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Invited review article

Applications and limitations of U-Pb thermochronology to middle and lower crustal thermal histories

A.J. Smye[a,*], J.H. Marsh[b], P. Vermeesch[c], J.M. Garber[a], D.F. Stockli[d]

[a] Department of Geosciences, Pennsylvania State University, University Park, PA 16801, USA
[b] Mineral Exploration Research Centre, Harquail School of Earth Sciences, Laurentian University, Sudbury, ON P3E 2C6, Canada
[c] Department of Earth Sciences, University College London, London, WC1E 6BT, UK
[d] Department of Geological Sciences, The University of Texas at Austin, Austin, TX 78712, USA

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ABSTRACT

Volume diffusion of Pb occurs over micron length scales in apatite and rutile at temperatures relevant to the evolution of the middle and lower crust. Continuous thermal history information can be resolved from inversion of intracrystalline U-Pb date profiles preserved within individual grains. Recent developments in microbeam analysis permit rapid measurement of these age profiles at sub-micron spatial resolution, thus heralding a new era for U-Pb thermochronology. Here, we review the theoretical, experimental and empirical basis for U-Pb thermochronology and show that rutile, in particular, presents an exceptional opportunity to obtain high-resolution thermal history information from the deep crust. We present a Bayesian procedure that is well suited to the inversion of U-Pb date profile datasets and balances computational efficiency with a full search of thermal history coordinate space. Complications relevant to accurate application of U-Pb thermochronology are discussed **i)** theoretically and **ii)** empirically, using a rutile U-Pb dataset from the lower crust of the Grenville orogeny. Purely diffusive date profiles are shown to be the exception to uniform, or step-like, young profiles, suggesting that processes other than thermally-activated volume diffusion may control U-Pb systematics in rutile residing in the lower crust. However, the data obtained from apparent diffusive profiles systematically match cooling histories inferred from other thermochronometers. This result emphasises the importance of integrating microtextural observations, and trace-element concentrations, with U-Pb age data in order to discriminate between diffusive and non-diffusive Pb transport mechanisms in accessory phases and thus minimize the risk of generating spurious thermal histories.

1. Introduction

Geodynamic processes impart characteristic thermal signatures to the lithosphere that are recorded by the distribution of daughter nuclides in minerals with radiogenic parent elements. The noble gas decay systems $^{40}Ar/^{39}Ar$ and (U-Th)/He harness thermal history information from temperatures ≤ 500 °C and have been routinely applied to tectonic and geomorphological investigations of the middle and upper crust (Farley, 2002; McDougall and Harrison, 1999). Conversely, volume diffusion of Pb in apatite, rutile and, potentially, titanite is effective at temperatures characteristic of the deep crust (> 400 °C). U-Pb thermochronology can thus be used to constrain cooling from high temperature, and, by inference, exhumation rates of deep seated metamorphic and plutonic rocks in active and ancient orogenic belts (e.g. Cochrane et al., 2014; Flowers et al., 2006; Kooijman et al., 2010; Kylander-Clark et al., 2008; Mezger et al., 1989; Mezger et al., 1991; Möller et al., 2000) as well as long-duration cooling of cratonic lower crust to investigate continent stabilization (e.g. Blackburn et al., 2011; Blackburn et al., 2012; Davis, 1997; Davis et al., 2003; Schmitz and Bowring, 2003; Schoene and Bowring, 2007). Traditionally, U-Pb thermochronology has been applied using whole-grain isotope dilution analysis in which the measured U-Pb date is assigned to a nominal, volume-averaged closure temperature (Dodson, 1973). Whilst this approach has been successfully applied to constrain thermal histories of crustal rocks, interpolation between discrete temperature-time (*T-t*) data points derived from whole grain analyses **i)** yields low-resolution thermal history information and **ii)** assumes that the effective diffusion radius is the entire grain. In contrast, near-continuous thermal history information can be obtained through numerical inversion of within-grain U-Pb date profiles (Harrison et al., 2005). Until recently, measurement of U-Pb date profiles was only possible by secondary ion mass spectrometry (Grove and Harrison, 1999; Harrison et al., 2005);

* Corresponding author.
E-mail address: smye@psu.edu (A.J. Smye).

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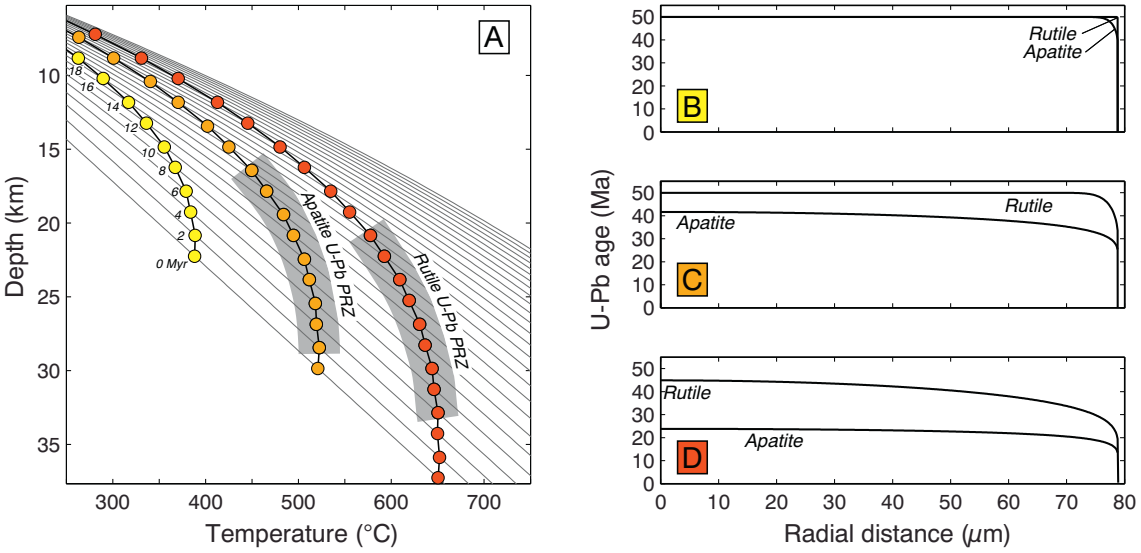

