Detrital Thermochronometry - Recorder of Earth's Dynamic Past

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Abstract

Advances in detrital noble gas thermochronometry by $^{40}Ar/^{39}Ar$ and (U-Th)/He dating are improving the resolution of sedimentary provenance reconstructions and providing new insights into the evolution of the Earth's surface through time. While detrital petrography and geochronology can illuminate sedimentary provenance and reconstructions of ancient drainage networks and sedimentary basins, they can be hampered by sediment recycling or monotonous source signatures and often do not provide quantitative insights into the tectonic or erosional evolution of drainage basins. Detrital thermochronometry has the added ability to quantify tectonic unroofing or erosion, temporal and dynamic connections between source and sink, sediment lag-times and transfer rates, depositional timing, and post-depositional burial heating. Hence, detrital thermochronometry provides the unique ability to use the detrital record in basins to reconstruct the Earth's dynamic long-term landscape evolution and coupling of basins and their hinterland.

Keywords: thermochronology, detrital, provenance, source-to-sink, lag times, basin evolution

Introduction

The Earth's surface has been modified through the interplay between lithospheric, hydrologic, and atmospheric processes throughout geological times. These dynamic interactions have been archived in sedimentary records preserved in the sedimentary basins of the world.

These archives of material eroded from continents and mountain belts provide an invaluable, long-term record of tectonism and erosion in the hinterland – a record that is often no longer accessible in the bedrock of the source region due to progressive tectonic or metamorphic overprinting or subsequent erosion.

While petrographic studies have long been used to unravel sedimentary provenance and thus hinterland tectonics and erosion, single-grain detrital isotopic techniques are increasingly used as a potent tool for reconstructing hinterland tectonics, past drainage systems, landscapes, linkages between sediment sources and depositional sinks, or hydrocarbon reservoir characterizations. This revolution is largely attributable to technological and analytical advances, in particular zircon U-Pb laser-ablation inductively-coupled-plasma mass-spectrometry (LA-ICP-MS), making data more affordable and more readily available in large numbers (e.g., Gehrels, 2014). However, interpretations based on zircon U-Pb crystallization ages can be hampered by non-diagnostic source signatures and sediment recycling, preventing discrimination between different source terranes . Thus, although these traditional provenance tools can shed light on the evolution of drainage basins, low-temperature thermochronometers can deliver quantiative insights into the dynamic and thermal evolution related to tectonic unroofing or erosional denudation of different portions of the source area (e.g., Ehlers and Farley, 2003; Reiners and Ehlers, 2005). Hence, detrital thermochronometry affords the unique ability to constrain the history of source regions in terms of both the timing and rates of exhumation or erosion.

Detrital thermochronometry has been applied on very different spatial scales, ranging from individual drainages to elucidate geomorphic or erosional processes, to regional drainage systems to reconstruct source-to-sink linkages and tectonic processes in the hinterland, to continental scale reconstruction of drainage system evolution or mantle-driven dynamic topography. Detrital thermochronometry, based on either noble gas or fission track measurements, produced by radiogenic alpha particles, has mainly been used to decode cooling histories recorded by K-bearing rock-forming and U-Th bearing accessory minerals that are common detrital phases in modern and ancient siliciclastic sedimentary deposits (e.g., Bernet and Spiegel, 2004; Hodges et al., 2005). Although fission track techniques have low precision single grain ages compared to $^{40}Ar/^{39}Ar$ and (U-Th)/He dating, interpretations are never based on an age of a single grain, but always populations, age peaks, or weighted averages of a number of grains to shed light on the exhumational history of different portions of the source area or reveal abrupt changes in the source area. These are characterized by nominal closure temperatures for these minerals of ~350°C for muscovite and ~350-180°C for K-feldspar $^{40}Ar/^{39}Ar$, ~250°C for zircon and ~100°C for apatite fission track, and ~180°C for zircon and ~60°C for apatite (U-Th)/He (e.g., Reiners, 2009). See Gautheron and Zeitler (this issue) for further discussion of this concept. These different moderate- to low-temperature sensitivity windows can make them either excellent detrital recorders of tectonic and erosional signals in the source area or sensitive to post-depositional burial heating and resetting. Overall, improved and novel noble gas thermochronometric methods and their applications, integrated with innovative new conceptual and numerical models, provide an improved quanitative understanding of timing, rates, and spatial patterns of long-term landscape evolution, erosion budgets, and tectonic and geodynamic processes.

