of the Ouachita embayment. In accepting the idea of an Iapetus Ocean basin south of Laurentia through most of Paleozoic time, Gleason et al. (1995) (and many others, including myself) have discounted the possibility of an orogenic provenance south of the Ouachitas before Mississippian time, but the Blaylock requires reconsideration. Possibly a subduction complex, including an accretionary prism and perhaps a microcontinent that remained distant to the Laurentian margin, gave rise to a north-directed submarine fan that pinched out northward on the abyssal plain south of Laurentia. The large proportion of tectonic shortening within the Ouachita allochthon combined with the large translation of the allochthon over the Laurentian shelf suggests that extensive slope and abyssal-plain sediment has been telescoped into the orogenic core (Viele and Thomas, 1989).

The Marathon synorogenic clastic wedge poses yet another set of questions. Marathon Nd isotopes are indistinguishable from those of the Sevier, Black Warrior, Illinois, and Arkoma basins, leading Gleason et al. (1995, p. 1207) to conclude that the Marathon succession "reflects the increasing dominance of recycled Appalachian detritus." Aside from the great distance, uncertain route, and timing problems with an "Appalachian" source, the Devonian metamorphic boulders in the Pennsylvanian Haymond Formation suggest a local orogenic provenance (Denison et al., 1969). Carbonate clasts in the same unit are part of the Cambrian shelf of Laurentia (Palmer et al., 1984). The Devonian metamorphic clasts have no known source, yet the size of the clasts requires a proximal source. No Devonian rocks in the Marathon succession suggest nearby orogenic activity; indeed, the Devonian Caballos Novaculite, like the Arkansas Novaculite in the Ouachita succession, indicates very low sedimentation rates in a deep-water off-shelf setting. Nevertheless, the Haymond boulders require that at least a fragment of a Devonian orogen was incorporated into the provenance. That orogen must have been distant from the Marathon embayment of Laurentia during Devonian time, but nonetheless it was caught up in the subduction complex that formed the late Paleozoic Marathon thrust belt. The carbonate clasts must have been derived from proximal sources within the growing Marathon thrust wedge in which part of the passive-margin shelf was imbricated, tectonically similar to the source of clasts in the Blount clastic wedge in the Sevier (Taconic) foreland basin. Although the Marathon provenance was evidently quite different in composition from other late Paleozoic orogenic belts around Laurentia, that difference is not shown in the Nd isotopes (Gleason et al., 1995). The exotic clasts and Laurentian carbonate clasts argue for a local Marathon orogenic source, rather than recycling from more than 2000 km away.

CONCLUSIONS

The great diversity of rocks in the Appalachian (Taconic and Alleghanian) orogen is unrecognizable in the Nd isotopes reported by Gleason et al. (1995). First, sediment from the Taconic orogen, which was composed of rocks of the Laurentian margin and arc terranes, is indistinguishable in Nd isotopes from sediment from the Alleghanian orogen, including a large-scale composite metamorphic allochthon driven by continent-continent collision (Hatcher, 1989). Secondly, the inability of Nd isotopes to discriminate between sediment derived from the northern Appalachians (and possibly the southeastern Canadian shield) and sediment derived from the Ouachita arc-continent–collision orogen (or even the southern Appalachians in the interpretation of Gleason et al., 1995) indicates homogenization of a great variety of rock types and masking of all but the most general characteristics of the orogen. Nd data clearly differentiate tuffs from contemporaneous synorogenic clastic sediment, a distinction that is obliterated with minimal mixing of volcanic debris into sediment.

The uniformity of Nd isotopes in synorogenic sediment is interpreted by Gleason et al. (1995) to reflect a single, uniform provenance called "Appalachian." The great lithotectonic variety encompassed by the Appalachian orogen, however, shows that other orogenic provenances, including Ouachita and Marathon, cannot be eliminated from consideration on the basis of Nd isotopic signature. All of the potential orogenic sources seem to have one component in common, namely the early Paleozoic passive-margin off-shelf slope-and-rise succession of Laurentia; however, where Alleghanian orogenesis overprinted the Taconic orogen, that preorogenic off-shelf succession may be represented only in recycling from Taconic clastic wedges. Grenville-age basement rocks constitute another likely persistent component, because Grenville rocks are widely distributed along the Appalachian-Ouachita-Marathon region of Laurentia. In contrast, accreted terranes of various lithotectonic compositions and ages, volcanic arcs, and synrift rocks are irregularly distributed and impart distinctive lithotectonic aspects to segments of the orogenic belt. The Marathon provenance included a Devonian orogen, as well as thrust sheets of the Laurentian margin; and basement rocks along that margin are Grenville. The as-yet-unknown provenance of the Blaylock Sandstone must have incorporated the distal rise deposits of the Laurentian margin, and the initial sediment from that source might have contributed to the pre-Blaylock change in Nd isotopes at 450 Ma in the Ouachita succession. The challenge is to find a clastic sedimentary rock of Ordovician to Pennsylvanian age that does not have the post–450 Ma Nd isotopic signature and to characterize the tectonic setting of that provenance as a contrast to the Appalachian-Ouachita-Marathon provenances.

