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 × 10¹⁸ 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.

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 Pipirigos, 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 × 10³ km² (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.
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 20 μm deep on the exterior of unmodified grains mounted on tape. Quoted U/Pb ages are based on 206Pb/238U for zircons younger than 1300 Ma and 207Pb/206Pb for all older ones. These ages were corrected for common Pb based on a 208Pb 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 concerning Appendix A for details). This approach leads to the following relationship (see Appendix B [footnote 1] for details):

\[ A_t = A_0 \times (1 - F_s) + A_{me} \]

where \( A_t \) is the corrected age, \( A_0 \) is the depositional age of the sedimentary rock, \( A_{me} \) is the measured age, and \( F_s \) 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).

α-ejection correction needs to be applied only to the post depositional part of the grain’s history. This approach leads to the following relationship (see Appendix B [footnote 1] for details):

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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 ~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 206Pb/238U and 207Pb/206Pb 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 ~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-
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.

DISCUSSION

The majority of the zircons in this study (66%) have combined crystallization and cooling ages between 1200 and 950 Ma, consistent with the timing of formation of the Appalachian orogenesis. 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.
humation (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 eloniates 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 (<5 km) material over timescales 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 palaeotopography. 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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