Detrital Thermochronometry

The sedimentary records of basins have long been linked to the erosion of mountain belts to document hinterland erosion and tectonic activity and quiescence. At the same time, bedrock thermochronometry has become a routine approach to recover thermal histories of mountain belts and thus to quantify their short- and long-term tectonic, exhumational and erosional unroofing histories (Fig. 1). Detrital thermochronometric methods combine these two approaches and have been applied to sedimentary archives in order to reconstruct erosional and tectonic processes in large-scale orogenic systems (e.g., Bernet and Spiegel, 2004; Malusà and Fitzgerald, 2019). Early studies focused mainly on giant orogenic systems, such as the Himalayas and associated foreland basin and large-scale depocenters of the Indus and Bengal Rivers, in light of high to ultra-high exhumation rates (>5 km/Myrs) in the orogenic hinterland and the substantial sedimentary archives (Najman, 2006). These early studies relied mainly on detrital ^{40}Ar/^{39}Ar thermochronometry, as this could be accomplished by high-precision, single-grain ^{40}Ar/^{39}Ar dating of detrital muscovite and K-feldspar, and the fact that exhumation rates and magnitudes were sufficient to reset ^{40}Ar/^{39}Ar ages in the source terranes. Practically, this methodology also benefited from the possibility of ^{40}Ar/^{39}Ar dating large numbers of individual detrital grains by laser, yielding statistically robust datasets. However, the cost and speed of analysis (notably the need for neutron irradiations) represents an impediment for detrital ^{40}Ar/^{39}Ar dating. Furthermore, the relatively high closure temperatures of ^{40}Ar/^{39}Ar minerals (>300°C) limits their thermal sensitivity to upper-crustal processes in the source area.

Detrital thermochronometry of refractory accessory phases, such as zircon, titanite, or apatite, by (U-Th)/He dating has experienced dramatic growth over the last decade. Many of these detrital low-temperature thermochronometers leverage their <200°C closure temperatures to reveal upper-crustal (<6 km) tectonic activity and erosion in sediment source areas. Besides refining provenance, detrital thermochronometry is able to recover source terrane exhumation rates by using the concept of lag-time – a measure of the temporal difference between cooling age of the detrital mineral grain in the source region, and the depositional age of the sedimentary host rock (Figs. 1 and 2). Whereas application of apatite fission-track dating in detrital studies has been hampered by both post-depositional burial resetting and low single-grain precision, thus relying on multi-grain pooled ages, detrital fission track dating of zircon has been more widely applied in mega-orogenic source to sink studies (e.g, Carter et al., 2019). Most detrital zircon fission-track provenance studies exploit its low closure temperature (~250°C) to provide insights into source area denudation and temporal variations in exhumation rates in the Himalayas and North American Cordillera (Cerveny et al., 1988, Garver and Brandon, 1994). Increasingly, these studies couple zircon fission track dating with U-Pb dating of the same crystal to refine provenance identification, and identification of volcanic grains (U-Pb age = low-temperature thermochronometeric age) (Fig 2). This double-dating approach can provide more detailed insight into the cooling history of specific hinterland terranes (e.g., Carter and Moss, 1999). However, the applicability of zircon fission track dating has been limited by analytical complexities (e.g. etching), single-grain precision, and uncertainties in thermal sensitivity due to lack of a robust track annealing model (Malusà and Fitzgerald, 2019).

