Detrital-zircon geochronology and sedimentary provenance

William A. Thomas*
GEOLOGICAL SURVEY OF ALABAMA, 420 HACKBERRY LANE, P.O. BOX 869999, TUSCALOOSA, ALABAMA 35486-6999, USA

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INTRODUCTION

The article on sources of Paleozoic sediment in the Grand Canyon by Gehrels et al. (2011) in the June issue of *Lithosphere* illuminates progress in studies of sedimentary provenance, which have evolved dramatically during the past fifty years. During my dissertation research at Virginia Tech, Professor Wally Lowry advised me to think of "sandstones as microconglomerates" in which some sand grains are small rock fragments, characterizing the lithology of the source of the sediment. The lithic grains indicated sediment sources within the Appalachian orogen for Mississippian sandstones in the Appalachian foreland basin (Thomas, 1959). Increasingly sophisticated applications of sandstone petrography in provenance studies led to the use of ternary diagrams of sandstone components (QFL, QmFLt) to distinguish the tectonic (orogenic, arc, or cratonic) setting of the sediment source (e.g., Dickinson and Suczek, 1979; Dickinson et al., 1983). Focus on the lithic grains allowed more specific characterization of the provenance, distinguishing between arc, low-grade metamorphic, high-grade metamorphic, ophiolitic, and sedimentary sources (e.g., Dickinson and Suczek, 1979; Ingersoll and Suczek, 1979; Mack et al., 1981, 1983; Hiscott, 1984).

While sandstone petrography continues to provide unique information about provenance, more recently, detrital-zircon geochronology has evolved as the choice for provenance studies. Detrital zircons are ubiquitous in sandstones, because zircon is highly resistant to both chemical and physical weathering. The age of a single zircon grain is interpreted to be the crystallization age of a rock in the provenance. A sedimentary deposit likely contains components from multiple crystalline sources as a result of multiple magmatic episodes in one locality, of tectonic juxtaposition of rocks of different ages, of mixing by confluence of drainage from multiple localities, and/or of recycling of older sediment and mixing with younger primary sources. Therefore, to fully characterize all components of the sedimentary provenance, all ages within a population of detrital zircons from a single sandstone sample must be determined (well illustrated by Gehrels et al., 2011). With the advent of sensitive high-resolution ion microprobe (SHRIMP) and laser-ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS), large populations of detrital zircon grains can be analyzed quickly. The combination of the ubiquity of detrital zircons, the precision of age determinations, and the opportunity to analyze large populations from a single sandstone sample has made detrital-zircon geochronology a powerful tool in provenance studies.

Because of remarkable durability, detrital zircons may be reworked through multiple sedimentary cycles. A mixed sedimentary population of zircons will endure metamorphism, but younger metamorphic events may be recorded in overgrowths (rims) on cores that record initial crystallization. Zircons may be recycled from sedimentary and/or metamorphic rocks and mixed with zircons from primary sources. For provenance studies, the good news is once in the system, zircons stay in the system; and the bad news is once in the system, zircons stay in the system. The durability of zircon is a challenge, because multi-cycle sedimentation may be masked, leaving an incorrect interpretation of exclusively primary sources, and compromising an interpretation of provenance.

The study of provenance has two distinct and equally important components. U/Pb analysis of the age populations of detrital zircons in a sandstone allows identification of a potential provenance by matching detrital-zircon ages with crystallization ages of potential source rocks. The identity of a provenance from detrital-zircon age populations, however, is non-unique; and documentation of the dispersal path of sediment from the inferred provenance to the depositional site is equally critical. Determination of the dispersal path depends on fitting the zircon data into a stratigraphic, sedimentologic, tectonic, and paleogeographic framework. Confluence of multiple dispersal paths may bring together a diverse assemblage of detrital zircons from multiple separate original primary and/or recycled secondary sources. Nevertheless, tracking detrital-zircon populations along potential dispersal paths is both practical and essential for provenance interpretation, and constitutes a new opportunity for provenance studies and paleogeographic reconstruction.

DETRITAL-ZIRCON POPULATIONS IN THE GRAND CANYON SUCCESSION

Detrital zircons in the Paleozoic succession in the Grand Canyon exhibit distinctive components of the age population, and those ages are used to identify a provenance (Gehrels et al., 2011). For the younger components of the detrital-zircon population, the source for sediment in the Mississippian–Permian succession in the Grand Canyon is identified specifically as the distant Appalachian orogen, including Mesoproterozoic (1200–1000 Ma) Grenville basement and/or recycled Grenville-age zircons; Iapetan synrift (760–530 Ma) rocks; accreted Gondwanan (680–530 Ma) terranes; and Taconic (490–440 Ma), Acadian (420–350 Ma), and Alleghanian (330–270 Ma) synorogenic rocks. Important older components of the detrital-zircon populations in the Grand Canyon correspond to more local sources (1800–1600 Ma Yavapai and Mazatzal in the Ancestral Rockies, and the 1480–1340 Ma Granite-Rhyolite province in the southern Midcontinent), and these are common throughout the Cambrian–Permian succession. The Devonian Temple Butte Formation has a somewhat enigmatic component of 521–403-Ma zircons (Gehrels et al., 2011). The selection of the Appalachians as the source of zircons in the Mississippian–Permian succession in the Grand Canyon drives a necessary interpretation of the dispersal system—a large transcontinental river or rivers from the Appalachians to the Grand Canyon (Gehrels et al., 2011).

