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Apatite (U-Th-Sm)/He thermochronology on the wrong side of the tracks

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ABSTRACT

Despite the increasing application of apatite (U-Th-Sm)/He thermochronology in a range of settings, the technique suffers from two major unresolved problems which preclude reliable thermal history interpretations on a routine basis. One problem is the common but unexplained over-dispersion of single grain ages compared to predictions based on accepted models of diffusion systematics (including enhanced He retentivity due to the buildup of radiation damage in the apatite crystal lattice). A second related problem is that the widely adopted "RDAAM" model does not provide an accurate representation of the degree to which helium retentivity is enhanced as a result of the accumulation of radiation damage. Until these problems are resolved and eliminated, thermal history interpretations derived from this method cannot be regarded as reliable. Routine application of the technique requires a more rigorous quantitative understanding of these factors. Further experimental studies are required to identify all significant sources of variation in measured ages and to develop more accurate models of the thermal response of the system, combined with rigorous calibration and validation against independent methods in well-constrained natural settings. Only once this is achieved will the technique be capable of producing robust and reliable interpretations.

1. Introduction

Apatite (U-Th-Sm)/He thermochronology is based on the balance between the production of He due to alpha-emitting trace elements and the loss of He as a result of thermally controlled diffusion. The method developed rapidly around the turn of the century (Farley, 2000; Warnock et al., 1997; Wolf et al., 1996, 1997, 1998; Zeitler et al., 1987), offering the promise of higher precision and sensitivity to lower temperatures compared to established apatite fission track methods. Since that time, the He method has seen a number of enhancements. Early work required analysis of multiple grain aliquots, whereas analysis of single crystals is now routine. Initial diffusion models based on laboratory experiments (Farley, 2000; Wolf et al., 1998) have been supplemented by models incorporating enhanced retention of He due to accumulation of radiation damage within the apatite lattice (Flowers et al., 2009; Gautheron et al., 2009; Willett et al., 2017). The contribution of α-decays from ^{147}Sm has also been included and the method is more properly termed apatite (U-Th-Sm)/He thermochronology (Grist and Zentilli, 2005), but for brevity we use the shortened form of "apatite He thermochronology" or simply "apatite He" to refer to the method here.

Apatite He thermochronology has found application in many diverse fields of geology, and new publications addressing a variety of problems, particularly in relation to uplift and denudation rates in mountainous regions and landscape development in non-tectonic settings and basement terrains, appear regularly. Often the technique is applied in tandem with apatite fission track (AFT) methods and sometimes with other thermochronological systems, but in many cases it is used in isolation and this trend appears to be increasing.

Despite the initial optimism and apparently successful application in a number of cases, a growing number of studies has shown that the apatite He technique is beset by major problems which have so far prevented the initial promise from being achieved in routine application. We suggest that because of these problems, which we document here, results from the technique cannot be regarded as reliable, and further studies are required to eliminate these problems or understand the underlying processes in quantitative terms before the technique can be successfully applied on a routine basis.

In discussing these problems we prefer not to cite individual studies, in order to avoid being too critical of individuals. Instead, we list in Table 1 a selection of recent papers which have led us to the conclusions outlined here. The problems fall predominantly into two areas, a) excessive dispersion of individual grain ages within a single sample, and b) failure to accurately predict enhanced He retentivity due to radiation damage. These problems are most obvious in studies of Paleozoic and older rocks, and it is generally thought that application in settings involving rapid Cenozoic cooling provides more reliable results. This may be so, or it may be that the problems are less noticeable where young

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Table 1
Sources of information on apatite (U-Th-Sm) thermochronology used in production of this paper.

Source	AFT data in same or adjacent samples	Number of grains analysed per sample	Excessive dispersion of individual gran ages?	Ages plotted vs eU?	Age plotted vs grain size?	Flowers and Kelley cited (2011)?	Excessive dispersion explained by eU and/or grain size
Kasanzu (2017)	Yes	1–4	Yes	Yes	Yes	Yes	No
Glorie et al. (2017)	Yes	1–4	Yes	No	No	No	No
Wildman et al. (2017)	Yes	2–18	Yes	Yes	Yes	No	No
Recanati et al. (2017)	Yes	5–13	Yes	Yes	Yes	No	eU in some samples
Orme (2017)	No	3–5	Yes	Yes	No	No	No
Powell et al. (2017)	Yes	4	Yes	Yes	Yes	No	No
Safipour et al. (2015)	Yes	2–5	Yes	No	No	No	No
Kasanzu et al. (2016)	Yes	1–4	Yes	Yes	Yes	Yes	No
Cogné et al. (2016)	Yes	1–5	Yes	No	No	No	No
Szymanski et al. (2016)	No	Aliquots	–	–	–	–	–
Bernard et al. (2016)	Yes	4	Yes	No	No	No	No
Zattin et al. (2016)	No	1–5	Yes	Yes	No	No	No
Hall et al. (2016)	Yes	2–5	Yes	No	No	No	No
Wildman et al. (2016)	Yes	5–21	Yes	Yes	Yes	Yes	No
Verdel et al. (2016)	No	3–4	Yes	Yes	No	No	Yes
Amidon et al. (2016)	Ages only	2–9	Yes	No	No	No	No
Ricketts et al. (2016)	Yes	5	Yes	Yes	No	Yes	eU in some samples
Murray et al. (2016)	Yes	4–26	Yes	Yes	No	No	eU in some samples
Dewing et al. (2016)	No	aliquots	Yes	No	No	No	No
Zhang et al. (2016)	No	5	yes	No	No	No	No
Torres Acosta et al. (2015)	Yes	2–3	Yes	Yes	No	No	No
Mandal et al. (2015)	Yes	2–5	Yes	Yes	Yes	Yes	No
Sahu et al. (2013)	Yes	1–7	Yes	Yes	Yes	Yes	No
Fillon et al. (2013)	Yes	2–5	Yes	Yes	No	No	eU in some samples