The higher precision of single-grain (U-Th)/He dating of accessory phases overcomes some of the limitations of detrital fission track dating. In particular, zircon (U-Th)/He dating, with a single-grain age precision (~8%) and a nominal closure temperature of ~180°C, has become widely utilized for revealing upper-crustal exhumation histories and tectonic activity in source terranes (e.g., Rahl et al., 2003; Reiners, 2005). Importantly, zircon is also very conducive to U-Pb-He double dating of the same detrital grain, enabling more differentiated and sophisticated provenance interpretations by linking source area crystallization ages with source area exhumation histories (e.g., Reiners et al., 2005; Thomson et al., 2017; Carter, 2019). Detrital apatite (U-Th)/He dating can also be a powerful tool in modern geomorphic and active tectonic studies, given its low to very low thermal sensitivity window (e.g., Stock et al., 2006), although limitations arise due to the need for intact, inclusion-free apatite, and its propensity for undergoing mechanical abrasion during transport and post-depositional burial (partial) resetting.

Earth's Dynamic Past in a Grain of Sand

Detrital thermochronometry has become more versatile and sophisticated through an expanded analytical repertoire, innovative conceptual approaches, and numerical modeling, making it more applicable to a wider spectrum of tectonic and geomorphic environments. These data can constrain the timing and rates of hinterland erosion and tectonic unroofing or maximum depositional ages and presence of first-cycle volcanic zircons, as illustrated in the following sections

Improved Sedimentary Provenance

Zircon U-Pb geochronology has exploded as a sedimentary provenance tool over the past decade with the advent of LA-ICP-MS analysis, making data available in staggering numbers. Detrital zircon U-Pb provenance studies, based on source crystallization ages, have worked exceedingly well in geological settings with highly-variable crustal formation ages, such as North and South America, and the Himalayas. However, as shown by modern river studies, this is ofen not the case, due to either monotonous source sigantures or significant recycling of older sedimentary strata.

U-Pb-He double dating can differentiate between different sources with the same or similar zircon U-Pb age signatures (Fig. 2). For example, in the Paleogene foreland basin of the southern Pyrenees, Thomson and others (2019) showed that identical Variscan U-Pb ages from the foreland and the orogenic wedge can readily be differentiated by (U-Th)/He double dating. While Variscan zircons from the foreland are characterized by Permian zircon He ages, Variscan zircons from the Pyrenees yielded early Paleogene He cooling ages reflecting rapid tectonic exhumation of the fold and thrust belt (Fig. 3). Similarly, Xu and others (2018) showed that U-Pb-He double dating of Miocene strata in the northern Gulf of Mexico is able to differentiate detrial zircons with non-diagnostic, invariant late Mesoproterozoic (Grenvillian) ages by leveraging their different Appalachian, Laramide, and Cenozoic zircon He cooling ages and thus improve sediment provenance reconstructions on the basis of otherwise non-diagnostic zircons.

Hinterland's Dynamic Past

In addition to refining sedimentary provenance, detrital thermochronometry potentially makes lag time calculations possible, with the aim of quantifying hinterland bedrock exhumation rates from the detrital signature. Lag time, as defined above, is a measure of the time elapsed between a mineral grain's passage through its closure isotherm to its surface exposure, erosion and deposition (e.g., Ruiz et al., 2004; Saylor et al., 2012). Hence, assuming negligible transport and recycling duration, minimum lag times reflect the rapidity of source terrane exhumation rates and give a measure of the dynamic evolution of the hinterland (Fig. 1). While short lag times reflect rapid unroofing, long lag-times are indicative of slow exhumation or long-term intermediate storage. The temporal evolution and variation in hinterland exhumation rates can be assessed by comparing lag time estimates from different stratigraphic horizons. A temporal decrease in lag time can be interpreted as an increase in source terrane exhumation rate, while an increase in lag time might signal either a decrease in exhumation rate or a change in sediment source (e.g. Saylor et la., 2012).

Detailed zircon (U-Th)/He and apatite fission track analyses from the northern Alpine Molasse foreland basin in central Switzerland illustrate the insights that can be gleaned from high-resolution lag-time reconstructions (Fig. 4). The Swiss Molasse basin is characterized by two major shallowing-upward Oligo-Miocene sedimentary sequences, divided by a marine transgression in the early Miocene (Schlunegger et al., 1997). While it has been suggested that thrusting and erosion might have waned during the transgression, thermochronometric lag times tell a different story. Lag times are uniformly ~5-10 Myrs during deposition of the Lower Freshwater Molasse, but decrease abruptly to ~0 Myrs at the transgressive base of the Upper Freshwater Molasse at ~19 Ma, signaling a major phase of accelerated exhumation of the fold-and-thrust belt, possibly due to either out-of-sequence thrusting or syn-orogenic hinterland extension. Lag times again increase to >10 Myrs at ~12 Ma, interpreted as a decrease in shortening in the Helvetic thrust belt, the onset of shortening in the Jura Mountains, and the Molasse basin becoming a piggy-back basin. Hence, high-resolution lag time studies have great potential to elucidate tectonic and erosional evolution of an orogenic hinterland (Fig. 4).

