Combined single-grain (U-Th)/He and U/Pb dating of detrital zircons from the Navajo Sandstone, Utah

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ABSTRACT

Radioisotopic dating of detrital minerals in sedimentary rocks can constrain sediment sources (provenance), elucidate episodes and rates of ancient orogenesis, and give information on paleogeography and sediment-dispersal patterns. Previous approaches have been restricted to the application of a single technique, such as U/Pb or fission-track dating, to detrital grains. These methods provide crystallization and cooling ages, respectively, of sediment sources (terranes). However, evidence for source regions from a single technique can be ambiguous because candidate source terranes often have similar ages for a given radioisotopic system. This ambiguity can be avoided by applying multiple radioisotopic systems to individual detrital grains. Here we present a method for measuring both (U-Th)/He and U/Pb ages of single crystals of detrital zircon, providing both formation and cooling ages (through ~180 °C). We applied this technique to zircons from the Lower Jurassic Navajo Sandstone, which represents one of the largest erg deposits in the geologic record. A large fraction of these zircons was derived from crust that formed between 1200 and 950 Ma, but cooled below ~180 °C ca. 500–250 Ma. This history is characteristic of Grenvillian-age crust involved in Appalachian orogenesis (and subsequent rifting) in eastern North America. Our finding requires the existence of a transcontinental sediment-dispersal system capable of moving a large volume of detritus westward (modern coordinates) throughout the late Paleozoic and early Mesozoic.

Keywords: (U-Th)/He, U/Pb, geochronology, zircon, Navajo Sandstone.

INTRODUCTION

Geochronology of detrital minerals in sedimentary rocks provides a valuable record of orogenic and paleogeographic dynamics. Zircon is particularly useful in this respect, both because of its resistance to weathering and because it allows relatively precise dating by the U/Pb, fission-track, and (U-Th)/He methods. The U/Pb system in zircon records the time of formation (or high-temperature resetting) of the grain in an igneous (or high-grade metamorphic) source terrane because closure temperatures approach crystallization temperatures. In contrast, low-temperature thermochronometers, such as the fission-track or (U-Th)/He methods, record the cooling of zircons as they approach the surface during exhumation.

Traditionally, detrital geochronologic studies designed to identify sedimentary provenance have involved the application of a single dating technique to a suite of grains. The resulting age spectrum could be compared with results from candidate terranes in order to identify a sedimentary source (e.g., Gehrels et al., 1995). Low-temperature thermochronometers, such as the zircon fission-track system, have also been used to constrain the exhumation history and provenance of sediments (e.g., Garver et al., 1999).

The (U-Th)/He system in zircon has a closure temperature of ~180 °C (Reiners et al., 2002, 2003) and provides several advantages over zircon fission-track dating. (U-Th)/He dating is not limited by track density bias, so (U-Th)/He ages can be measured on older or higher-U zircons. (High radiation dosages of $2–4 \times 10^{18}$ α/g, unusual for most detrital zircons, are required for significant low-temperature He loss [Nasdala et al., 2003].) Additionally, the precision of He ages is generally higher than that of fission-track ages (2σ reproducibility is typically ~4%–8%, as opposed to 10%–15%). Assuming a typical geothermal gradient of 20–30 °C/km, the closure depth for the zircon He system will reside at 6–9 km. In active orogens, accelerated erosion and faulting typically cause exhumation rates on the order of 0.5–5 km/m.y. (Ring et al., 1999). Thus, we consider (U-Th)/He ages as nearly coincident with exposure of the grain at the surface, because zircons exhumed at these rates will reach the surface ~1–18 m.y. after closure of the zircon He system. Given this, if independent geologic information exists about when mountain belts were active, low-temperature ages from detrital grains can be used to identify a given source terrane.

Clear discrimination of source regions by use of any single chronometer is often ambiguous because multiple candidate source terranes may have similar crystallization or cooling ages. Furthermore, with their strong resistance to thermal resetting, U/Pb ages from sediments with a polycyclic history may identify an older (rather than immediate) source terrane. In contrast, low-temperature data are subject to ambiguities regarding whether the grains correspond to crystallization or exhumation ages (Carter and Moss, 1999). One solution to these problems is to obtain ages corresponding to different parts of a grain's thermal history, thereby allowing a greater resolution in identifying sedimentary sources. We present a technique, combined He-Pb dating, to obtain both U/Pb and (U-Th)/He ages from single grains. Determination of both high- and low-temperature ages on the same detrital crystal offers great potential for improving interpretations of provenance and the dynamics of ancient orogens.

