Recovering tectonic events from the sedimentary record: Detrital monazite plays in high fidelity

Jack Hietpas\textsuperscript{1}, Scott Samson\textsuperscript{1}, David Moecher\textsuperscript{2}, and Axel K. Schmitt\textsuperscript{2}

\textsuperscript{1}Syracuse University, Department of Earth Sciences, Syracuse, New York 13244, USA
\textsuperscript{2}University of Kentucky, Department of Earth and Environmental Sciences, Lexington, Kentucky 40506, USA
\textsuperscript{3}University of California–Los Angeles, Department of Earth and Space Sciences, Los Angeles, California 90095, USA

\section*{ABSTRACT}

Measurement of detrital zircon U-Pb ages has become the method of choice for single crystal–based investigations of provenance for both modern and ancient sediments. Recent studies, however, demonstrated the failure of zircon to record major tectonic events in source terranes, revealing the need for a more robust provenance methodology. A direct comparison between the utility of crystallization ages of detrital zircon and monazite as provenance indicators has been made using modern river alluvium derived from known sources. While detrital zircon does not fully record the multiple collisional phases that are the hallmark of the Appalachian orogen, detrital monazite accurately records all the major tectonic events. The physical and petrogenetic differences between zircon and monazite are the primary factors for differing detrital age spectra. Zircon, owing to its extreme refractory nature, skews detrital age spectra toward older ages and limits its ability to record low-grade thermotectonic events in orogens. Monazite recrystallizes over a broader range of metamorphic conditions than does zircon. Consequently, monazite has the potential to record metamorphic events that might otherwise be absent from the detrital zircon record, thus providing a more accurate record of source terranes in regions characterized by moderate thermal events.

\section*{INTRODUCTION}

Recent advances in microanalytical in situ methods have greatly accelerated the acquisition of U-Pb dates of single zircon crystals, which in turn has led to an explosion of zircon-based provenance studies (Gehrels et al., 2008). Detrital zircon geochronology has also proven useful for constraining paleogeographic reconstructions (Cawood and Nemchin, 2001), and for recognition of paleodrainage patterns (Rainbird et al., 1992). Despite this, detrital zircon–based studies reveal shortcomings in the single-mineral provenance approach (Moecher and Samson, 2006, and references therein). These include (1) the unresponsiveness of zircon growth during nonmagmatic to marginally magmatic thermotectonic events. If a tectonic event did not reach sufficient grade, little new zircon would be formed, thus rendering the event absent from the detrital zircon record. (2) Zircon inheritance in granitoids is common. Zircon has a low solubility in metaluminous and peraluminous melts generated by partial melting at temperatures \~700–800 °C (Watson and Harrison, 1983). Xenocrystic zircon serves as nucleation seeds for new zircon growth. Crystallization ages of overgrowths are not routinely measured in typical zircon-based provenance protocols, but we present data demonstrating that significant age information can be gleaned if such analyses are undertaken. Zircon shed from plutons that contain significant inheritance will appear to be derived from an older source if only cores are analyzed, when in reality they have simply survived a younger magmatic event that may be more characteristic of the orogen providing detritus to the basin. (3) Zircon is ultrastable in terms of resistance to chemical and mechanical weathering, leading to recycling of zircon through time (Mange and Maurer, 1992). Recycling produces a natural bias in the detrital record, resulting in the overrepresentation of older crust compared to that providing the majority of detritus for the sediment under investigation.

Paleozoic sediment derived from the Appalachian orogen demonstrates the potential shortcomings of detrital zircon as a provenance indicator (Fig. 1). The Appalachians, partly assembled on Grenville-aged (ca. 1300–950 Ma) basement rocks of the Laurentian margin, are traditionally viewed as having formed by the combined effects of the Taconian orogeny (ca. 470–440 Ma), the Acadian orogeny (ca. 420–380 Ma), and the Alleghanian orogeny, resulting from continental collision between Laurentia and western Gondwana (ca. 320–280 Ma) (Hatcher, 1987). On the basis of previous studies, if the tectonic history of the southern Appalachians were based solely on detrital zircon age populations of Paleozoic sandstones or modern alluvium, one would not conclude that Laurentia and western Gondwana collided to form the supercontinent Pangea (Eriksson et al., 2003, 2004; Thomas et al., 2004; Becker et al., 2005, 2006).