The analyses of zircon ages and the matching of age components with those of potential sediment sources by Gehrels et al. (2011) are statistically and mathematically elegant; however, documentation of a dispersal

*E-mail: geowat@uky.edu

path from the inferred Appalachian provenance to the depositional site in the Grand Canyon is a necessary critical test of the hypothesis. Is transport of sediment from the Appalachians to the Grand Canyon consistent with available data for depositional systems and sediment dispersal along the path? And are the Appalachians the only possible source of these zircon populations? To match the elegance of the analysis and matching of the detrital-zircon population requires a much more rigorous approach to documenting the dispersal path from the source to the depositional site.

TRACING A DISPERSAL PATH FROM THE APPALACHIANS TO THE GRAND CANYON

Mississippian

Excepting a few grains in the Devonian Temple Butte Formation, the effects of the inferred Appalachian provenance first appeared in the Grand Canyon in the Late Mississippian Surprise Canyon Formation (Gehrels et al., 2011). In the proximal part of the inferred sediment-dispersal path to the Grand Canyon, Late Mississippian temporal equivalents of the Surprise Canyon Formation are synorogenic clastic-wedge deposits—Mauch Chunk Group in the central Appalachian, and Floyd and Pennington Formations in the southern Appalachian foreland basin (Fig. 1) (e.g., Thomas and Schenk, 1988). Detrital-zircon populations from the Mauch Chunk Group include ages representative of the Acadian and Taconic orogenies but no grains younger than (ca. 400 Ma) Acadian (Park et al., 2010); the population is dominated by Grenville ages and includes older zircons. Zircons, representing a range of ages from the Superior province to the Grenville, were incorporated in some Iapetan synrift sediment (Cawood and Nemchin, 2001) and recycled into the Appalachian foreland basin (Thomas et al., 2004). The lack of detrital zircons younger than Devonian indicates that synorogenic zircons from the early Alleghanian orogeny did not reach the foreland basin, which was in the headwaters of any possible transcontinental drainage to the Grand Canyon. The Mauch Chunk and Floyd-Pennington clastic facies grade westward into shallow-marine carbonates (Thomas and Schenk, 1988), suggesting that little or no synorogenic siliciclastic sediment reached the western distal side of the Appalachian foreland basin.

West of the Appalachian foreland in the Midcontinent, in the Illinois intracratonic basin, the Upper Mississippian cyclic succession of limestone, mudstone, and sandstone (Collinson et al., 1988) has been interpreted to include delta-front sandstones, representing the maximum southwestward extent of a Late Mississippian delta complex (e.g., Swann, 1964). The Illinois basin (Fig. 1) is critically located across the possible drainage from the Appalachians to the Grand Canyon; ages of detrital zircons in Mississippian sandstones there would provide an important test of the provenance.

South of the Midcontinent, synorogenic foreland basins rim the Ouachita and Marathon orogenic belt (Thomas et al., 1989). The easternmost of the Ouachita foreland basins, the Black Warrior basin (Fig. 1), is south of the Illinois basin. Drainage through the Illinois basin has been suggested as the source of Mississippian deltaic and shallow-marine sediments in the Black Warrior basin (e.g., Welch, 1978). The sandstones in the Black Warrior basin are petrographically distinct from those in the Illinois basin, however, indicating that the two basins did not share a common provenance or

