A direct comparison of the ages of detrital monazite versus detrital zircon in Appalachian foreland basin sandstones: Searching for the record of Phanerozoic orogenic events

Jack Hietpas a, Scott Samson a,*, David Moecher b

a Syracuse University, Dept. Earth Sci., Syracuse, NY 13244, USA
b University of Kentucky, Dept. Earth & Env. Sci., Lexington, KY 40506, USA

A R T I C L E  I N F O
Article history:
Received 12 May 2011
Received in revised form 19 August 2011
Accepted 23 August 2011
Available online 1 October 2011

Editor: R.W. Carlson

Keywords:
provenance
detrital monazite
detrital zircon
Appalachian foreland basin
SIMS

A B S T R A C T
The provenance potential of detrital monazite was investigated by in situ measurement of $^{232}$Th–$^{208}$Pb dates of grains isolated from six Middle Carboniferous–Permain sandstones from the Appalachian foreland basin. Provenance assessment of these units was previously investigated by measuring U–Pb crystallization ages of detrital zircon (Thomas et al., 2004; Becker et al., 2005, 2006). Approximately 90% of the detrital zircon ages record Mesoproterozoic or older ages, with only 10% recording the three major pulses of tectonism (Taconian, Acadian and Alleghanian) that are the hallmark of the Appalachian Orogen. $^{232}$Th–$^{208}$Pb ages of detrital monazite, however, strongly record the complex phases of Paleozoic orogenes. Nearly 65% of the ages record Paleozoic events, while 35% record Neoproterozoic or older ages. In several of the analyzed sandstones, detrital monazite ages record Paleozoic orogenic events that are completely missed by detrital zircon ages, demonstrating that monazite ages more accurately reflect the character of the sediment source rocks. The inferred maximum age of sediment deposition, as determined by the youngest monazite grains, is ~550 Ma younger for two of the analyzed sandstones compared to depositional constraints based on the youngest detrital zircon. The different physical properties and petrogenesis of zircon and monazite are interpreted to be factors for the dramatic differences in sediment provenance information provided by each mineral. The results from this study have important implications for determining sediment provenance, constraining maximum age of sediment deposition, and developing robust regional tectonic models.

© 2011 Elsevier B.V. All rights reserved.

1. Introduction

Sediment provenance studies have dramatically increased over the past few decades. This expansion is largely driven by advances in micro-analytical instrumental methods as well as the development of single mineral trace element systematics (Wark and Watson, 2006; Zack et al., 2004), which have provided the ability to exploit provenance information recorded in single detrital mineral species (Adams and Kelley, 1998; Chakraborty et al., 2010; Gehrels and Dickinson, 1995; Morton, 1985; Zack et al., 2004). Incorporating single-mineral analyses with other sedimentological and field-based data-sets has advanced our understanding and resolution of provenance studies to an unprecedented scale (Link et al., 2005). Recently, provenance studies have relied primarily, even exclusively, on the results from single mineral-based investigations, typically U–Pb detrital zircon ages. However, detrital mineral geochronology has limitations (Becker et al., 2005; Eriksson et al., 2004; Gray and Zeitler, 1997; McLennan et al., 2001; Moecher and Samson, 2006; Thomas et al., 2004). A recent investigation compared the provenance information gleaned from detrital zircon and monazite from the French Broad River, which drains portions of the southern Appalachian Orogen (Hietpas et al., 2010). The results from that study demonstrated that detrital zircon recorded an abundance of Mesoproterozoic ages (mostly 1.25–1.0 Ga; i.e. Grenville-aged) but recovered only limited Paleozoic signals. Detrital monazite recorded the complex Paleozoic history of the region with much higher fidelity, thus providing a more accurate record of the volume of rock of each age. This initial study clearly demonstrated the utility of monazite as a provenance indicator in modern environments. The purpose of the present study is to investigate the utility and provenance potential of monazite in ancient sedimentary systems.