GEOLOGIC SETTING

To illustrate the advantages of the combined He-Pb dating method, we analyzed detrital zircons from the Lower Jurassic (193–187 Ma) Navajo Sandstone of southwestern Utah (Peterson and Pipiringos, 1979). One of the largest eolian deposits known in the sedimentary record, the original areal extent of the Navajo-Nugget-Aztec erg has been estimated as $265–660 \times 10^3$ km^2 (Marzolf, 1988; Fig. 1). Cross-bedding patterns throughout the region show that during the time of Navajo deposition, wind direction (in modern coordinates) was predominantly south to southeast (Peterson, 1988). However, there is no clear consensus on the provenance of the sediment. Proposed sources include the Ancestral Rockies (Kocurek and Dott, 1983), pre-Jurassic strata from the north (Peterson, 1988; Kocurek and Dott, 1983), the Ouachitas (Marzolf, 1988), and the Appalachians (Dickinson and Gehrels, 2003). We separated zircons from two samples stratigraphically 600 m apart from one site in southwestern Utah. There were no significant differences in the age populations of the two samples, and we treat the data as a single set.

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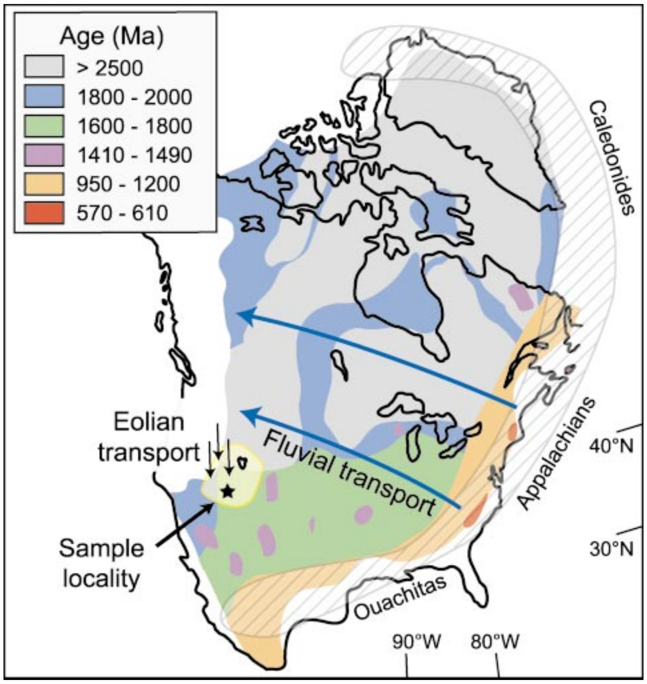
Figure 1. Generalized geologic map of North America showing U/Pb bedrock ages and inferred Early Jurassic sediment-distribution pattern. Base map is after Hoffman (1989). Locations of anorogenic granites are after Anderson (1983). U/Pb and (U-Th)/He age data presented here require transcontinental transport from Appalachians to western coast of Laurentia. Approximate bounds of Navajo-Nugget-Aztec erg (shown in pale yellow) and eolian transport of sediment to Navajo-Nugget-Aztec erg are shown schematically (after Peterson, 1988). Sample locality (N37°16′15″, W112°56′52″) is indicated by star.



METHODS

Individual, highly rounded zircon crystals were U/Pb dated by laser-ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), in a single pit 29 μm in diameter and $\sim$20 μm deep on the exterior of unmodified grains mounted on tape[1]. Quoted U/Pb ages are based on ^{206}Pb/^{238}U for zircons younger than 1300 Ma and ^{207}Pb/^{206}Pb for all older ones. These ages were corrected for common Pb based on a ^{208}Pb technique, though generally the common Pb content of these zircons is small and the correction is trivial (see footnote 1 concerning Appendix A for details). Grains were then retrieved and (U-Th)/He ages were measured by standard procedures involving Nd-YAG laser heating and Parr bomb dissolution (Reiners et al., 2003). The laser-ablation process does not alter (U-Th)/He ages, as has been demonstrated by multiple single-grain replicates of zircons from the Fish Canyon Tuff and other standards (see footnote 1).

