

## Resolving tectonic problems by dating detrital minerals

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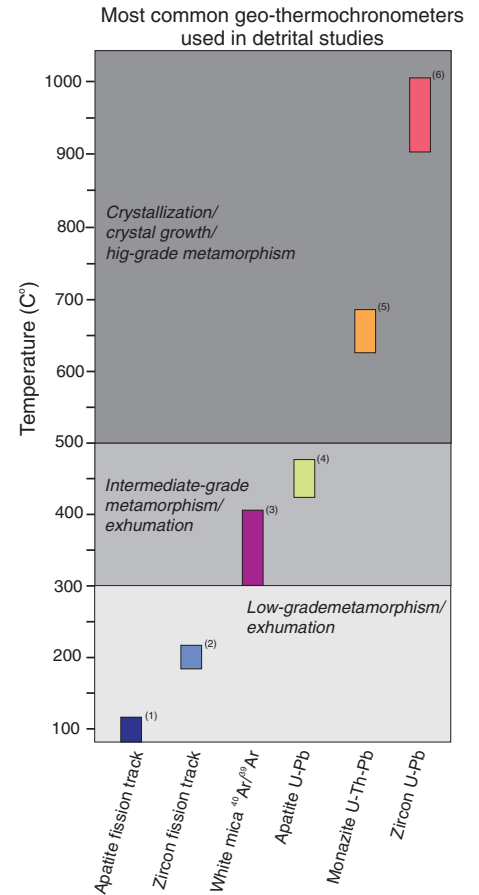
Geochronology and thermochronology applied to detrital minerals such as zircons, monazites, white micas, and apatites have received increasing attention in the past decade for their unique power to determine the timing of crystallization and multiple tectono-thermal events, with relevance for sediment provenance, tectonic processes, and erosion. Recent breakthroughs in multi-dating (applying different geochronologic and thermochronologic systems to the same detrital grains) allow for unprecedented levels of detail in provenance and tectonic studies of detrital sediments. The common pre-conditions for application of these methods are: (1) the source areas are characterized by rocks with different tectonic histories recorded by distinctive crystallization and cooling ages, and (2) the source rocks contain the selected mineral. Whereas zircons occur in most magmatic, metamorphic, and sedimentary rocks, other minerals, such as apatite, monazite, and white mica, are less abundant. This is why zircon geochronology and thermochronology is a particularly useful approach to detrital studies. In cases where different sources are characterized by the same zircon U-Pb ages, differential metamorphism and/or exhumation may produce distinctive thermochronological ages. It is also important to note that different mineral geochronometers and thermochronometers can only answer specific questions. For example, if we want to determine the provenance of detrital minerals by studying the long history of crystallization of a tectonically complex source region, then U-Pb zircon geochronology is the ideal approach. The main strength of zircons resides in the fact that they are capable of surviving multiple phases of physical and chemical weathering, erosion, and deposition.

The increased use of multicollector-laser ablation-inductively coupled plasma-mass spectrometry (MC-LA-ICPMS) in recent years is a significant advancement in the application of U-Pb geochronology to provenance and tectonic problems, because the technique can efficiently generate a large number of analyses (Gehrels et al., 2008). The method has become a common approach for determining sediment provenance, dispersal patterns, and recycling (Dickinson and Gehrels, 2008, 2009a, 2009b), timing of tectonic processes such as the onset and kinematic history of mountain building (White et al., 2002; DeCelles et al., 2004), maximum depositional age of otherwise undatable sedimentary units by

using the youngest age component (Surpless et al., 2006; Fildani et al., 2003; DeCelles et al., 2007), and source-sedimentary basin evolution (Rahl et al., 2003; Fildani et al., 2009).