Detrital monazite dates were determined for crystals isolated from six Appalachian foreland sandstones from which detrital zircon ages have been previously determined. These sandstones were selected because approximately 90% of the detrital zircon ages are Grenvillian (1.25–1.0 Ga) or older. Just 10% of the total analyzed zircon crystals record the complex Paleozoic tectonic history of the central and southern Appalachians. Of those 10%, only a single zircon overgrowth

* Corresponding author.
E-mail address: sdsamson@syr.edu (S. Samson).
provides evidence for the collision between eastern Laurentia and western Gondwana, culminating in the formation of Pangaea (Becker et al., 2005; Becker et al., 2006; Thomas et al., 2004). The current study provides a rigorous comparison between the age information provided by detrital monazite and that provided by detrital zircon in Late Paleozoic sandstones.

2. Monazite formation and preservation

Monazite, a light rare-earth-element orthophosphate ((La, Ce, Nd)PO₄), is an accessory mineral that forms in both igneous and metamorphic rocks (Williams et al., 2007). Monazite is common in S-type granites (Sawka et al., 1986), but less so in I-type granites (Kelts et al., 2008). Monazite solubility is low in peraluminous melts but progressively increases toward meta-aluminous melt compositions (Rapp et al., 1987; Rapp and Watson, 1986). Therefore, there exists the potential for inherited monazite in some magmatic systems (Copeland et al., 1988; Harrison et al., 1995; Kalt et al., 2000; Kelts et al., 2008). Monazite, however, is much more abundant in metamorphic rocks with pelitic protoliths (Williams et al., 2007). The formation and stabilization of metamorphic monazite have been shown to be in addition to pressure–temperature conditions of metamorphism, dependent on (1) whole-rock chemistry, particularly CaO content (Rasmussen and Muhling, 2009; Wing et al., 2003), (2) nucleation/dissolution of REE-rich phosphates, thorite, titanite, and allanite (Catllos et al., 2002; Kingsbury et al., 1993; Smith and Barreiro, 1990), (3) metasomatism (Grapes et al., 2005), and to a lesser extent (4) the break-down of silicates (Fitzsimons et al., 2005; Kohn and Malloy, 2004). Monazite forms over a large range of metamorphic conditions, spanning sub-clinectic grade to granulite facies. Because it can crystallize at much lower metamorphic pressure–temperature conditions than zircon, it has a greater potential to record lower-grade thermotectonic events.

3. Monazite as a detrital phase and provenance indicator

The survivability of monazite in the ancient sedimentary record is critical to its utility in provenance/tectonic reconstruction studies. Although the stability of monazite is a complex phenomenon, it is generally considered a stable mineral in terms of its resistance to chemical/mechanical processes (Mange and Maurer, 1992; Pettijohn et al., 1973). Because monazite has both a lower hardness and is less resistant to diagenesis than zircon, monazite is less likely to be multiply recycled compared to the well-established recycling history of detrital zircon into sedimentary units (Campbell et al., 2005; Eriksson et al., 2004). Although detrital monazite has been utilized in some previous provenance studies (Adachi and Suzuki, 1994; Budzyn et al., 2008; Evans et al., 2001; Ferguson et al., 2001; González-Álvarez et al., 2006; Iizuka et al., 2010; Kusiak et al., 2006; Rasmussen and Muhling, 2009; Ross et al., 1991; Wagani et al., 2011; White et al., 2001; Yang et al., 2006), most have been limited in scope (i.e. number of grains and/or geographic coverage). Our present study systematically investigates the utility of detrital monazite crystallization ages as a provenance indicator by directly comparing monazite ages to the provenance information obtained from detrital zircon ages from the same Carboniferous–Permian sandstones. Because our study takes advantage of a high-throughput SIMS methodology it allows for a statistically significant number of detrital monazite ages to be measured for each sample, thus providing a more rigorous assessment of the provenance potential of monazite.