Farley et al. (1996) demonstrated that (U-Th)/He ages typically require correction for the effects of α ejection from crystals. Alpha stopping distances in zircon are $\sim$15–20 μm, so those generated near crystal rims may be ejected from the crystal, causing anomalously low daughter/parent ratios along grain boundaries and too-young bulk crystal ages. This bias is a function of the surface area to volume ratio of the crystal and can be accurately corrected given certain assumptions. Although this approach has proved successful for euhedral igneous and metamorphic zircons, it will be in error to some degree when applied to detrital grains because abrasion during sedimentary transport can remove the He-depleted rim. In an extreme case, if enough material has been removed from the grain edges, age determinations for recently deposited detrital grains would require no α-ejection correction (assuming no other complicating effects such as parent-nuclide zonation or diffusive rounding of the He profile). However, if a significant fraction of a grain age includes a subsequent postdepositional phase of He production at low temperature, a new He-depleted rim will form during residence in the modern sedimentary host. Thus, for (U-Th)/He dating of significantly abraded detrital grains, α-ejection corrections should be applied to only a part of a grain's history.

We have developed a modified version of the standard α-ejection correction factor applicable to abraded grains. The total (U-Th)/He age of a grain consists of two parts, the first corresponding to the time between closure of the He system and the time of erosion, and the second corresponding to the time between deposition and the present. In the extreme, abrasion can completely remove the He-depleted rim developed in the first stage. Here we assume that total removal of the He-depleted rim occurs instantaneously at the time of deposition. In this case, the standard α-ejection correction needs to be applied only to the postdepositional part of the grain's history. This approach leads to the following relationship (see Appendix B [footnote 1] for details):

$$A_c = A_d \times (1 - F_t) + A_m, \qquad (1)$$

where A_c is the corrected age, A_d is the depositional age of the sedimentary rock, A_m is the measured age, and F_t is the retentivity (Farley et al. 1996), which is a function of grain morphology and dimensions. The difference between ages corrected by the traditional α-ejection procedure and this method could potentially be 30% or more (see footnote 1). Because of the highly rounded morphology of the Navajo grains we apply the detrital method, but show error bars extending to ages corresponding to the traditional method.

A recognized potential problem in (U-Th)/He dating is intracrystalline U-Th zonation, which can produce inaccurate α-ejection corrections and biased ages. Because these zircons were transported by eolian processes, any systematic U-Th zonation in the outermost rims of these zircons has likely been removed by extensive abrasion. Nonetheless, we obtained backscattered electron and cathodoluminescence images of $\sim$30 grains; these results show that most of these grains lack strong systematic zonation (see footnote 1).

RESULTS AND INTERPRETATIONS

Figure 2A shows the U/Pb and (U-Th)/He ages of Navajo zircons in a probability density plot. Of 40 dated zircons, 31 yielded concordant U/Pb ages, with concordancy defined as agreement of ^{206}Pb/^{238}U and ^{207}Pb/^{206}Pb ages to 2%. Discordant or strongly zoned zircons were rejected, as were those in which pits intersected inclusions. We interpret the U/Pb ages to record the crystallization or high-temperature metamorphism. In contrast, the low-temperature (U-Th)/He ages ($n = 24$) record cooling of zircons below $\sim$180 °C during exhumation.

The U/Pb and (U-Th)/He data both show a broad spread of ages extending into the Precambrian, but several dominant modes exist for each system. U/Pb ages range from 2700 to 400 Ma, with four main clusters: (1) 2700–2600 Ma, (2) 1510–1430 Ma, (3) 1200–950 Ma, and (4) 610–540 Ma. For the (U-Th)/He ages, three main groups are recognized: (1) 1350–1100 Ma, (2) 450–300 Ma, and (3) 250–225 Ma. We directly relate the U/Pb and (U-Th)/He ages by plotting single-crystal Pb ages vs. He ages (Fig. 2B).

The oldest zircons have U/Pb ages (2.7–2.6 Ga) consistent with derivation from the Canadian Shield or Wyoming craton (Fig. 1). The combined He-Pb data show that these zir-

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[1] GSA Data Repository item 2003110, Appendix A (data and analytical techniques), Appendix B (alpha-ejection correction for abraded detrital grains), Figures DR1–DR5, and Tables DR1 and DR2, is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org, or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