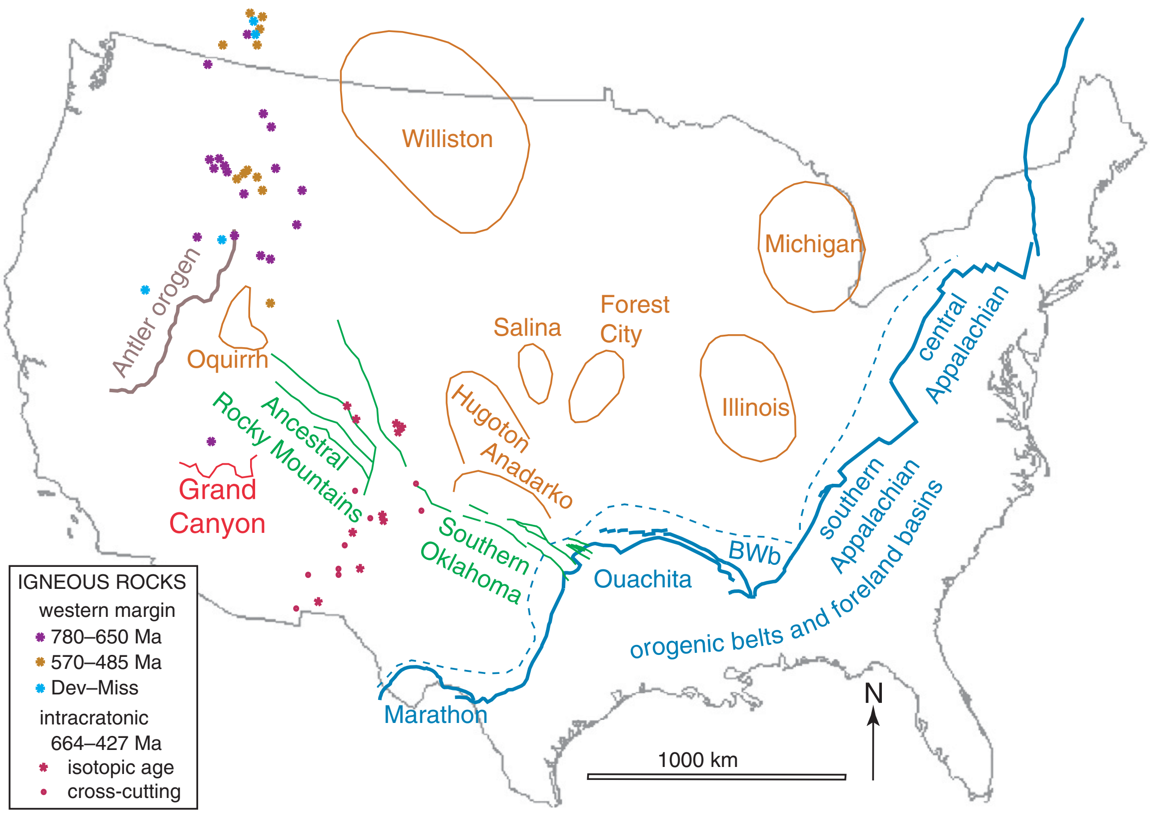

Figure 1. Map of late Paleozoic structures in the United States: intracratonic basins (orange) and fault systems (green), and orogenic belts (blue and brown). Locations and ages of igneous rocks are from Lund et al. (2010) and McMillan and McLemore (2004). Abbreviation: BWb—Black Warrior basin.

drainage network (Mack et al., 1981). Petrography and facies relationships show that the Black Warrior basin was filled with northeastward prograding clastic sediment from an arc/forearc complex within the Ouachita orogen (Mack et al., 1983; Thomas, 1988; Mars and Thomas, 1999). In the eastern Black Warrior basin, the synorogenic Mississippian clastic facies grades northeastward into a coeval shelf carbonate, further indicating northeastward sediment dispersal in the eastern Ouachita foreland, not westward or southwestward from the Appalachians (Thomas, 1988).

Pennsylvanian–Permian

Detrital-zircon populations in Lower Pennsylvanian sandstones along the length of the Appalachian foreland basin (Gray and Zeitler, 1997; Thomas et al., 2004; Becker et al., 2005) include ages representative of the Taconic and Acadian orogenies but *not* of the contemporaneous Alleghanian orogeny. This observation prompted a conclusion that the Appalachian synorogenic clastic wedges commonly have detrital-zircon age populations that are one orogeny behind (Thomas et al., 2004), suggesting that erosional unroofing of synorogenic zircon-yielding rocks was not far enough advanced to include those zircons in the detritus (indicating a long "lag time" as used by Gehrels et al., 2011).

Geochemical data indicate that Alleghanian-age plutons in the southern Appalachians represent anatexis of continental crust (e.g., Samson et al., 1995), and the zircons commonly contain xenocrystic cores (Heatherington and Mueller, 2004). One zircon grain in Permian strata (Washington Formation) has a 314-Ma rim around an 1108-Ma core, constituting the earliest record of Alleghanian detrital zircons in the Appalachian foreland basin (Becker et al., 2006). The dominance of xenocrystic cores may account for the paucity of Alleghanian-age zircons in the Appalachian foreland, and abrasion of rims may limit survival for long distances of transport.