Recently Malusà and Fitzgerald (2020) explored some of the assumptions and limitations of quantitative lag-time interpretations. They pointed out that for reliable lag-time quantification, ages need to reflect mineral closure ages resulting from a simple cooling history (no partial resetting), source terrane isotherms should be in steady-state through time, and sediment transport time from source to sink should be negligible. Importantly, for reliable lag-time estimates, it is critical to exclude first-cycle volcanic grains as they do not track the exhumation path from closure to erosion. This is best accomplished by U-Pb-He double-dating and the exclusion of volcanic grains with identical crystallization and cooling ages (Saylor et al., 2012).

Short- and Long-Term Landscape Evolution

Detrital geo- and thermochronometry are potent tools for reconstructing past drainages and landscapes or continental paleogeographies, and elucidating their long-term erosional and landscape evolution. Detrital zircon U-Pb dating has been the principle workhorse for these reconstructions, but detrital thermochronometry has both refined these reconstructions and, more importantly, provided unique quantitative insights into the dynamic evolution of continents.

Detrital thermochronometry is not limited in its application to large-scale, deep-time reconstructions; studies have also used detrital thermochronometric data to track geomorphic processes, such as the locus of erosion within a catchment or the nature and efficiency of erosive agents (e.g., glaciers). This approach is most effective if the distribution of bedrock thermochronometric ages within a drainage are spatially variable and well-defined, for pinpointing where sediment came from, and attributing detrital ages to a specific portion or elevation within a drainage.

Stock and others (2006) utilized apatite (U-Th)/He to investigate glacial, fluvial, and hillslope erosion processes in the Sierra Nevada. By using statistical comparison of observed and predicted age distributions, based on catchment hypsometry, they were able to point to the locations of sediment generation and storage in mountain-scale catchments. Using a similar comparison of catchment erosion in the Nepal Himalayas using detrital muscovite $^{40}Ar/^{39}Ar$ ages, Ruhl and Hodges (2005) reconstructed catchment-averaged erosion rates to evaluate spatial uniformity or heterogeneity of erosion, and to explore possible transience in erosional processes and their departure from steady-state over the million-year timescale. Finally, detrital thermochronometry from modern catchments has proven useful in mapping late Cenozoic exhumation patterns in large, inaccessible regions such as the ice-covered mountains of Alaska (Lease et al., 2016).

Stratigraphic Age Constraints

U-Pb dating of first-cycle detrital volcanic zircons has been extensively used to determine depositional ages in strata that lack biostratigraphic age constraints (Dickinson and Gehrels, 2009). Although this methodology has been shown to work well in tectonic basins adjacent to magmatic arcs, such as forearc and back- or retro-arc basins, it is commonly not applicable in basins associated with continent-continent collisions, rifts, or continental margins due to the lack of new magmatic zircon generation. In these cases, the youngest mode of detrital thermochronological cooling ages, assuming no post-depositional resetting, can be used to estimate maximum depositional ages. This approach relies on the fact that, in rapidly exhuming regions, the youngest mode of cooling ages has very short or negligible lag times and therefore approximates the stratigraphic age.