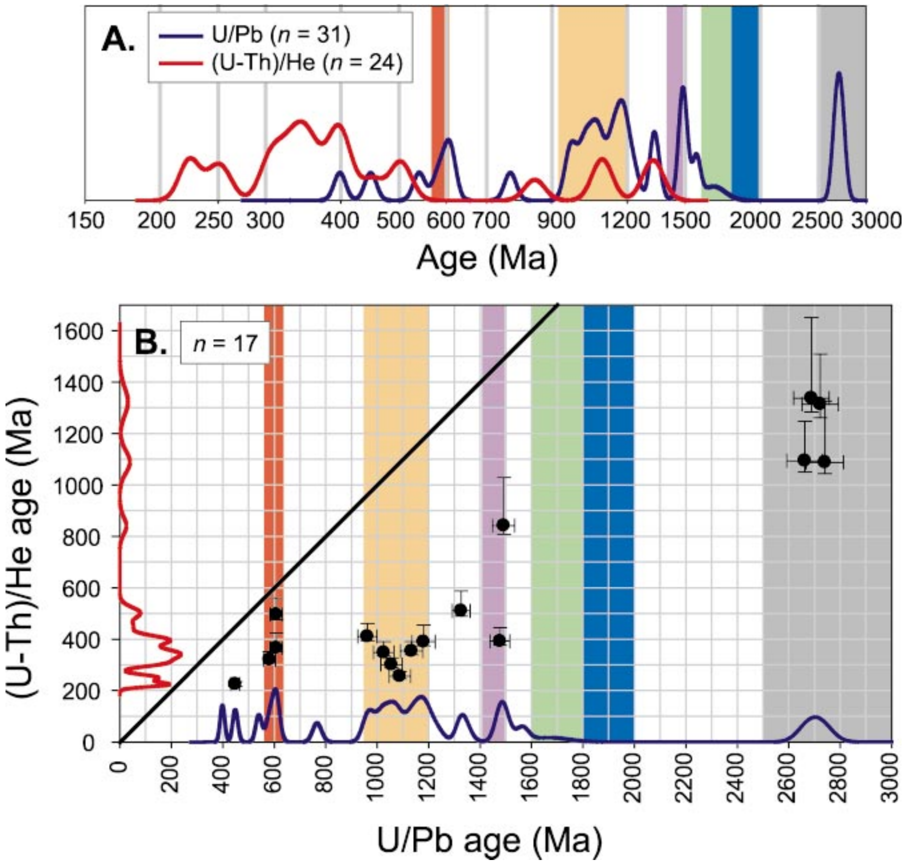

Figure 2. U/Pb and (U-Th)/He ages from detrital zircons analyzed in this study. A: Probability density plots for U/Pb (blue line) and (U-Th)/He (red line), created using methods of Brandon (1996). Note log scale for ages (*x*-axis), used to preserve relative heights of specific peaks despite greater uncertainty for older measurements (Brandon, 1996). Colored background blocks in U/Pb plot represent expected age ranges for most areally extensive potential bedrock sources in North America and correspond to colors in Figure 1. Local bedrock sources (green) are not represented in Navajo Sandstone. Many of grains appear to have been derived from eastern North America, whether from Grenville province (orange) or early Paleozoic terranes of Avalonia or Carolina Slate belt (red). B: Plot showing He age vs. U/Pb age for subset of data from individual zircon grains. Black line connects points of equal He and Pb age. U/Pb and lower limit (U-Th)/He error bars are 1σ. Upper limit He error bars are ages using standard alpha-ejection correction instead of detrital approach described within text. We regard these ages as an extreme upper limit, because all grains show significant rounding. Linear versions of probability density plots from A are shown for reference.

cons have (U-Th)/He ages of ca. 1300–1100 Ma. This exhumation age is not easily associated with tectonic events in the Wyoming craton, but it does coincide with orogenesis in northeastern North America (Davidson, 1998). A likely origin for these zircons is thus from Laurentian basement that was exhumed through the zircon helium closure isotherm during Grenvillian orogenesis, as might be expected for parts of eastern Canada (e.g., Harper, 1967). Rainbird et al. (1992) noted that Neoproterozoic sedimentary rocks of northwestern Canada contain zircons with both Grenvillian (1.3–1.1 Ga) and Archean (2.6 Ga) U/Pb ages, suggesting the possible involvement of shield rocks in Grenvillian orogenic events.

Two of the observed peaks in the U/Pb age spectra are consistent with an origin in eastern North America. The U/Pb ages ranging between 1200 and 950 Ma suggest derivation from the Grenville province, while the youngest ages of ca. 600–550 are consistent with an origin in the Gondwana terranes such as Avalonia and the Carolina Slate belt (Hoffman, 1989). It could be argued that the older grains were derived from minor 1200–950 Ma sources in western North America, but the power of the double-dating method is that it eliminates this as a realistic possibility. The 1200–950 U/Pb age grains have He ages that record cooling through 180 °C between ca. 400 and 250 Ma, consistent with erosion during the primary period of Appalachian tectonism (Fig. 2B). Of the zircons dated by both methods, 35% (6 of 17) show these ages, indicating that the source for these grains was volumetrically significant. This combination of crystallization and cooling ages is difficult to find in abundance elsewhere in North America or other continental regions potentially in sedimentary communication with the Jurassic Navajo erg. The 600–550 U/Pb age grains also show cooling between 500 and 225 Ma, consistent with the timing of formation of the Appalachians or the subsequent breakup of Pangea. Together, these two populations make up 66% of the U/Pb-dated zircons. The most realistic interpretation of these data is that all zircons with He ages between 500 and 225 Ma were exhumed during tectonism in the Appalachian Mountains.