Whether the cause is the rate of unroofing or fragile rims on xenocrystic zircons, the general lack of Alleghanian-age detrital zircons in the proximal parts of the Alleghanian foreland basin limits bypassing to the Grand Canyon with a short lag time. The inferred dispersal path to the Grand Canyon has many exposures of Pennsylvanian strata (Fig. 1), for example the classic cyclothems of the Illinois basin (Collinson et al., 1988) and across cratonic basins and arches farther west (Bunker et al., 1988). A small area of Permian rocks (Mauzy Formation) is preserved in the southern part of the Illinois basin in western Kentucky (Kehn et al., 1982). These outcrops of Pennsylvanian and Permian strata offer opportunities to document the ages of detrital zircons along the inferred dispersal path from the Appalachians to the Grand Canyon. South of the Midcontinent, large-amplitude basement uplifts along the Southern Oklahoma (Arbuckle-Wichita-Amarillo) fault system (Fig. 1) provided local sources of clastic sediment, beginning with Pennsylvanian "granite wash" (Johnson et al., 1988).

Along the western side of the Midcontinent, the Ancestral Rocky Mountains (Fig. 1) formed a dominating supply of clastic sediment from basement uplifts during Pennsylvanian and Permian (e.g., Baars, 1988). Outwash from the Ancestral Rockies must have blocked transcontinental drainage across the region between the Marathon foreland on the south and Wyoming on the north and, also, provided local sources of Pennsylvanian–Permian detritus, culminating in the Fountain, Sangre de Cristo, Maroon, and Cutler red beds. Facies distributions suggest significant dispersal of sediment (and correlation of specific stratigraphic units) westward from the Ancestral Rockies to the Grand Canyon (Baars, 1988). Detrital-zircon populations from specific units in the Ancestral Rockies could clarify which components of the Grand Canyon sediment came from sources outside the Ancestral Rockies.

OTHER CONSIDERATIONS IN IDENTIFYING SEDIMENT SOURCES FROM DETRITAL-ZIRCON AGES

Recent research suggests other considerations in the use of detrital-zircon populations in provenance interpretations. Sandstones in the Appalachian foreland, as well as elsewhere, are dominated by Grenville-age zircons, consistent with very high concentrations of zirconium in Grenville rocks (Moecher and Samson, 2006). Abundant Grenville-age zircons have remained in the system for recycling and constitute widespread dominance of detrital populations. Grenville-age detrital zircons were distributed across most of the Laurentian craton during the Neoproterozoic and incorporated in Neoproterozoic–Cambrian sandstones in western North America (Rainbird et al., 1992; Stewart et al., 2001; Bloch et al., 2006; Mueller et al., 2007). Erosion of Neoproterozoic–Cambrian sedimentary rocks potentially unleashed a new flood of recycled Grenville-age zircons, in addition to primary Grenville sources.

The rate of unroofing, or lag time, is a critical factor in controlling detrital-zircon populations, for example, the lack of Alleghanian-age zircons in Pennsylvanian Appalachian foreland sandstones suggests delayed exhumation of Alleghanian plutons early in the erosional history of the orogen. The ultimate result of unroofing may be the complete removal of some components of the provenance, allowing that a detrital-zircon population may include some components that are no longer present or are sparsely represented in the eroded roots of the source area. For example, a Proterozoic silicic volcanic field, subsequently eroded away except for rare granite plutons, is inferred to be a possible source of 1100-Ma detrital zircons in western North America (Stewart et al., 2001). In an orogenic setting, previous sources of zircons from shallow plutons may have been completely removed and be represented at present only by deeply exhumed crystalline rocks.

Availability of zircons to erosion and transport from either primary crystalline sources or recycled sedimentary sources requires that the zircon-bearing rocks be exposed at the appropriate time (or times). For example, much of the area of primary crystalline rocks in the Laurentian craton was covered by early–middle Paleozoic sediment during the late Paleozoic and was not available as a source of sediment. Later unroofing may restore a temporarily covered sediment source, "turning the source off and on."

Because of the durability of zircons, recycling from older sedimentary deposits may constitute a more significant source than from primary crystalline sources. Recycling complicates interpretation of sediment dispersal, because the time of "storage" of zircons in first- or multi-cycle sediments may mask successive dispersal events of different paths and tectonic settings. For example, Gehrels et al. (2011) suggest that detrital zircons from original Appalachian sources, now in eolian sandstones in the Grand Canyon succession, were transported first northwestward by transcontinental rivers (from the Appalachians) and then southward by prevailing winds. This hypothesized sediment transport encompasses two independent dispersal processes and paths, and illustrates the complexities of interpreting multi-cycle detrital zircons. This example could be tested for the ages of detrital zircons in Pennsylvanian sandstones in the inferred storage (however brief) deposits in the region to the north of the Grand Canyon, as well as along the paths both northwestward from the Appalachians and southward to the Grand Canyon.