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INTRODUCTION

Thomas' (1997) reinterpretation of the Nd isotopic data for Paleozoic clastic sedimentary rocks of the Ouachita-Marathon fold belt and associated foreland and cratonic basins of the Appalachian-Ouachita region raises several important points in addition to those made in a previous discussion of our work (see Thomas, 1995; Gleason et al., 1995a).

Thomas considers our Appalachian provenance model for Paleozoic sediment dispersal into the Ouachita region to be overly simplistic for the following reasons: (1) progradation of clastic wedges toward the Ouachita region from the southern Appalachian Taconic highlands most likely would have occurred before the inferred ca. 450 Ma provenance shift in the Ouachita succession; (2) the shift of eight ε_{Nd} units in the Ouachita succession at ca. 450 Ma occurred within an interval of decreasing sedimentation rate and may therefore be unrelated to sediment influx from a new source; (3) the homogeneous Nd isotopic signature of Ouachita-Marathon-Appalachian sedimentary rocks post ca. 450 Ma may mask significant regional variability in sediment sources through time; (4) the Appalachians were not likely a homogeneous source of sediment in either the temporal or spatial sense after ca. 450 Ma, and (5) westward dispersal of sediment from the Appalachian foreland into the Ouachita trough via the Black Warrior basin is not likely because of subsurface stratigraphic evidence to the contrary.

We disagree with Thomas (1997, p. 779) regarding the "lack of resolution of provenance characteristics in Nd isotopes" in our data set, and point rather to "the remarkable uniformity of Nd isotopes after 450 Ma" (Thomas, 1997, p. 779) throughout the Appalachian-Ouachita region as evidence for long-lived, large-scale homogenization and dispersal of sediment

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from a single orogenic provenance. Within this context there is, of course, considerable latitude for interpretation regarding dispersal routes, which we are sure will continue to change as new data are acquired.

INTERPRETATION OF THE CIRCA 450 MA PROVENANCE SHIFT

Our goal in sampling the ca. 460 Ma Tellico turbidites in the Sevier basin was to demonstrate that material of the correct Nd isotopic signature was available in large volume for transport from the southern Appalachian Taconic highlands (Blountian clastic wedge) to the Ouachita region by ca. 450 Ma. Thomas is correct to point out that some material may have also been dispersed across the craton from the northern Taconic highlands (Martinsburg-Shawangunk clastic wedge) into the Ouachita region after ca. 450 Ma (e.g., Sylvan Shale), a possibility that is fully compatible with our model but that needs to be tested further; however, alternative dispersal routes tapping homogeneous Appalachian sources probably existed. On the basis of the resolution of our sampling and uncertainties in age assignments of the Womble-Bigfork succession in the Ouachitas (Ethington et al., 1989), we estimate that the provenance change occurred within a 20 m.y. interval between 460 and 440 Ma. If the provenance change occurred closer to 460 Ma during Womble time, material shed cratonward from the southern Taconic highlands (Blount clastic wedge) could have been delivered directly to the Ouachita trough via known dispersal routes (e.g., Athens Shale). Alternatively, a southern extension of the Taconic orogen could have supplied sediment to the Ouachita trough from the southeast, a possibility that we favored (Gleason et al., 1995b) and that is consistent with northwestward progradation of Blaylock turbidites from sources to the southeast as inferred from paleocurrent data. Because the provenance change occurs within an interval comprising the Womble Shale and Bigfork Chert, the change may not coincide with a decrease in depositional rate. Recent recognition of an orogenic clastic wedge in the Womble Formation in Oklahoma (Dix et al., 1995) suggests a regionally diachronous provenance shift in the Ouachita succession linked to a single Taconic source region, which lay south of the modern continental margin and which likely also supplied the Blaylock turbidites.

In summary, we note the remarkable similarity in Nd isotopes of Taconic clastic wedge deposits of both Blountian (Tennessee) and Martinsburg (New York and Tennessee) age as evidence for large-scale homogenization of recycled orogenic material (Bock et al., 1994; Gleason et al., 1995b; Andersen and Samson, 1995; Krogstad et al., 1994) along the length of the Appalachian orogen between 470 and 430 Ma. Our own analyses of the Tellico and Martinsburg formations in Tennessee fall precisely within the range of values for the Bigfork–Polk Creek–Blaylock Middle to Upper Ordovician succession in the Ouachitas, thus arguing for close proximity in the Appalachians of voluminous, well-homogenized, recycled orogenic material of matching isotopic composition. We agree that more comprehensive studies would be useful in order to establish firmer links between these depositional systems. Systematic dating of detrital zircons from turbidites throughout the Appalachian-Ouachita region should be undertaken for this purpose, and higher resolution Nd isotopic studies based on detailed biostratigraphic correlation between basins are also needed to further resolve the timing and source of the Ordovician provenance shift in the Ouachitas.

