S3 Text. Detailed Apatite (U-Th)/He Methods

(U-Th)/He analyses were performed by the University of Colorado Thermochronology Research and Instrumentation Lab (CU TRaIL). Individual mineral grains were handpicked using a Leica M165 binocular microscope equipped with a calibrated digital camera and capable of both reflected and transmitted, polarized light. The grains were screened for quality, including crystal size, shape, and the presence of inclusions. After characterization, grains were placed into small Nb tubes that are then crimped on both ends. This Nb packet was then loaded into an ASI Alphachron He extraction and measurement line. The packet is placed in the UHV extraction line (~3 X 10-8 torr) and heated with a 50W diode laser to ~800-1100°C for 5 to 10 minutes to extract the radiogenic 4He. The degassed 4He was then spiked with approximately 13 ncc of pure 3He, cleaned via interaction with two SAES getters, and analyzed on a Balzers PrismaPlus QME 220 quadrupole mass spectrometer. This procedure was repeated at least once to ensure complete mineral degassing. Degassed grains were then removed from the line and taken to a Class 10 clean lab for dissolution. Apatite grains, still enclosed in the Nb tubes, were placed in 1.5 mL Cetac vials, spiked with a 235U - 230Th – 145Nd tracer in HNO3, capped, and baked in a lab oven at 80°C for 2 hours. Once the minerals were dissolved, regardless of the dissolution process, they were diluted with 1 to 3 mL of doubly-deionized water, and taken to the ICP-MS lab for analysis. Sample solutions, along with normal solutions and blanks, were analyzed for U, Th, and Sm content using an Agilent 7900 Quadrupole inductively-coupled plasma mass spectrometer equipped with an inert sample introduction system. Once the U, Th, and Sm contents had been measured, He dates and all associated data were calculated on a custom spreadsheet made by CU TRaIL staff using the methods described in Ketcham et al (2011). Every batch of samples includes standards run sporadically throughout the process to monitor procedures and maintain consistency from run to run.

Analytical uncertainty is at – 2-sigma in millions of years, only including propagated direct analytical uncertainties for He, U, Th, and Sm. Analytical uncertainties can be considered the minimum uncertainty on a single measured date. Some uncertainties, like that associated with the alpha-ejection correction, are poorly quantified at present, making it challenging to properly include them in uncertainty estimates for single-grain (U-Th)/He dates. Ongoing work is aimed at improving our understanding of uncertainties associated with the alpha-ejection correction, to enable their appropriate incorporation into single-grain uncertainty estimates.

References:

Ketcham, R. A., Gautheron, C., and Tassan-Got, L., 2011, Accounting for long alpha-particle

stopping distances in (U-Th-Sm)/He geochronology: Refinement of the baseline case. Geochmica Et Cosmochimica Acta, 75(24), 7779–7791. <http://doi.org/10.1016/j.gca.2011.10.011>

***Explanation of Data Columns Provided by CU TRaIL***

**Full Sample Name** – Sample Name, the subscripts such as \_ap1 or \_zir1 refer to separate analyses from the same sample

**length and width** – measurements of the grain dimensions in micrometers. Each grain is measured from two different angles to ensure that the grain geometry is fully captured. These values are used to calculate alpha ejection corrections and crystal volumes and masses using the techniques described by Ketcham et al., (2011).

**2X Term** – Notes whether or not the grain is doubly terminated.

**Np** – The number of pyramidal terminations of the grain, used in the alpha ejection correction.

**Dim Mass** – The dimensional mass (in micrograms) is calculated based solely on the volume of the crystal (determined from the measurements) and average apatite density.

**rs –** The radius of a sphere with an equivalent surface are to volume ratio as your crystal. This value is required if you wish to do any thermal modeling of your grains using HeFTy.

**4He (nmol/g)** – the amount of 4He measured in the crystal via isotope dilution. This includes all of the He if multiple degassing steps were required. The ± column is 1-sigma analytical uncertainty.

**U (ppm)** – the amount of total U in the sample, measured via isotope dilution on an ICP-MS. The ± column is 1-sigma analytical uncertainty. A value of 0.00 indicates measurements that are not larger than analytical uncertainty.

**Th (ppm)** – the amount of total Th in the sample, measured via isotope dilution on an ICP-MS. The ± column is 1-sigma analytical uncertainty. A value of 0.00 indicates measurements that are not larger than analytical uncertainty.

**Sm (ppm)** – the amount of total Sm in the sample, measured via isotope dilution on an ICP-MS. The ± column is 1-sigma analytical uncertainty. A value of 0.00 indicates measurements that are not larger than analytical uncertainty.

**eU** – the effective Uranium, a measurement of the total amount of radiation experienced by the crystal, equivalent to U + .235Th.

**He (ncc)** – the total amount of He, blank corrected, in nano-cc’s, measured from the sample. This is not referenced to the grain mass.

**Re (%)** - the percent of the total He that was degassed during the first laser extraction. For apatites, this number should be 99.9% or higher. Lower values are thought to indicate the presence of inclusions or other low-diffusivity zones. For zircons this value is not as instructive.

**U (ng)** – the total amount of Uranium measured in the sample in nanograms. This is not referenced to grain mass.

**Th (ng)** – the total amount of Thorium measured in the sample in nanograms. This is not referenced to grain mass.

**Sm (ng)** – the total amount of Samarium measured in the sample in nanograms. This is not referenced to grain mass.

**Th/U** – The Thorium/Uranium ratio for the sample.

**Raw Date It (Ma)** – the age calculated directly from He, U, Th, and Sm measurements. The ± column is 1-sigma analytical uncertainty. This date, as well as the corrected date, are calculated iteratively using equation #34 from Ketcham et al., (2011).

**Ft** – The alpha ejection correction calculated using the method of Ketcham et al., (2011). Ft is a measure of the amount of He that was ejected from the crystal. An Ft of 1.00 would indicate that no He had been lost. This is a purely geometric correction. The ± column is 1-sigma uncertainty on the alpha ejection correction, and is estimated based on the size of the crystal, using the method of Ehlers and Farley, (2003).

**Corrected Date It (Ma)** – The alpha-ejection corrected age, essentially equal to the Raw Age divided by the alpha-ejection correction, calculated iteratively using equation #34 from Ketcham et al., (2011).

**Analytic. Unc (Ma) 2-sigma** – 2-sigma uncertainty in millions of years, only including propagated direct analytical uncertainties for He, U, Th, and Sm. Analytical uncertainties can be considered the minimum uncertainty on a single measured date. Some uncertainties, like that associated with the alpha-ejection correction, are poorly quantified at present, making it challenging to properly include them in uncertainty estimates for single-grain (U-Th)/He dates. Ongoing work is aimed at improving our understanding of uncertainties associated with the alpha-ejection correction, to enable their appropriate incorporation into single-grain uncertainty estimates.