ALTERNATE SOURCES, IF NOT THE APPALACHIANS

Specifically for the Grand Canyon examples, if the Appalachian source cannot be confirmed by detrital-zircon tracking of the dispersal path, are other potential sources available? The basement rocks of the Yavapai and

Mazatzal provinces in the Ancestral Rockies clearly constitute a proximal source of Paleoproterozoic detrital zircons for the Grand Canyon strata (Gehrels et al., 2011). Could that same source have supplied some of the younger zircons? In southern Colorado and New Mexico (the southern part of the Ancestral Rockies, Fig. 1), the basement rocks are cut by plutons that range in age from 664 to 427 Ma (McMillan and McLemore, 2004); these could supply zircons with ages that correspond to "Taconic," "Iapetan synrift," and "accreted Gondwanan terranes," which are not distinguishable by age alone from Iapetan synrift rocks.

Consideration of regional north-to-south eolian sediment transport of Appalachian-derived sand to the Grand Canyon (Gehrels et al., 2011) suggests that other alternatives for sources of the sediment could be linked by multi-element dispersal systems. The Grenville-age zircons that are common in the Mississippian to Permian (but not older) strata in the Grand Canyon could have been recycled from Neoproterozoic–Cambrian sandstones in northwestern Laurentia (e.g., Rainbird et al., 1992; Stewart et al., 2001; Mueller et al., 2007). Alternatively, the well-documented southward wind transport might reflect local reworking along coastal dunes of lithic and muddy sands of the distal Cutler Group from the Ancestral Rocky Mountains (e.g., Baars, 1988).

Although available detrital-zircon data from the Antler orogenic belt (Fig. 1) do not show a good match for the detrital-zircon populations in Grand Canyon (Gehrels et al., 2011), the western margin of Laurentia is a geologically complex region worthy of further consideration and analysis. Rift-related igneous rocks, with ages of 780–485 Ma, are known to be scattered along the western margin from northern Canada to Nevada (Fig. 1); less common Devonian–Mississippian igneous rocks are documented locally along the same margin (summary in Lund et al., 2010). This range of ages spans much, but not all, of the range of ages of post-Grenville detrital zircons in the Grand Canyon, constituting a viable source if sediment were transported from north to south generally along the Antler foreland. Accreted terranes, in and trailing the Antler orogenic belt, contain a wide variety of rock types and ages (e.g., Gray, 1986; Dickinson, 2000; Dickinson and Gehrels, 2000; Unterschutz et al., 2002; Wright and Wyld, 2006). Have other potential sources been displaced tectonically along strike, covered by later allochthons, covered by younger sediment, or eroded away from the present landscape? Tests of potential drainages from the synorogenic and post-orogenic Antler orogen could further evaluate these alternatives. For any of these alternatives, the dispersal path could be tracked by analysis of detrital-zircon populations in, for example, the Pennsylvanian succession in the Oquirrh basin and the Tensleep and Weber Sandstones on the western Wyoming shelf.

The Ouachita and Marathon orogenic belts (Fig. 1) along the southern margin of Laurentia are not considered as likely sources of detritus for the Grand Canyon because of a lack of good matches for the detrital-zircon populations (Gehrels et al., 2011), a conclusion that is supported by regional facies distributions. Because the late Paleozoic synorogenic sediment in the Ouachita and Marathon foreland basins is largely in deep-water turbidites (Viele and Thomas, 1989), it is unlikely that much clastic sediment prograded onto the distal continental platform from the sources of orogenic sediment. The Ouachita and Marathon foreland basins formed sinks rather than dispersal paths for clastic sediment.

Several patterns of detrital-zircon age distributions in the Grand Canyon data may provide more clues to multiple sources (figures 5 and 6 in Gehrels et al., 2011). Yavapai, Mazatzal, and Granite-Rhyolite ages dominate the Cambrian detrital-zircon populations, as well as the Devonian; however, the Devonian Temple Butte Formation has a few zircons with ages of 521–403 Ma. Beginning with the Upper Mississippian and continuing through the Permian units, important components of Grenville and younger ages are added progressively to the pre-Grenville components. A non-systematic upward increase in diversity and range of both older and younger ages characterizes the Mississippian–Permian post-Grenville detrital-zircon populations, beginning with a range of 500–400 Ma in the Mississippian Surprise Canyon Formation and culminating with a range of 700–250 Ma in the Permian Kaibab Limestone. A similar pattern is not evident in the Appalachian populations, and several residual-age peaks indicate mismatches of the Grand Canyon and Appalachian Permian detrital-zircon populations (figure 9 in Gehrels et al., 2011). The progressively increasing diversity through Mississippian–Permian indicates addition of multiple or expanding sources during that time frame.

The Devonian Temple Butte and Mississippian Surprise Canyon Formations both overlie carbonate-platform facies and fill channels on unconformities that extend over the western craton. The Mississippian unconformity truncates the top of the regional Redwall–Leadville Limestone and includes karst-fill red beds (Molas Formation) in the Ancestral Rockies (Baars, 1988). Both unconformities and the channel-filling formations suggest significant reworking of sediment across a wide, nearly planar surface on shelf carbonates, possibly allowing for concentration of resistant detritus and mixing of sediment from diverse sources.