Monazite [(La,Nd,Ce)PO\textsubscript{4}] is common in high-silica granitoids and pegmatites and is nearly ubiquitous in metapelites and metapsammites (Spear and Pyle, 2002; Williams et al., 2007). It forms over a range of conditions, spanning low-pressure contact aureoles to granulite facies and ultrahigh-pressure pelitic rocks (Spear and Pyle, 2002). Because monazite can crystallize at much lower grade conditions than zircon, it has the ability to record metamorphic episodes potentially missed by zircon. However, as a consequence of its petrogenesis, monazite would be of limited utility as a provenance proxy for regions that are primarily defined by large volumes of igneous rock, such as major batholiths (e.g., Sierra Nevada). Monazite incorporates U and Th at weight percent concentrations but does not incorporate Pb to a significant level during crystall growth. Consequently, monazite is a reliable U-Th-Pb geochronometer, and its age can be determined by a variety of analytical techniques.

Figure 1. Histogram and probability density distribution for previously published detrital zircon ages for Pennsylvanian through modern river sediments derived from southern Appalachian source terranes (Gray and Zeitler, 1997; Eriksson et al., 2003, 2004; Thomas et al., 2004; Becker et al., 2005, 2006). Note dominance of Pennsylvanian age modes and suppressed Paleozoic signals.

© 2010 Geological Society of America. For permission to copy, contact Copyright Permissions, GSA, or editing@geosociety.org.
Chemical and mechanical weathering during erosion, transport, and lithification (Cherniak et al., 2004) and because it is moderately resistant to chemical breakdown (e.g., Hering and Zimmerle, 1963). However, it is less abundant than zircon in mature sandstones and is more susceptible to chemical breakdown (to ThSiO$_4$ plus allanite or florencite) in sandstones of moderate-grade metamorphism (Rasmussen and Muhling, 2009). The lower durability of monazite means that it less likely to survive multiple episodes of sedimentary recycling compared to zircon, thus increasing the probability it will act as a first-cycle provenance proxy.

Detrital monazite has been utilized in remarkably few provenance studies (Ross et al., 1991; Evans et al., 2001) and in those studies the suitability of detrital monazite as a provenance proxy proved to be ambiguous. Our study is the first to fully assess the utility of detrital monazite as a provenance proxy by taking advantage of a novel high-throughput, less matrix-dependent analytical method that allows for the generation of data sets that are statistically robust.

**METHODS**

Samples of coarse sand were collected from the French Broad River and six tributaries in the Appalachian Blue Ridge (Fig. 2). The tributaries are predominantly draining the Ashe Formation, which consists of schists and gneisses with inferred Neoproterozoic clastic protoliths. Detrital zircon and monazite were isolated using standard methods, i.e., sieving, Wilfley table concentration, heavy liquids, and Frantz magnetic separations. Monazite and zircon were selected from all recognizable populations based on size, crystal morphology, and color. Individual crystals, along with age standards, were embedded in epoxy. Cured mounts were then ground to expose the interiors of the crystals. Each crystal was imaged by secondary electron and backscattered electron imaging using a JEOL 8600 Superprobe. Zircon was also imaged using cathodoluminescence (CL). Monazite $^{208}$Pb/$^{232}$Th isotopic dates were measured using secondary ion mass spectrometry (SIMS) at the University of California–Los Angeles using a 22.5 keV mass-filtered $^{16}$O primary beam with an intensity of ~5 nA. Secondary ions were accelerated to 10 kV, with the exception of $^{208}$Pb, $^{232}$Th, and $^{232}$Th$^{6+}$ ions, for which an energy offset of ~20 to ~30 eV was applied. Preliminary tests indicated that analysis of high-energy ions for $^{208}$Pb and Th species mitigates matrix effects resulting from variable Th abundances in monazite, although we find that Th abundances of unknown monazites studied here are generally comparable to reference monazite MOM3 (age 481.8 Ma). Common Pb correction is based on measuring $^{208}$Pb, after adjustment for intensity loss affecting high-energy $^{208}$Pb, and a $^{144}$NdThO$^+$ isobaric interference from measurement of $^{144}$NdThO$^+$. The relative sensitivities of Pb and Th were determined on reference monazite MOM3 using a previously described calibration technique (Harrison et al., 1995). Detrital zircon U-Pb ages were determined either by SIMS or by laser ablation-multicollector inductively coupled plasma–mass spectrometry (as described in Hietpas, 2009). Monazite and zircon data are provided in the GSA Data Repository.

**RESULTS**

Following standard methods, we initially analyzed only the cores of detrital zircon crystals from six tributaries that feed the French Broad River. The zircon age populations are dominated by Grenville ages with a limited Taconian signal (Fig. 3). Detrital monazite from these same tributaries, however, yields essentially one age (ca. 460 Ma), corresponding to a limited Taconian metamorphic event between 480 and 490 Ma (Ross et al., 1991). Monazite ages thus accurately reflect the time of tectonometamorphism of this sediment source in contrast to detrital zircon, which records much older ages,

---

1GSA Data Repository item 2010033, zircon and monazite data, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

