SUPPLEMENT 1: THERMOCHRONOLOGY: DETAILED METHODOLOGY

(U-Th)/He Dating

(U-Th)/He dating was conducted at the Arizona Radiogenic Helium Dating Laboratory (ARDHL), University of Arizona. Zircon and apatite grains were examined under a polarizing stereo-microscope and selected for (U-Th)/He on the basis of grains size (>60 µm diameter), morphology, clarity, and lack of inclusions. Final grains were imaged, their dimensions measured, and then loaded into Nb packets. To measure He, aliquots were heated with a diode laser to ~1300 ˚C for 18-20 minutes for zircon, and to ~900 ˚C for four minutes for apatite. One or more gas re-extractions (lasing) for 20-21 minutes at higher temperatures were performed for zircon grains and no gas re-extracts were done for apatite grains. Extracted He was spiked with ^{3}He, purified using cryogenic and gettering methods, and measured with a quadrupole mass spectrometer. A known amount of ^{4}He was measured every 8th analysis to monitor instrument drift. Degassed apatite grains were retrieved, spiked with a ^{233}U-^{229}Th-^{147}Nd-^{42}Ca tracer, dissolved in HNO_3, and U, Th, Nd, and Ca isotopes were analyzed on an Element 2 high-resolution inductively-coupled plasma mass spectrometer (HR-ICP-MS). Following addition of a ^{233}U-^{229}Th spike, equilibration, and dissolution in HF in a Parr bomb, the U and Th isotopes of zircon aliquots were measured on an Element 2 HR-ICP-MS. Grain masses were used to calculate U, Th, Sm, and He concentrations. For apatite grains, the mass was calculated from Ca measurements and stoichiometry following the protocols of Guenthner et al. (2016). For zircon grains, we report the dimensional mass calculated from grain length measurements and assumptions about morphology following the protocols of Hourigan et al. (2005). Durango apatite and Fish Canyon tuff zircon were used as standards to assess dissolution protocols and HR-ICP-MS analyses. Blank-corrected (U-Th-

Sm)/He and (U-Th)/He ages were calculated with propagated analytical uncertainties from U, Th, Sm, and He measurements. Alpha-ejection corrections were applied using grain measurements and assuming apatite and zircon are unzoned with respect to U, Th, and Sm (Hourigan et al., 2005; Ketcham et al., 2011).

Fission Track Dating

Fission track dating was performed at the Arizona Fission Track Laboratory, University of Arizona. Apatite grains were mounted in epoxy resin, polished with alumina powder, and spontaneous fission tracks revealed by etching with 5.5M HNO_3 at 21°C (±1 °C) for 20 (±0.5) seconds (Donelick et al., 2005). Samples were analyzed by the external detector method (Gleadow, 1981) using very low uranium, annealed muscovite mica detectors, and irradiated at the Oregon State University Triga Reactor, Corvallis, USA. The neutron fluence was monitored using European Institute for Reference Materials and Measurements (IRMM) uranium-dosed glasses IRMM 540R. After irradiation, induced fission tracks in the mica external detectors were revealed by etching with 48% HF at 20°C for 20 minutes. Spontaneous and induced fission track densities were counted using an Olympus BX61 microscope at 1250x magnification using an automated Kinetek Stage system. Apatite horizontal confined fission track lengths and D_{par} (mean fission-track etch pit diameter parallel to the crystallographic c-axis - Donelick et al., 2005) values were measured using FTStage software, an attached drawing tube, and a digitizing tablet (supplied by Trevor Dumitru of Stanford University) calibrated against a stage micrometer. Central ages (Galbraith and Laslett, 1993; Galbraith, 2005) were calculated using the IUGS recommended zeta-calibration approach of Hurford and Green (1983). An apatite IRMM 540R weighted mean zeta calibration factors of 343.1±8.7 was obtained by repeated calibration against internationally agreed age standards including Fish Canyon tuff and Durango apatite, according to the recommendations of Hurford (1990).