What were the dispersal directions of the clastic sediment within the Grand Canyon succession? For example, aside from the eolian sands, what was the direction of sediment transport of the muddy and sandy units that represent fluvial to shallow-marine deposition? Are these the distal deposits of the Paradox basin—the Permian Cutler Group facies such as White Rim and Cedar Mesa Sandstones, and Halgaito and Organ Rock mudstones? Patterns of facies distribution and prograding directions at the site of deposition also are important in considering possible paths of sediment dispersal.

DISCUSSION AND CONCLUSIONS

Independent documentation of dispersal systems rests largely on large-scale facies relationships and the prograding direction of clastic tongues within carbonate facies (e.g., Thomas, 1988), as well as the direction of progradation and downlap of clastic parasequences (e.g., Mars and Thomas, 1999). Although paleocurrents commonly are invoked for directions of regional sediment dispersal, they can be properly interpreted only in the context of depositional systems (e.g., Thomas and Mack, 1982). I have stood on a westward-prograding offset distributary mouth bar at South Pass of the Mississippi River delta and observed west-directed longshore and tidal currents and associated sedimentary structures. A simple interpretation of current indicators points to a source directly to the east; however, of course, the sediment actually came from the drainage basin of the Mississippi River and tributaries such as the Missouri River and Ohio River, indicating a provenance that extends northwest to the Rocky Mountains and east to the Appalachians. Paleocurrent data yield the direction of the last current to move the sediment, and have no necessary local relationship to the long-distance dispersal from provenance to depositional site, which is better documented by regional facies distribution and progradation directions.

Tracking dispersal paths through the analysis of detrital-zircon populations is a promising new application for zircon geochronology. Detrital zircons offer an excellent way to track the dispersal system from source to sink. Such a test could begin with critical areas first; for example, a lack of Alleghanian-age zircons in Pennsylvanian-age sandstones in the proximal sediments in the Appalachian foreland basin characterizes the headwaters of an inferred dispersal path from the Appalachians to the Grand Canyon. While matching detrital-zircon age populations with crystallization ages of potential source(s) of sediment provides a non-unique identification of the possible provenance, critical analysis of dispersal systems seems to have lagged behind and is a clearly essential next step for provenance studies. If large-scale facies distributions and prograding directions can serve as the principal guide to directions of sediment dispersal, detrital-zircon geochronology provides a powerful test of the complete dispersal system from source to sink.

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REFERENCES CITED

Baars, D.L., 1988, Triassic and older stratigraphy; Southern Rocky Mountains and Colorado Plateau, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 53–64.

Becker, T.P., Thomas, W.A., Samson, S.D., and Gehrels, G.E., 2005, Detrital zircon evidence of Laurentian crustal dominance in the lower Pennsylvanian deposits of the Alleghanian clastic wedge in eastern North America: Sedimentary Geology, v. 182, p. 59–86, doi:10.1016/j.sedgeo.2005.07.014.

Becker, T.P., Thomas, W.A., and Gehrels, G.E., 2006, Linking late Paleozoic sedimentary provenance in the Appalachian basin to the history of Alleghanian deformation: American Journal of Science, v. 306, p. 777–798, doi:10.2475/10.2006.01.

Bloch, J.D., Timmons, J.M., Crossey, L.J., Gehrels, G.E., and Karlstrom, K.E., 2006, Mudstone petrology of the Mesoproterozoic Unkar Group, Grand Canyon, U.S.A.: Provenance, weathering, and sediment transport on intracratonic Rodinia: Journal of Sedimentary Research, v. 76, p. 1106–1119, doi:10.2110/jsr.2006.107.

Bunker, B.J., Witzke, B.J., Watney, W.L., and Ludvigson, G.A., 1988, Phanerozoic history of the central midcontinent, United States, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 243–260.

Cawood, P.A., and Nemchin, A.A., 2001, Paleogeographic development of the east Laurentian margin: Constraints from U-Pb dating of detrital zircons in the Newfoundland Appalachians: Geological Society of America Bulletin, v. 113, p. 1234–1246, doi:10.1130/0016-7606(2001)113<1234:PDOTEL>2.0.CO;2.

Collinson, C., Sargent, M.L., and Jennings, J.R., 1988, Illinois Basin region, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 383–426.

Dickinson, W.R., 2000, Geodynamic interpretation of Paleozoic tectonic trends oriented oblique to the Mesozoic Klamath-Sierran continental margin in California, *in* Soreghan, M.J., and Gehrels, G.E., eds., Paleozoic and Triassic Paleogeography and Tectonics of Western Nevada and Northern California: Geological Society of America Special Paper 347, p. 209–245.