Fig. 1. U-Pb thermochronology.
Panel **A** illustrates the effect of erosion on the temperature-depth evolution of three rock samples initially located at 22.5 (yellow particle), 30 (orange) and 37.5 km depth (red). Gray lines are geotherms, plotted at 2 Ma intervals. Shaded regions delineate the zones of partial retention for Pb in apatite and rutile. Calculations performed using an erosion/exhumation rate of 1 km/Ma. Panel **B** shows calculated ^{238}U-^{206}Pb date profiles for single grains of apatite and rutile in each of the three rocks shown in panel **A** after 50 My of erosion. Both apatite and rutile date profiles were calculated using experimentally determined Pb diffusion parameters (Cherniak, 2000; Cherniak et al., 1991) and a cylindrical geometry (200 × 250 × 100 μm).

however, technological developments have enabled routine measurement of radiogenic Pb and trace-element concentrations at sub-micron spatial resolution by laser ablation inductively-coupled plasma mass spectrometry (e.g. Cottle et al., 2009; Smye and Stockli, 2014; Stearns et al., 2016; Steely et al., 2014). The ease, rapidity, precision, and spatial resolution of LA-ICP-MS herald a new era for deep lithosphere thermochronometry.

Proliferation of high spatial resolution U-Pb measurements raises the challenge of accurately interpreting intracrystalline U-Pb date distributions as forming in response to a host of diffusive or non-diffusive processes. Various intragrain transport processes, including recrystallization, short-circuit diffusion, secondary growth and volume diffusion, can each affect the topology of a U-Pb date profile. Furthermore, the effect of neighboring mineral phases and the presence/absence of grain-boundary fluids may have significant effects on the boundary conditions for volume diffusion of Pb through accessory phases. Such effects have been shown to influence the incorporation of extraneous ^{40}Ar (e.g. Kelley, 2002; Smye et al., 2013) and the efficacy of recrystallization (e.g. Villa and Hanchar, 2017) in K-bearing minerals. Developing an understanding of the kinetic controls on Pb transport over sub-micron length scales in accessory minerals is critical to accurately identifying U-Pb datasets that are suitable for U-Pb thermochronology, and avoiding generation of spurious or non-unique thermal histories. Complementary analysis of trace-element abundances collected from the same analytical volume as U-Pb dates has the potential to shed light on these processes (e.g. Kylander-Clark, 2017; Kylander-Clark et al., 2013). Motivated by recent methodological advances, this paper reviews and demonstrates the basis for U-Pb thermochronology by evaluating the kinetic processes that control the topology of U-Pb date distributions.

2. (U-Th)/Pb thermochronometry

2.1. Theory

The physics describing volume diffusion-controlled thermochronology are well established (Dodson, 1986; Dodson, 1973; Fechtig and Kalbitzer, 1966); here, we provide an overview of fundamental concepts applied to the U-Pb system in apatite, rutile and titanite. Length scales (L) of Pb diffusion through monazite and zircon are predicted to be limited at temperatures < 900 °C ($L \approx 1$ μm for monazite and 3 μm for zircon at 900 °C, over 10 Ma); such short length scales of diffusive transport limits their use as thermochronometers to regions of the lithosphere cooling from (ultra-)high temperature conditions (Cherniak and Watson, 2001b; Cherniak et al., 2004). Therefore, we do not consider zircon and monazite further, but the concepts discussed below are relevant to monazite and zircon U-Pb thermochronology.

The concentration of radiogenic Pb, C_r^i, at radial position, r, within mineral i residing at temperature T, for duration t, is given by:

$$\frac{\delta C_r^i}{\delta t} = D^i \nabla^2 + S_r \quad (1)$$

where, D^i is the diffusivity of Pb described by an Arrhenius law ($D^i = D_0{}^i e^{(-E_a{}^i/RT)}$), where $D_0{}^i$ is the diffusivity at infinite T, $E_a{}^i$ is the activation energy and R is the universal gas constant), ∇ is the Laplacian operator and S_r represents radiogenic production of Pb, controlled by the spatially-dependent concentration of ^{238}U, ^{235}U and ^{232}Th. From inspection of Eq. 1, the concentration of radiogenic Pb at any point in time and space within a mineral grain reflects a competition between diffusive loss and radiogenic production. The rate of diffusive loss exceeds the rate of production at high temperatures, and vice-versa at low temperatures. Between these two end-member behaviours, there exists a region of $T(t)$ space in which the rate of diffusive loss is comparable to the rate of radiogenic production; the absolute magnitude of this "partial retention zone" (PRZ) depends on D^i, dT/dt, and L.

Fig. 1 shows the relationship between PRZ and U-Pb date profile for single grains of apatite and rutile undergoing cooling during exhumation from the deep crust. Titanite is not considered here due to uncertainties over Pb diffusion parameters that are discussed in section 2.3. We assume here that Pb diffusive loss only occurs at the outermost grain boundary, and that each mineral crystallizes immediately prior to the onset of exhumation at 50 Ma. In this example, progressive exhumation advects heat to shallow crustal levels where conductive heat loss to the surface occurs. These competing effects increase dT/dz (gray geotherms, Fig. 1a) and dictate that exhuming rocks will experience a monotonically increasing dT/dt as long as exhumation continues.