The U/Pb age spectrum has an additional peak, ca. 1440 Ma, consistent with derivation from the belt of 1.49 and 1.41 Ga anorogenic granites extending from southern California to Labrador (Anderson, 1983). Only two of these grains were analyzed for He, and they reveal disparate cooling ages, 841 Ma and 392 Ma. These zircons may have been derived from anorogenic granites exposed in the Ancestral Rocky uplifts (e.g., Dickinson and Gehrels, 2003). Although these He ages predate Ancestral Rockies tectonism (ca. 310 Ma) (Kluth, 1986), the grains may have resided for some time in the shallow crust above the zircon He closure depth prior to exhumation.

DISCUSSION

The majority of the zircons in this study (66%) have combined crystallization and cooling ages that strongly suggest a source in present-day eastern North American. Large volumes of Appalachian-derived detritus in the western United States require a sediment-dispersal system fundamentally different from the modern one and capable of transporting material from the eastern to western coast of North America between at least 225 Ma (the youngest cooling ages) and 190 Ma (the time of deposition of the Navajo Sandstone). Pell et al. (2000) showed that, for modern Australian dune fields, much of the sediment was transported fluvially for distances as great as hundreds of kilometers prior to its incorporation into the eolian system. Thus, we envision a system in which rivers with their headwaters in the Appalachians carried material to the Jurassic western shore of North America, flowing to the north of any residual topography associated with the Ancestral Rockies (Fig. 1). From there, material was blown southward and incorporated into the Navajo-Aztec-Nugget erg (Peterson, 1988). This scheme is similar to one proposed by Dickinson and Gehrels (2003) on the basis of U/Pb ages alone.

The Appalachian zircons in the Navajo Sandstone appear to record two separate cooling episodes (ca. 400–300 and 250–200 Ma), possibly corresponding to major pulses of exhumation (Figs. 2A, 2B), during both construction of the Appalachian orogen and subsequent rifting associated with the opening of the Atlantic. It is unclear where the sediment resided after its exposure at the surface but before its incorporation into the erg. One possibility is that the grains were deposited in a foreland basin near the Appalachians. McLennan et al. (2001) reported Devonian sedimentary rocks in upstate New York with zircons of Ordovician and Grenvillian age. In this scenario, the rifting event remobilized detritus in these sediments and transported it toward the west coast. However, Dickinson and Gehrels (2003) have found Grenvillian-aged zircons in Pennsylvanian eolianites of the Colorado Plateau. Thus, it appears that the transcontinental drainage system must have been active at least since the late Paleozoic, so first-cycle storage adjacent to the Appalachians is not required.

Despite their proximity, few grains with crystallization ages appropriate for the Ancestral Rockies (1800–1600 or 1490–1410 Ma) were observed. In contrast, Dickinson and Gehrels (2003) noted the existence of a minor population of 1800–1600 Ma zircons in the Navajo Sandstone, and they argued that these were derived from Ancestral Rockies uplifts. The absence of grains of this age in our study may be due to the relatively small number of zircons ($n = 31$) analyzed here, but in any case, these data suggest that the Ancestral Rockies were at most only a minor contributor of sediment to the Navajo sandstone.

The 1300–1100 Ma zircon (U-Th)/He ages are among the oldest reported terrestrial He ages and demonstrate that geologically reasonable zircon cooling ages can be obtained from the Proterozoic. They also require storage of upper-crustal ($<\sim$5 km) material over time scales of $>$1 b.y. Combined He-Pb dating of Precambrian zircons provides a potentially powerful tool to unravel ancient continental development, and holds promise for identifying exhumation during ancient mountain-building events. Although only the roots of many ancient orogens may remain today, detrital minerals in Precambrian sedimentary rocks may contain a record of cooling of specific orogenic belts.

CONCLUSIONS

We have developed a technique for measuring both crystallization and cooling ages of single zircon crystals. The application of two radioisotopic techniques corresponding to high- and low-temperature ages can improve resolution of provenance determinations, elucidate ancient orogenic episodes and sediment-dispersal systems, and indirectly constrain paleotopography. Application of this technique to the Jurassic Navajo Sandstone demonstrates that the bulk of the material in the Navajo Sandstone was ultimately derived from the Appalachians of eastern North America and transported westward in a continental-scale drainage system, similar to that of the modern-day Amazon.

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