CARBONIFEROUS DISPERSAL ROUTES

Studies by Pashin et al. (1990), Liu and Gastaldo (1992), and Driese et al. (1994; see also Driese et al., 1995) have called into question Thomas' interpretation for converging clastic wedges in the Carboniferous Black Warrior basin and instead argue for westward transport of Appalachian-derived clastic detritus across the Black Warrior basin during the Carboniferous as originally proposed by Schlee (1965) and Graham et al. (1975; 1976) and by Archer and Greb (1995). These studies document (1) dominantly west-directed paleocurrents determined from unimodal cross-bedding orientations in conglomerate-bearing, fluvial sandstones throughout the Lower Pennsylvanian Pottsville sandstone in the eastern Black Warrior basin, (2) the presence of igneous and metamorphic clasts of Appalachian aspect in units (lower part of the upper Pottsville) interpreted by Thomas to have a Ouachitan provenance, (3) interfingering of northeast-trending barrier shoreline sandstones with fluviodeltaic sandstones derived from Appalachian highlands to the southeast in the same upper Pottsville sequence, and (4) evidence for southward transport of craton-derived Mississippian sandstone in strata interpreted by Thomas to be part of a clastic wedge prograding into the Black Warrior basin from the southwest. Although we see no reason to rule out significant westward sediment dispersal across the Black Warrior basin into the Ouachita trough during the Carboniferous, we note that sediment contributions from sources all around the periphery of the Black Warrior basin are fully compatible with the Himalayan-Bengal model of Graham et al. (1975) for Carboniferous flysch dispersal into the Ouachita trough (Dickinson, 1988). The Nd isotopic data simply require that the sediment delivered to the Black Warrior basin tapped the same homogenized sources as Carboniferous sediments in the Appalachian basin, the Illinois basin, the Arkoma basin, and the Ouachita trough. Reworking of this Appalachian-derived material into subduction complexes south of the Black Warrior basin along the arc-continent collision zone is to be expected of complex dispersal systems tapping distant sources (see Archer and Greb, 1995; Dickinson, 1988), and is fully compatible with models calling for dominantly recycled sediment sources lying south of the Ouachita trough in the Carboniferous (Mack et al., 1983).

The notion that the Ouachita flysch contains a significant volcanic arc component is in conflict with all available data (see Gleason et al., 1994; 1995a, 1995b), which instead require dominantly sedimentary fold-thrust belt sources for the Carboniferous Ouachita flysch and fluviodeltaic sediments of the Arkoma, Black Warrior, Appalachian, and Illinois basins (see point counts in Gleason et al., 1995b). Mississippian tuffs appear to be the only significant material to have entered the Ouachita trough from volcanic arc sources to the south, which were clearly isotopically distinct from flysch sources.

In the Marathon basin, granitoid clasts of Devonian age (ca. 400 Ma) in Pennsylvanian strata indicate a more complex provenance involving multiple sources which, as we pointed out (Gleason et al., 1995b), probably included a nearby eroded plutonic terrane which may have also been the source of the exotic Devonian clasts. This inference is based partly on the higher feldspar content of Marathon flysch compared to the Ouachita flysch, requiring a nearby source not sampled by the Ouachita flysch. What proportion of the Marathon flysch this additional provenance composes cannot be quantified by Nd isotopic data alone, but it was probably minor compared to the main source of sediment. We proposed that the main sediment source was likely a subduction complex or complexes composed of recycled Appalachian-derived sediment further reworked from deformed sea-floor deposits and recycled into Carboniferous Marathon flysch. Because sediment of Appalachian provenance probably covered the sea floor south of North America after ca. 450 Ma, this material would have been available for reworking into the Marathon basin commencing with deposition of the Mississippian Tesnus flysch or beforehand.

SUMMARY

What is remarkable about the Nd isotopic data set is that it clearly identifies three distinct isotopic populations, which we view as an indication of how sensitive Nd isotopes can be to significant shifts in sediment source.

However, it is important to bear in mind that the Nd isotopes are measuring only changes in the average age of basement source materials being tapped over a wide region through several cycles of sedimentation, and therefore can be used as true provenance indicators only in the context of regional geologic interpretation, as Thomas points out. We conclude from just such a comprehensive analysis that the Appalachian fold-thrust belt was the primary sediment source for sea floor south of North America after 450 Ma, and that no other source could have been positioned strategically enough to deliver such a large volume of isotopically homogeneous sediment to so many sedimentary basins throughout the Appalachian-Ouachita-Marathon region during the ≈150 m.y. time span involved. We are confident that ongoing regional studies of paleo-river systems (e.g., Archer and Greb, 1995) and systematic detrital zircon U-Pb dating will further clarify our knowledge of Paleozoic sediment dispersal routes.

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