Dickinson, W.R., and Gehrels, G.E., 2000, Sandstone petrofacies of detrital zircon samples from Paleozoic and Triassic strata in suspect terranes of northern Nevada and California, *in* Soreghan, M.J., and Gehrels, G.E., eds. Paleozoic and Triassic Paleogeography and Tectonics of Western Nevada and Northern California: Geological Society of America Special Paper 347, p. 151–171.

Dickinson, W.R., and Suczek, C.A., 1979, Plate tectonics and sandstone composition: The American Association of Petroleum Geologists Bulletin, v. 63, p. 2164–2182.

Dickinson, W.R., Beard, L.S., Brakenridge, G.R., Erjavec, J.L., Ferguson, R.C., Inman, K.F., Knepp, R.A., Lindberg, F.A., and Ryberg, P.T., 1983, Provenance of North American Phanerozoic sandstones in relation to tectonic setting: Geological Society of America Bulletin, v. 94, p. 222–235, doi:10.1130/0016-7606(1983)94<222:PONAPS>2.0.CO;2.

Gehrels, G.E., Blakey, R., Karlstrom, K.E., Timmons, J.M., Dickinson, B., and Pecha, M., 2011, Detrital zircon U-Pb geochronology of Paleozoic strata in the Grand Canyon, Arizona: Lithosphere, v. 3, p. 183–200, doi:10.1130/L121.1.

Gray, G.G., 1986, Native terranes of the central Klamath Mountains, California: Tectonics, v. 5, p. 1043–1054, doi:10.1029/TC005i007p01043.

Gray, M.B., and Zeitler, P.K., 1997, Comparison of clastic wedge provenance in the Appalachian foreland using U/Pb ages of detrital zircons: Tectonics, v. 16, p. 151–160, doi:10.1029/96TC02911.

Heatherington, A.L., and Mueller, P.A., 2004, U-Pb zircon ages from the Inner Piedmont terrane: Implications for a Laurentian origin: Geological Society of America Abstracts with Programs, v. 36, no. 2, p. 74–75.

Hiscott, R.N., 1984, Ophiolitic source rocks for Taconic-age flysch: Trace-element evidence: Geological Society of America Bulletin, v. 95, p. 1261–1267, doi:10.1130/0016-7606(1984)95<1261:OSRFTF>2.0.CO;2.

Ingersoll, R.V., and Suczek, C.A., 1979, Petrology and provenance of Neogene sand from Nicobar and Bengal fans, DSDP sites 211 and 218: Journal of Sedimentary Petrology, v. 49, p. 1217–1228.

Johnson, K.S., Amsden, T.W., Denison, R.E., Dutton, S.P., Goldstein, A.G., Rascoe, B., Jr., Sutherland, P.K., and Thompson, D.M., 1988, Southern Midcontinent region, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 307–359.

Kehn, T.M., Beard, J.G., and Williamson, A.D., 1982, Mauzy Formation, a new stratigraphic unit of Permian age in western Kentucky: U.S. Geological Survey Bulletin 1529-H, p. H73–H86.

Lund, K., Aleinikoff, J.N., Evans, K.V., duBray, E.A., Dewitt, E.H., and Unruh, D.M., 2010, SHRIMP U-Pb dating of recurrent Cryogenian and Late Cambrian–Early Ordovician alkalic magmatism in central Idaho: Implications for Rodinian rift tectonics: Geological Society of America Bulletin, v. 122, p. 430–453, doi:10.1130/B26565.1.

Mack, G.H., James, W.C., and Thomas, W.A., 1981, Orogenic provenance of Mississippian sandstones associated with southern Appalachian-Ouachita orogen: The American Association of Petroleum Geologists Bulletin, v. 65, p. 1444–1456.

Mack, G.H., Thomas, W.A., and Horsey, C.A., 1983, Composition of Carboniferous sandstones and tectonic framework of southern Appalachian-Ouachita orogen: Journal of Sedimentary Petrology, v. 53, p. 931–946.

Mars, J.C., and Thomas, W.A., 1999, Sequential filling of a late Paleozoic foreland basin: Journal of Sedimentary Research, v. 69, p. 1191–1208.

McMillan, N.J., and McLemore, V.T., 2004, Cambrian-Ordovician magmatism and extension in New Mexico and Colorado: New Mexico Bureau of Geology and Mineral Resources Bulletin 160, 11 p.

Moecher, D.P., and Samson, S.D., 2006, Differential zircon fertility of source terranes and natural bias in the detrital zircon record: Implications for sedimentary provenance analysis: Earth and Planetary Science Letters, v. 247, p. 252–266, doi:10.1016/j.epsl.2006.04.035.