4. Geologic setting

The Appalachians, built in part on Grenville-aged (~1250–950 Ma) basement rocks of eastern Laurentia, are traditionally viewed as having formed by the combined effects of the Taconian Orogeny, commonly attributed to volcanic arc accretion at ~470–440 Ma, the Acadian Orogeny, resulting from microcontinent collision (~420–380 Ma), and the Alleghanian Orogeny driven by continental collision between Laurentia and western Gondwana, culminating in the assembly of the supercontinent Pangaea (~330–280 Ma) (Hatcher, 1989). Sediments produced during the Alleghanian Orogeny formed the sandstones under investigation (Table 1). In addition to Grenville regions, potential sediment sources within Laurentia include: the Superior province (~2800–2600 Ma), the mid-continent, including the Trans-Hudson, Penokean, Central Plains, Yavapi and Mazatzal (1900–1600 Ma) regions, and the Granite–Rhyolite province (1500–1300 Ma).

Six sandstone samples were collected along strike of the Appalachian foreland basin, spanning ~800 km. These samples were characterized by measuring the crystallization ages of detrital monazite crystals. Five of these samples have Middle–Late Carboniferous depositional ages and one has an Early Permian depositional age. The Middle–Upper Carboniferous sandstones, all members of the Pennington–Lee clastic wedge, include the following formations: Sewanee Conglomerate, Lee Formation, Pocahontas Formation, Racoon Mountain Formation, and the Cross Mountain Formation, (Fig. 1). The youngest sandstone, Lower Permian Greene Formation, is a member of the Dunkard Group (Fig. 2). The following are brief descriptions of each sedimentary unit under investigation.

4.1. Sewanee Conglomerate (N35.652333, W85.182389)

This unit is the basal Pennsylvanian stratigraphic unit in eastern Tennessee (Becker et al., 2005). The unit is an extremely mature, quartz-rich, fine to coarse-grained sandstone with locally abundant pebbles (Milici et al., 1979). The depositional age of this unit is 320–310 Ma (Thomas et al., 2004). This formation is interpreted to represent deltaic-barrier island facies (Thomas et al., 2004).

4.2. Lee Formation (N36.91675, W82.665278)

This unit is an extremely quartz-rich mature sandstone. The unit is interpreted to represent either beach and barrier-island facies or incised fluvial channels (Becker et al., 2005). The Lee Formation is considered to be time equivalent to the Sewanee Conglomerate. Cross-bedding and ripple marks indicate fluvial transport parallel to the strike of the Appalachian highlands (Becker et al., 2005).

4.3. Racoon Mountain Formation (N34.417333, W85.229806)

The depositional setting for this quartz-rich mature sandstone is interpreted to be a fluvial–deltaic succession prograding westward from uplifted Appalachian source terranes (Thomas and Cramer, 1979). The depositional age of this unit is Early Pennsylvanian (Becker et al., 2005). It lies conformably above Mississippian shales.

4.4. Pocahontas Formation (N37.29403, W81.20493)

This unit is interpreted to represent either barrier-island bars or incised river channels with sediment sources derived from uplifted Appalachian sources to the east (Becker et al., 2005; Englund, 1974). The depositional age of this unit is Early Pennsylvanian and is thought to be approximately time equivalent to the Racoon Mountain Formation. The sandstone is less mature than the others in our study. It contains approximately 22% lithic fragments (Becker et al., 2005).

4.5. Cross Mountain Formation (N36.294639, W84.256778)

The unit is an extremely quartz-rich mature sandstone. The depositional age of this sandstone is estimated to be ~305 Ma, on the basis of a sanidine 40Ar/39Ar date of 312±1 Ma from the underlying Fire Clay tonstein (Lyons et al., 1992).
4.6. Greene Formation (N39.80715, W80.25956)

This fine-grained quartz and mica-rich sandstone unit was collected from the Greene Formation of the Lower Permian Dunkard Group. The sediment supply is interpreted to have been from the south or southeast (Becker et al., 2006). The depositional setting for the Dunkard Group has been interpreted to be a heterogeneous one, oscillating between fluvial/fluvial–swamp to fluvial–lacustrine environments (Becker et al., 2006).