Inverse Thermal History Modeling

Inverse thermal history modeling was conducted using the software QTQt version 5.8.0 (Gallagher, 2012). For apatite fission track, the annealing model of Ketcham et al. (2007) for 5.5M nitric acid etchant was used with D_{par} as an additional kinetic parameter, and initial track length calculated from the compositional (D_{par}) information. For apatite (U-Th)/He data, we used the apatite radiation damage accumulation and annealing model (RDAAM) of Flowers et al. (2009), and for the zircon (U-Th)/He data we used the zircon radiation damage accumulation and annealing model (ZRDAAM) of Ginster et al. (2019) using default spherical grain geometry. Modeling was conducted only on those samples with results from two or more thermochronometers, with the exception of sample 191014E from the southern Pütürge massif transect with only AHe data. All (U-Th)/Th ages from each sample were used in the modeling except for several anomalously old AHe ages highlighted in red in Table S2. Also note that QTQt uses AHe and ZHe ages uncorrected for alpha-ejection, as He-ejection is calculated as part of the modeling following Ketcham et al. (2011). The time range for the inverse modeling prior was set as the oldest age (either AFT central age or uncorrected ZHe age, whichever was older) ± that age. The temperature range for all modeling runs was set at 120±120 °C. Present day temperature was set at 5±10 °C, with reheating allowed. For the vertical transect model runs the sample offset was set to give a geothermal gradient of 25 ± 2.5 °C/km, with sample offset allowed to vary over time. The present day temperature gradient (atmospheric lapse rate) was set at 7±2 ° C/km. Note that for vertical transects in QTQt, the present day temperature is set for the highest sample (at around 2000m). The mean annual temperature of Pütürge at ~1200m is 12.3°C (https://en.climate-data.org/), thus the mean annual temperature at 2000m is within the range of 5±10°C. The maximum allowed heating/cooling rate was set at 100 °C/m.y. For the vertical transect sample runs we ran a total of 100,000 Markov Chain Monte Carlo (MCMC) iterations: 50,000 burn-in, and 50,000 post-burn-in, with thinning parameter of 1. For the two individual sample QTQt runs (CAT13-29, and 191014G) we ran a total of 200,000 Markov Chain Monte Carlo (MCMC) iterations: 100,000 burn-in, and 100,000 post-burn-in, with thinning parameter of 1.We also set QTQt to resample proposed models (time-temperature points) outside the initial prior ranges, and not to reject complex models that do not improve the data-fit, with default values used for all other parameters.. The preferred thermal history predicted by QTQt is the so-called Expected Model, which is effectively the weighted mean time-temperature path, where the weighting is provided by the posterior probability of post-burn-in accepted thermal histories (Gallagher, 2012). QTQt produces several other model thermal histories including a maximum likelihood model (the thermal history that best predicts the data, but that is often too complex); a maximum posterior model (the thermal history with maximum probability that is generally too simplistic); and a maximum mode model, a thermal history that represents the maximum peak of the probability distribution of post-burn-in accepted thermal histories over time and temperature. We found that the maximum mode model produced more likely fits to the observed data, and thus we present the maximum mode modeling results as our preferred thermal histories in main text Fig. 3. The results for other models are provided in the supplementary information. As highlighted in Fig. 1 of Vermeesch and Tian (2014), the Expected Model, being a weighted mean path, can sometime produce an oversimplified thermal histories that may smooth temperature extremes within individual maximum likelihood thermal histories. For the temperatures of the AFT partial annealing zone (PAZ) and AHe partial retention zone (PRZ) used in Fig. 3 we assign values of 60 °C to 110 °C for the AFT PAZ (for average composition apatite), and 35 °C to 65 °C for the AHe PRZ based on an isothermal hold time of ~10 million years (Reiners and Brandon, 2006; Flowers et al., 2009).

Note: Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. government.

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