In fold and thrust belts this thermochronometric approach to determining depositional ages has been applied in a number of studies to date syn-tectonic continental siliciclastic deposits. Najman and other (1997) employed laser muscovite ^{40}Ar/^{39}Ar dating in NW India to corroborate the syn-tectonic nature of early Himalayan foreland basin sediments, and to constrain their maximum depositional ages. Short-lag time detrital ages reflected the very rapid, Oligo-Miocene exhumation of mid-crustal, muscovite-bearing rocks from the crystalline core of the Himalayas. While maximum depositional age constraints, based on muscovite ^{40}Ar/^{39}Ar dating, require ultra-rapid exhumation in the tectonically-active hinterland, (U-Th)/He data can yield reliable depositional ages, based on short lag-time ages, even with limited magnitudes of upper-crustal exhumation. Thomson and others (2017) demonstrated that, despite the absence of volcanic input, the youngest zircon (U-Th)/He age modes from foreland basin strata in the southern Pyrenees yielded maximum depositional age constraints for most of the Paleocene to Eocene section, similar to biostratigraphic and magnetostratigraphic age estimates. In fact, even samples with 5 Myrs lag time yield maximum depositional ages that would only be an overestimation of 10% for sediments that otherwise lack any depositional age information.

This approach has proven particularly powerful to resolve the stratigraphy of the Nubian sandstone of NE Africa and Arabia – a massive, undifferentiated mega-sequence of Paleozoic and Mesozoic quartz-arenite sandstones with a monotonous and non-diagnostic detrital zircon signatures, dominated by Pan-African and older zircons. In contrast, the youngest mode of detrital zircon (U-Th)/He ages allows for an amazingly clear identification of different Carboniferous, Triassic, and Cretaceous stratigraphic packages (Fig. 5). Age-diagnostic detrital zircon (U-Th)/He signatures record the tectonic evolution of source terranes in response to different tectonic events, such as Hercynian block faulting, Triassic and Jurassic Tethyan extension and rifting, and Late Cretaceous inversion. These age constraints allow for both chronostratigraphic unraveling of a km-scale monotonous sedimentary package as well as genetic attribution of different units to tectonic events affecting the region (Fig. 5). Szymanski and others (2016) showed how this approach can also be applied to relatively small continental extensional basins. Their work on a Saudi Red Sea rift basin differentiated between pre- and syn-rift strata and provided direct age constraints on undated continental syn-rift strata in a small (<3 km) half-graben by documenting the presence of reset early Miocene apatite (U-Th)/He ages derived from the exhumed extensional footwall.

Conclusions and Prospectives

Detrital thermochronometry has evolved into a powerful and versatile apporach that is no longer only limited to large-scale mega-tectonics. In particular, detrital noble gas thermochronometry has reinvented itself through new analytical tools, more readily available high-resolution and large datasets of precise single-grain ages, and analytical, conceptual, and numerical integration, allowing for a higher thermal, temporal, and spatial resolution of tracking and quantification of geological processes.

Detrital thermochronometry is a potent means to provide lag time estimates that illuminate hinterland erosion and tectonic exhumation magnitudes and rates, and thus quantify the dynamic evolution of sedimentary source terranes with considerable temporal and spatial resolution. Furthermore, geo- and thermochronometric double dating (e.g., U-Pb-He double dating) can provide more accurate sedimentary provenance information. This approach allows for a better characterization of sediment contributions from volcanic, first-cycle basement, or recycled sedimentary input into source-to-sink systems on the basis of both lag time and age difference between crystallization and cooling ages. Lastly, a rapid growth area of detrital noble gas thermochronometry lies in its application of delineating maximum depositional ages in areas that lack input of volcanic zircons. The use of ultra-short lag time cooling ages in foreland basins, continental rifts, or continental margins is proving to be a reliable way of providing stratigraphic age constraints, a means to differentiate monotonous continental sedimentary packages, and to illuminate their associated tectonic drivers.

Detrital thermochronometry has been applied in a range of tectonic environments, from orogenic systems to continental rifts. High-octane orogenic systems and fold-and-thrust belts, such as the Himalayas or Andes, have long been the playground for detrital provenance and thermochronometry studies, as the thermochronometric signals, like the mountains themselves, are big. Analytical advances have dramatically improved our ability to resolve the timing and rates of hinterland exhumation, making it possible to tie detrital fluxes and depositional records to specific thrust sheets, and to provide a detailed record of the dynamic past of an orogen. In extensional rifts and continental margins, bedrock thermochronometry has been a compelling technique to elucidate the temporal and exhumation histories, while isotopic provenance studies have focused on large-scale source provenance reconstructions, basin fill history, and reservoir characterizations. Detrital thermochronometry is starting to play a more important role in reconstructing rifts and continental margins, and elucidating the dynamic interactions of crustal and lithospheric tectonics. Application of lag-times, maximum depositional age estimates, and better quantification of post-depositional thermal effects, have allowed detrital thermochronometry to become a more sophisticated tool in reconstructing the dynamic evolution of continental rifting and break-up.