5. Methods

Approximately 5–7 kg of each sandstone was crushed and disk milled. Each sample was wet sieved using 500, 250, 105 and 50 μm...
Dispersed detrital monazite crystals were removed from the carbon tabs and ed monazite crystals were removed from the carbon tabs and ed monazite crystals were removed from the carbon tabs and ed monazite crystals were removed from the carbon tabs and ed monazite crystals were removed from the carbon tabs and ed monazite crystals were removed from the carbon tabs and

6. Results

The detrital monazite age spectrum (n = 115) from the Raccoon Mountain Formation, which has the oldest age of the analyzed sandstones, is dominated by Paleozoic ages (Fig. 5). Devonian dates are the primary signal, followed in abundance by Ordovician and Silurian. Eight detrital monazite crystals have Neoproterozoic dates. Mesoproterozoic monazite account for only 8% of the age populations.
Neoarchean–Paleoproterozoic dates were recorded in 7% of the total analyzed monazite crystals. The detrital monazite age spectrum from the Pocahontas Formation (n = 121) is dominated by Paleozoic and Mesoproterozoic ages (Fig. 5). Monazite crystals with Ordovician and Devonian dates account for the majority of the Paleozoic signal. Minor contributions also record Silurian and Cambrian ages. Neoproterozoic dates account for 27% of the total monazite age spectrum. Nearly 40% of the detrital monazite crystals from the Pocahontas Formation record Mesoproterozoic ages.

Approximately 60% of the analyzed monazite crystals from the Sewanee Formation (n = 92) record Paleozoic dates, with Silurian and Ordovician ages predominating. Minor contributions to the Paleozoic signal are Devonian and Cambrian grains. Neoproterozoic dates account for only 8% of the detrital monazite age spectrum. Approximately 18% of the monazite crystals record Mesoproterozoic ages. Neoarchean and Paleoproterozoic monazite dates account for 15% of the total analyzed detrital monazite crystals.

Nearly 70% of the detrital monazite crystals analyzed from the Lee Formation (n = 108) record Paleozoic dates (Fig. 5). Devonian ages are the most abundant, followed by Ordovician and Silurian. Both Neoproterozoic and Mesoproterozoic ages are minor contributors to the detrital age spectrum. Monazite crystals with Mesoproterozoic ages account for 15% of the ages.

Paleozoic ages heavily dominate the detrital age spectrum for the Cross Mountain Formation, the youngest analyzed Carboniferous sample (Fig. 6). Devonian and Ordovician ages are the principal modes with minor contributions from Silurian and Cambrian. Neoproterozoic ages account for 11% of the analyzed detrital monazite ages. Mesoproterozoic ages account for less than 15% of the detrital monazite ages. Neoarchean–Paleoproterozoic ages account for only 4% of the age spectrum.

The detrital monazite age spectrum for the Permian Greene Formation, the youngest sandstone analyzed in our study, is dominated (~85%) by Paleozoic ages (Fig. 6). These ages are equally distributed between Devonian, Silurian, and Ordovician. Three monazite crystals record Mississippian ages, the youngest recorded monazite ages in the six analyzed sandstones. Mesoproterozoic–Neoproterozoic ages are a minor contributor to the total detrital monazite age spectrum.