However, if one wants to study the details of metamorphic evolution or multiple tectono-thermal events characterized by a broad range of temperatures ( $T$ ), which are lower than the closure  $T$  for zircons ( $>900$  °C; Dahl, 1997), then a different approach is necessary. The first scenario can be better addressed by zircon secondary ion mass spectrometry (SIMS) analysis (Trail et al., 2007; Spandler et al., 2005); however, this technique requires extensive analytical time, rendering it less suitable for detrital studies in which large numbers of analyses are required (on average  $\sim 100$  per sample; Vermeesch, 2004). The second scenario necessitates a geo-thermochronological approach involving multi-dating of the same mineral or of different minerals with different “closure” temperatures covering the  $T$ -window of interest (Fig. 1), such as U-Pb dating of zircons and monazites (e.g., Hieptas et al., 2010, p. 167 in this issue of *Geology*),  $^{40}\text{Ar}/^{39}\text{Ar}$  of white micas, or double and triple dating of zircons and apatites (Rahl et al., 2003; Campbell et al., 2005; Bernet et al., 2006; Carrapa et al., 2009).

In particular, whereas monazite dating by a variety of techniques (isotope dilution mass spectrometry, SIMS, electron microprobe dating, and LA-ICPMS) has been commonly applied to metamorphic and igneous rocks (Harrison et al., 2002, and references therein; Grove and Harrison, 1999; Catlos et al., 2002; Kohn and Malloy, 2004; Williams et al., 2007, and references therein), the method has been underutilized in detrital sediments. Monazite is a common phosphate mineral in different rocks such as granite, pegmatite, felsic volcanic ash, low- to high-grade metamorphic rocks, and as a detrital mineral in sedimentary rocks, and can be used to date the ages of crystallization and of metamorphism in igneous and metamorphic rocks (Parrish, 1990). Its relatively stability under a variety of geological conditions, and resilience to radiation damage, make monazite a reliable geochronometer (Harrison et al., 2002). Early work on monazite showed large discrepancies between U-Pb and Th-Pb ages (Tilton and Nicolaysen, 1957), which were explained by Pb diffusion over significant  $T$  and time (Shestakov, 1969), or by Pb loss (Michot and Deutsch, 1970). Since then, much progress has



**Figure 1. Closure  $T$ -windows characteristic of different geochronometers and thermochronometers. Note that for most chronometers, the temperature ( $T$ ) at which the system became fully retentive (closed) depends on various parameters such as compositions, thermal history, and pressure, and on the details of diffusion. (1) Green et al., 1989; (2) Zaun and Wagner, 1985; (3) Purdy and Jäger, 1976; (4) Chamberlain and Bowering, 2001; (5) Dahl, 1997; (6) Dahl, 1997, and Mezger and Krogstad, 1997.**

been made to understand diffusion properties of monazite (Cherniak et al., 2004) as well as conditions of recrystallization and new growth (Williams, et al., 2007).

In this issue of *Geology*, Hieptas et al. show the potential of detrital monazite dating to reveal significant information about the histories of metamorphism of relatively proximal and well-known sources. In this example, the authors collected sand samples from the French

Broad River (western North Carolina–eastern Tennessee, United States) and six tributaries in the Appalachian Blue Ridge and analyzed them with both zircon and monazite U-Pb dating in order to investigate the geochronological signature of the source area and its tectonic significance. Whereas detrital U-Pb zircon ages (by MC-LA-ICPMS) record Grenville (ca. 1300–950 Ma) and Taconic (ca. 470–440 Ma) signals, they exhibit a very limited Acadian (ca. 420–380 Ma) signal and do not record the Alleghanian (ca. 320–280 Ma) event. Detrital monazites from the same sediments record the complete Paleozoic collisional history of the Appalachian orogen (including the Alleghanian event) as well as the main events for the Grenville basement. The authors point out that the younger signals are only partially recorded in rims of detrital zircons, and may be missed without careful imaging and domain sampling in a strictly detrital zircon approach. This study highlights the utility of a multi-dating geochronological approach to provenance analysis for resolving multiple orogenic phases spanning a range of temperatures. Overall, the advancement of new approaches and analytical techniques such as the one described by Hietpas et al., double and triple dating (e.g., Rahl, et al., 2003; Bernet et al., 2006; Carrapa et al., 2009), and geochronology combined with geochemical analysis (Flowerdew et al., 2007) of detrital minerals, open uncharted pathways into the complex tectono-thermal histories recorded by clastic material.

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