Looking to the future, as detrital noble gas thermochronometry and its combination with U-Pb double dating is experiencing rapid growth, more time- and cost-effective data acquisition is needed - the development of detrital laser (U-Th)/He dating should provide this boost (e.g., Horne et al., 2016). In addition, improved recovery of thermal information from single detrital grains would also be desirable. While this has been potentially possible, though rarely utilized, in the case of single-grain detrital $^{40}Ar/^{39}Ar$ step-heating, it should also be feasible in the case of $^{4}He/^{3}He$ thermochronometry (e.g., Shuster and Farley, 2005). To date, no detrital $^{4}He/^{3}He$ thermochronometric studies have been attempted. However, statistically more robust large-sample size studies and single-grain thermal history recovery in the future will also require better integration of numerical modeling, such as coupled thermo-mechanical, landscape, and geodynamic modeling, to warrant increased analytical effort.

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Figure Captions

Figure 1. Diagram illustrating the partical path from cooling, exhumation, erosion, transport, deposition, and burial in an extensional source-to-sink system. Detrital thermochronometric ages and their lag time (tL) can be used as a measure of the rate of exhumation in a source area by estimating the time difference between cooling through a closure isotherm (Tc) at time tc and

erosion at the surface (Ts) at time te and depositional age (td) at temperature (Td), assuming a negligible transport time (e.g., Ruiz et al., 2004). For obtaining accurate lag time estimates it is essential to exclude volcanic zircons (tv), identified as having identical crystallization and cooling ages (tv, U-Pb=He) (e.g., Saylor et al., 2012).

Figure 2. 3D tectonic cartoon landscape illustrating the power of U-Pb-He double-dating in detrital provenance studies by leveraging spatially variable cooling histories of different tectonic domains underlain by monontonous, non-diagnostic crystalline basement. While U-Pb ages (red line) fail to differentiate different sources, zircon He ages (shaded) allow for distinguishing between different basement terranes and proper attribution of detrital provenance. U-Pb-He double dating diagram graphically deconvolves sink detrital signature from basinal sink (E) and helps identify different provenance components.

Figure 3. Case study from the southern Pyrenean foreland basin demonstrating power of U-Pb-He double-dating in differentiating sediment input from foreland (red arrow) and orogenic hinterland (red arrow) in time and space despite non-diagnostic zircon U-Pb signature (modified after Thomson et al., 2019). While Cretaceous strata are dominated by Permo-Triassic cooling ages, the onset of Pyrenean provenance is marked by the abrupt shift to Paleocene-Eocene cooling ages derived from the exhuming Pyrenean fold-and-thrust belt.

Figure 4. Application of temporal variations in thermochronometric lag times in the Cenozoic Northern Alpine Foreland basin in central Switzerland. These data show how the detrital record can record the dynamic tectonic evolution of the orogenic hinterland – a rapid decrease in lag time (t_L), temporally coincident with the Burdigalian transgression in the foredeep, signals the onset of rapid Early Miocene thrust belt exhumation, while a Middle Miocene increase signals the onset of shortening in the Jura Mountains and the Molasse basin becoming a piggy-back basin (data from Miller, 2012). The diagonal lines are contours of constant lag times (tL=0, 10, 20, and 30 Myrs).

Figure 5. Application of Maximum Depositional age (MDA) estimates derived from rapidly-exhumed zircon He cooling ages with ultra-short lag times. The Nubian Sandstone covering much large parts of NE Africa and Arabia and spanning most of the Phanerozoic has largely lacked reliable bio- and chronostratigraphic constraints. Short-lag time detrital zircon He cooling ages (ZHe) provide crucial new chronostratigraphic constraints, allowing for stratigraphic differentiation and correlation, and link different stratigraphic packages genetically to tectonic events affecting the region (data from Pujols, 2011).