7. Discussion

Few studies have assessed the relative abundance of both zircon and monazite in the same Appalachian felsic plutonic rocks (Wark and Miller, 1993). However, empirical evidence is provided by the relative abundance of Mesoproterozoic monazite and zircon in modern French Broad River alluvium derived from weathering of southern Appalachian Blue Ridge and Western Inner Piedmont lithologies (Hietpas et al., 2010). The alluvium contains primarily Ordovician monazite of metamorphic origin, and only a minor amount of Mesoproterozoic monazite (magmatic or metamorphic) compared to Mesoproterozoic zircon (Hietpas et al., 2010; Moecher et al., 2011). In addition, Neoproterozoic clastic rocks of the Ocoee Formation, thought to have been derived from the weathering of Mesoproterozoic basement, also contain no monazite in the accessory mineral suite (Chakraborty, 2010). Paleozoic monazite crystallization ages have been obtained for some southern Appalachian plutons (Miller et al., 2006); monazite-bearing igneous rocks are, however, volumetrically insignificant compared to monazite-bearing metamorphic terranes. Although we cannot unequivocally discriminate between an igneous and a metamorphic origin for the detrital monazite in the Carboniferous clastic wedges, we believe that the majority of the monazite crystals analyzed in this study were originally derived from metamorphic rocks.

7.1. Monazite age domains

Individual monazite crystals are well known for potentially containing regions or domains which record multiple ages (e.g. Williams et al., 2007). Identification of potential multi-age domains relies on interpretation of element X-ray maps (typically U, Th, Pb, Ca, and Y), variations in gray-scale values in backscatter electron images, or mineral textural properties. In our study, we relied on textural observations and backscatter electron images to produce high-throughput images, as opposed to X-ray mapping, which would have been prohibitively time consuming for analyzing nearly 1000 detrital grains. For most of our analyzed sandstones, we did not identify a significant number of detrital monazite grains that appeared to have multi-age domains. However, monazite in the Sewanee Conglomerate and Pocahontas Formation did show textural differences in a number of detrital grains suggesting new monazite rim growth (Fig. 4). Fig. 4A is an inclusion-riddled detrital grain (r3g35) from the Pocahontas Formation. Two regions can be subly recognized in the backscatter image, however detailed textural analysis clearly shows an almost inclusion-free core engulfed by an inclusion-rich potential overgrowth. The age of the core (spot 1) is 1068 ± 18 Ma, while the rim is 469 ± 9 Ma. Based on these observations, this crystal was likely derived from a
source rock that contained pre-existing Grenvillian-age monazite that was subsequently either partially recrystallized, or experienced new monazite growth during a Taconian metamorphic event.

Another detrital grain (r3g44) isolated from the Pocahontas Formation shows two faint regions in a backscatter image (Fig. 4B) that suggest the possibility of distinct age domains. The age of the core (spot 1) of this crystal is 977 ± 14 Ma, the rim (spot 2) is 672 ± 13 Ma. The source of the crystal appears to be a region that contains Grenvillian monazite that experienced new monazite growth during the Neoproterozoic. The detrital crystal in Fig. 4C was isolated from the Sewanee Conglomerate. The age for the texturally homogeneous core (spot 1) region is 1125 ± 16 Ma and for the mottled rim is 509 ± 6 Ma. This crystal is interpreted to have been derived from a region that contained Grenvillian-aged (Shawinigan phase) monazite that experienced a subsequent event of high enough temperature to produce new monazite growth.

The detrital monazite crystal in Fig. 4D was isolated from the Raccoon Mountain Formation. This example demonstrates the value of utilizing textural observations for recognizing potential age domains. Detailed examination of the backscatter image provides subtle hints for core and rim regions, however the existence of fine-grained inclusions demarcate two regions: a homogeneous core and fissured inclusion-bearing overgrowth. The age for the homogeneous core (spot 1) is 1130 ± 17 Ma, the heterogeneous rim is 571 ± 17 Ma. The origin of this crystal is again similar to the preceding crystals; a region containing Grenvillian-aged (Shawinigan) monazite that was subsequently metamorphosed during younger events.

Fig. 4E and F illustrates two monazite crystals, isolated from the Sewanee Conglomerate, which both have potential age domains based on examination of their respective backscatter images. However the ages for the apparent age domains are indistinguishable from each other: grain r5g28 (Fig. 4E) spot 1 age is 444 ± 6 Ma with a “rim” age (spot 2) of 441 ± 6 Ma; grain r5g29 (Fig. 4F) core (spot 1) age is 1858 ± 24 Ma with a “rim” age (spot 2) of 1856 ± 24 Ma. These two examples demonstrate that while detailed examinations of monazite images are a critical step in identifying possible age domains, the presence of texturally (or even elementally) distinct regions is not a guarantee that multi-age domains exist.