Mueller, P.A., Foster, D.A., Mogk, D.W., Wooden, J.L., Kamenov, G.D., and Vogl, J.J., 2007, Detrital mineral chronology of the Uinta Mountain Group: Implications for the Grenville flood in southwestern Laurentia: Geology, v. 35, p. 431–434, doi:10.1130/G23148A.1.

Park, H., Barbeau, D.L., Jr., Rickenbaker, A., Bachmann-Krug, D., and Gehrels, G., 2010, Application of foreland basin detrital-zircon geochronology to the reconstruction of the southern and central Appalachian orogen: The Journal of Geology, v. 118, p. 23–44, doi:10.1086/648400.

Rainbird, R.H., Heaman, L.M., and Young, G., 1992, Sampling Laurentia: Detrital zircon geochronology offers evidence for an extensive Neoproterozoic river system originating from the Grenville orogen: Geology, v. 20, p. 351–354, doi:10.1130/0091-7613(1992)020<0351:SLDZGO>2.3.CO;2.

Samson, S.D., Coler, D.G., and Speer, J.A., 1995, Geochemical and Nd-Sr-Pb isotopic composition of Alleghanian granites of the Southern Appalachians: Origin, tectonic setting, and source characterization: Earth and Planetary Science Letters, v. 134, p. 359–376, doi:10.1016/0012-821X(95)00124-U.

Stewart, J.H., Gehrels, G.E., Barth, A.P., Link, P.K., Christie-Blick, N., and Wrucke, C.T., 2001, Detrital zircon provenance of Mesoproterozoic to Cambrian arenites in the western United States and northwestern Mexico: Geological Society of America Bulletin, v. 113, p. 1343–1356, doi:10.1130/0016-7606(2001)113<1343:DZPOMT>2.0.CO;2.

Swann, D.H., 1964, Late Mississippian rhythmic sediments of Mississippi Valley: The American Association of Petroleum Geologists Bulletin, v. 48, p. 637–658.

Thomas, W.A., 1959, Upper Mississippian stratigraphy of southwestern Virginia, southern West Virginia, and eastern Kentucky [Ph.D. thesis]: Virginia Polytechnic Institute, 322 p.

Thomas, W.A., 1988, The Black Warrior basin, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Geological Society of America, The Geology of North America, v. D-2, p. 471–492, Plate 8.

Thomas, W.A., and Mack, G.H., 1982, Paleogeographic relationship of a Mississippian barrier-island and shelf bar system (Hartselle Sandstone) in Alabama to the Appalachian-Ouachita orogenic belt: Geological Society of America Bulletin, v. 93, p. 6–19, doi:10.1130/0016-7606(1982)93<6:PROAMB>2.0.CO;2.

Thomas, W.A., and Schenk, P.E., 1988, Late Palaeozoic sedimentation along the Appalachian orogen, *in* Harris, A.L., and Fettes, D.J., eds., The Caledonian-Appalachian Orogen: Geological Society of London Special Publication 38, p. 515–530.

Thomas, W.A., Viele, G.W., Arbenz, J.K., Nicholas, R.L., Denison, R.E., Muehlberger, W.R., and Tauvers, P.R., 1989, Tectonic map of the Ouachita orogen, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Geological Society of America, The Geology of North America, v. F-2, Plate 9.

Thomas, W.A., Becker, T.P., Samson, S.D., and Hamilton, M.A., 2004, Detrital zircon evidence of a recycled orogenic foreland provenance for Alleghanian clastic-wedge sandstones: The Journal of Geology, v. 112, p. 23–37, doi:10.1086/379690.

Unterschutz, J.L.E., Creaser, R.A., Erdmer, P., Thompson, R.I., and Daughtry, K.L., 2002, North American margin origin of Quesnel terrane strata in the southern Canadian Cordillera: Inferences from geochemical and Nd isotopic characteristics of Triassic metasedimentary rocks: Geological Society of America Bulletin, v. 114, p. 462–475, doi:10.1130/0016-7606(2002)114<0462:NAMOOQ>2.0.CO;2.

Viele, G.W., and Thomas, W.A., 1989, Tectonic synthesis of the Ouachita orogenic belt, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Geological Society of America, The Geology of North America, v. F-2, p. 695–728.

Welch, S.W., 1978, Deposition of the Carter-Sanders zone of the Black Warrior basin, Mississippi and Alabama: Mississippi Geological Society Guidebook, 17th Field Trip, p. 25–33.

Wright, J.E., and Wyld, S.J., 2006, Gondwanan, Iapetan, Cordilleran interactions: A geodynamic model for the Paleozoic tectonic evolution of the North American Cordillera, *in* Haggart, J.W., Enkin, R.J., and Monger, J.W.H., eds., Paleogeography of the North American Cordillera: Evidence For and Against Large-Scale Displacements: Geological Association of Canada Special Paper 46, p. 377–408.

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