---

Figure 2. Simplified terrane map of southern Appalachian Blue Ridge. Inset diagram shows location of sampling area within western North Carolina–eastern Tennessee. Taconian regional metamorphism in drainage basin of French Broad River ranges from greenschist to upper amphibolite facies. Kyanite-sillimanite isograd occurs in vicinity of alluvium samples collected in small tributaries (rectangle) (Merchat and Weiner, 1988). Sillimanite-bearing metapelites in Ashe Metamorphic Suite are migmatitic, consistent with conditions suitable for zircon growth (Moecher and Samson, 2006). Black arrows mark sampling locations. Black square marks location of sampled tributaries. Geographic information system data are available from U.S. Geological Survey (EROS Data Center, Sioux Falls, South Dakota).
demonstrating the impact of recycling of zircon from a secondary stabilized crustal region.

Given the dramatically different geologic histories recorded by detrital monazite and zircon, zircon crystals were further analyzed by measuring the ages of thin rims, identified by CL images of each grain (Hoskin and Schaltegger, 2003). The measurement of rim ages dramatically changes the proportion of Taconian to Grenville ages, yielding a closer correlation with the actual proportion of ages and modes in the region (Fig. 3). These data clearly demonstrate the importance of an analysis methodology that is guided by the individual characteristics of each detrital grain. Valuable information could be lost, and inaccurate assessment of source lithologies could be inferred, if the fidelity of zircon-based studies is interpreted solely on the ages of cores.

The detrital zircon and monazite age spectra for the main trunk of the French Broad River are much more diverse than the smaller tributaries, reflecting the river’s regional sampling scale (Ingersoll, 1990; Cawood et al., 2003; Link et al., 2005). Detrital zircon cores faithfully record Grenville and Taconian signals, exhibit a very limited Acadian signal, and completely fail to record the Alleghanian event. Detrital monazite from these same sediments, however, records the complete Paleozoic collisional history of the Appalachian orogen and the main events for the Grenville basement (Fig. 4). Detrital monazite ages (n = 86) include a strong Taconian mode and the Acadian mode is more substantially represented than in zircon-based studies. In addition, the elusive ca. 300 Ma old Alleghanian-aged mode is repeatedly recorded by monazite.

With the goal of meticulously evaluating detrital zircon as a provenance proxy, we reanalyzed zircon crystals that, based on CL imaging, appeared to have overgrowths. The overall impact of overgrowth on the zircon age distribution was not as pronounced as that seen in the tributaries (Fig. 5). Only a single Alleghanian age was recorded. In total, ~850 zircon age measurements (cores and rims) from the tributaries and main trunk of the French Broad River were performed, yet the Acadian orogenic event was still underrepresented and the Alleghanian event was essentially missed. In fact, prior knowledge of the geologic history of the region is the only basis for assigning any weight to a single ca. 300 Ma rim age. In a region of unknown history, no stock would be placed in a single age, and certainly no one would deduce that a supercontinent-forming orogenic event had occurred.

CONCLUSIONS

The determination of ancient sediment provenance remains one of the key tools for understanding the complex dynamic history of the Earth. Detritus shed from ancient orogens may be the only remnant we have for determining the timing, evolution, geography, and existence of tectonic events that were active over the past 4.56 Ga of Earth’s history. Detrital zircon remains the provenance proxy of choice if felsic plutons and cratonic basement are the major components of a terrane. However, detrital zircon age spectra, owing to the super-refractory nature of the mineral, tend to record an overabundance of older age populations and to under-represent younger events. Based on our data, the crystallization ages of detrital monazite more effectively record moderate- to low-temperature metamorphic events that define many orogens, thus providing a more complete assessment of the sediment donor terranes for various regions.
of study. In addition, the data presented here demonstrate the importance of fully understanding how a chosen provenance proxy (mineral species) will behave in terms of its genesis, weathering from its protolith, transportation, lithification, and diagenesis. Finally, our data suggest that a dual-mineral approach to sediment provenance takes advantage of the complementary strengths of zircon and monazite, thus providing a more complete way to identify potential source terranes.

ACKNOWLEDGMENTS

This work was supported by National Science Foundation (NSF) grants EAR-0635643 and EAR-0635688. Grants from the NSF Instrumentation and Facilities Program, Division of Earth Sciences, supported the UCLA ion microprobe facility (EAR-0732691) and the Laserchron facility (EAR-0732436). Histograms and probability density plots were made using Keith Sircombe’s AgeDisplay Microsoft Excel macro. We thank Jacqueline Speir, Scott Miller, and Bryan Sell for help with the digital cartography, Suvankar Chakraborty for help in sample collection, and Carl Merschat of the North Carolina Geological Survey for providing heavy mineral separates isolated from the tributaries. We also thank George Gehrels, Frank Spear, and an anonymous reviewer for constructive criticism that significantly improved the manuscript.

REFERENCES CITED