7.2. Comparison of detrital monazite and zircon provenance information

$^{232}$Th-$^{208}$Pb crystallization ages of detrital monazite in all samples yield a stronger record of Paleozoic orogenic events than Mesoproterozoic or older events (Figs. 5–7). The monazite ages for the Raccoon Mountain Formation, oldest of the analyzed samples, are heavily dominated by Taconian and Acadian ages, with reduced signals derived from Grenvillian or older source regions. This is in stark contrast to the U-Pb ages of detrital zircon from this same formation. Zircon records an abundance of Grenvillian ages with only a limited signal of younger Paleozoic orogenic events. The total zircon Paleozoic signal equals the minor Paleoproterozoic signal, a source that is not currently exposed in the southern Appalachians. The minimal Ordovician and Devonian zircon signals are surprising given the volume of Taconian and Acadian source rocks in the Appalachians. Ordovician and Devonian detrital monazites, however, are extremely common, thus demonstrating a more complete record of the ages of local Paleozoic crustal areas was preserved.

Detrital monazite age spectra from the Pocahontas Formation (Fig. 5) record peaks associated with the Grenvillian, Taconian and Acadian events. The detrital zircon ages from this same unit, however, exclusively record Grenvillian and older ages, with no crystals capturing the complex Paleozoic pulses of orogenesis. Thus detrital monazite ages capture two very significant tectonic events that are entirely missed by detrital zircon ages. An increasing application of detrital zircon ages is to use the youngest grains to constrain the maximum age of sediment deposition (e.g. Dickinson and Gehrels, 2009). The depositional age for the Pocahontas Formation would be $\leq$900 Ma based on the youngest detrital zircon analyzed. For monazite, however, the age is $\leq$350 Ma, an increase in resolution of time of deposition by 550 Ma.

The detrital monazite and detrital zircon ages for the Sewanee Conglomerate are remarkably similar to each other (Fig. 5). Both sediment source proxies record strong signals for Taconian, Grenvillian,
and Trans-Hudson/Penokean sources (1800–1900 Ma); both also record minor peaks for Acadian sources and the Superior Province (2600–2800). The abundances of monazite ages are, however, skewed towards the younger events. In addition, Neoproterozoic to Cambrian detrital monazite ages are recorded, ages likely related to rifting (Mt. Rodgers, Catoctin, Robertson River Formations) (Aleinikoff et al., 1995) and missed by detrital zircon ages.

The detrital monazite ages for the Lee Formation (Fig. 5) are heavily skewed towards Taconian and Acadian ages, with minor signals derived from Grenvillian, Trans-Hudson/Penokean, and Superior Province sources. Given this age distribution, one would conclude that Taconian and Acadian sources were the most dominate donors for this unit. This is in stark contrast to what would be inferred from an examination of detrital zircon ages. The results from Becker et al. (2005) show that zircon records ages associated with Grenvillian, Granite-Rhyolite, Yavapi-Mazatzal, and Trans-Hudson-Penokean events, with a minor signal from the Superior Province, but does not record any Paleozoic orogenic events. A substantially biased view of past tectonic events would be obtained if only the detrital zircon record was examined.

The crystallization of detrital monazite from the Cross Mountain Formation are heavily skewed towards Acadian and Taconian orogenic events, with a reduced Grenvillian signal and minor signals derived from Trans-Hudson/Penokean and Superior provinces. This age distribution is similar to the detrital zircon age spectrum, however, zircon records a much higher percentage of the older Granite-Rhyolite, Yavapi-Mazatzal, and Superior province source regions, which monazite struggles to record (Fig. 6). These older events (Superior Province through Granite–Rhyolite) are interpreted to be present due to sediment recycling, and do not represent direct exposure of these crustal units. Thus we interpret the abundance of young (Taconian-to-Acadian) ages to be a more realistic identification of the characteristics of the major sediment donors for this unit.

The ages of detrital monazite from the Early Permian Greene Formation strongly record Taconian and Acadian orogenic events, with a reduced Grenvillian signal (Fig. 6). The Greene Formation also records the Alleghanian Orogeny, albeit only by three crystals. This is the only analyzed sample that records this elusive orogenic event. The Greene Formation has an approximate depositional age of ~300–285 Ma, thus demonstrating that metapelites (presumably) that experienced at least staurolite-grade metamorphism were exposed at the surface by the ~300–285 Ma age of foreland basin fill. Detrital zircon ages from this sample recorded only Grenvillian to Yavapi–Mazatzal events, although a single Cambrian age was recorded as was one Alleghanian-age rim on a Grenvillian core (Becker et al., 2006). While zircon does record this young age, few researchers would base a tectonic model on a single age. Monazite recorded the Alleghanian event in three separate crystals, increasing the confidence one would place in a suggestion that a tectonic event of that age had occurred.

Fig. 5. Detrital monazite and zircon age histograms and probability density plots for the four oldest analyzed sandstones. Detrital zircon U–Pb data from (Becker et al., 2005, 2006; Thomas et al., 2004).
8. Conclusions

The results of this study demonstrate the dramatic impact that a chosen provenance proxy mineral can have on the inferred identity of sediment donor regions. In this study detrital monazite ages record younger tectonic events far more often than detrital zircon (Fig. 7). In several of the analyzed sandstones, detrital monazite recorded multiple Paleozoic tectonic events that were entirely missed by the detrital zircon record. This is most explicitly demonstrated by the age distributions for the Lee and Pocahontas Formations (Fig. 5). In both of these samples, the Taconian and Acadian orogenies, both major pulses of tectonism that are hallmarks of the Appalachian Orogen, were captured by monazite but not by detrital zircon. In addition, the maximum age of sediment deposition inferred by detrital monazite ages rivaled, and in most cases far surpassed, the constraints on depositional ages based on the youngest detrital zircon.

The results of this study, and those of previous monazite-based provenance studies, demonstrate that monazite ages have a significant potential as a proxy of sediment sources, particularly in regions where extensive areas of metamorphic rocks were exposed. In addition to crystallization ages, Sm–Nd isotope tracer signatures can be determined on individual monazite grains (Ross et al., 1991). Monazite mineral chemistry can also be exploited to serve as an additional piece of provenance information, due to the “chemical promiscuity” of monazite during initial growth and subsequent recrystallization (Iizuka et al., 2010). A recent investigation by Richter et al. (2008) demonstrated the use of detrital monazite cathodoluminescence (CL) as a tool for sediment provenance, thus providing an additional tool to obtain provenance information for single detrital monazite crystals.

As different detrital mineral phases are investigated it is becoming apparent that each provenance proxy has its own strengths and limitations. A combined multi-mineral approach that takes advantage of the different, but complementary, characteristics of both detrital monazite and zircon would exploit the strengths of both minerals. Such an approach should provide a higher degree of confidence that all major sediment donor regions can be identified and that the areal significance of some regions are not being overestimated based on any bias due to differences in proxy mineral fertility for specific age intervals.

Acknowledgments

This research was supported by the National Science Foundation (EAR #0635643 and EAR #0635688). All histograms were made using the Microsoft Excel macro AgeDisplay developed by Keith Sircombe (Sircombe, 2003). We thank Axel Schmitt for extremely helpful guidance in collecting data at the UCLA SIMS facility. Grants from the NSF Instrumentation and Facilities Program, Division of Earth Sciences, supported the UCLA ion microprobe facility (EAR-0732691). In addition we thank Peter Cawood and an anonymous reviewer for their timely and insightful comments and suggestions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at doi:10.1016/j.epsl.2011.08.033.

References


