

*Tectonics*

Supporting Information for

# The Alichur dome, South Pamir, western India‒Asia collisional zone: detailing the Neogene Shakhdara–Alichur syn-collisional gneiss-dome complex and connection to lithospheric processes

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# Introduction

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Supporting Information: Text S1–S9

## Text S1. Microstructures: Alichur Shear Zone and Eastern South Pamir Shear Zone

We base our microstructural observations on features summarized in textbooks (e.g., Passchier and Trouw, 2005), reviews (e.g., Law, 2014), and case studies (e.g., Stipp et al., 2002). As summarized in the text, the temperatures during crystal-plastic (ductile) deformation in the Alichur shear zone (ASZ) grossly span ~300–450 °C; representative photomicrographs are shown in Figure S2. Locally, deformation temperatures may have reached ~500 °C, indicated by the transition from SGR (subgrain-rotation recrystallization) to GBR (grain-boundary migration recrystallization) in quartz, and the development of myrmikite at high-strain sites normal to the foliation. The mylonites and ultramylonites overwhelming show deformation in the SGR regime of quartz, locally with transitions to BLG (bulging recrystallization). The transition to cataclasite and ultracataclasite demonstrates that deformation progressed into the brittle field (<250‒300 °C) within the same kinematic framework. Feldspar exhibits brittle deformation in all cases, in accordance with deformation temperatures <500 °C. A dominant deformation mechanism in the ultramylonites, which originate from two-mica leucogranites, is reaction softening by the transformation of K-feldspar and plagioclase to white mica (e.g., Cole et al., 2007).

Microfabrics in the eastern South Pamir shear zone (SPSZ) broadly resemble those in the ASZ, with dominant SGR in quartz indicating deformation at ~300–450 °C (SPSZ samples J4709A1a, J4615B1a, and J4621C2; Figure S2). Locally higher deformation temperatures are evident from fibrolite grown along foliation planes in eastern SPSZ sample J4615D1 (>~550 °C), as well as SGR–GBM quartz textures in central-eastern SPSZ sample J4614A1 (~500 °C) (Figure S2). Confinement of systematically high deformation temperatures (>~500 °C) within the central SPSZ, as previously documented by Stübner et al. (2013a), contrasts with broadly lower deformation temperatures (~300–450 °C) in the eastern SPSZ and correlates with an evident, broad, eastward decrease in strain along the SPSZ.

## Text S2. Fluid-inclusion analyses

### Text S2.1. Methods

Before conducting microthermometry, extensive fluid-inclusion petrography was done to identify assemblages of coeval fluid inclusions and to note the phase assemblages and phase proportions within inclusions. Microthermometry was performed on fluid inclusion assemblages in 500–700 µm-thick, polished thick sections using a Linkam FTIR 600 heating/cooling stage at the University of Toronto with a measurement uncertainty of ±0.1 °C. The parameters measured for each inclusion depended on the composition/density of the inclusion and thus on the sequence of phase changes observed during heating, including 1) melting temperature of CO2 (*T*m,CO2); 2) ice melting temperature (*T*m,ice); 3) clathrate melting temperature (*T*m,clath); 4) homogenization temperature of carbonic liquid and vapor (*T*h,CO2); 5) mode of homogenization and volume fraction of the carbonic portion at *T*h,CO2; and 6) total homogenization temperature (*T*h,tot). Low-temperature analyses were conducted first, to measure melting temperatures of CO2, ice, and clathrate. Heating measurements to obtain *T*h,CO2 or *T*h,tot were conducted second. For inclusions showing evidence of high CO2 contents, heating to total homogenization was not attempted, in order to avoid decrepitation by overpressure. Compositions, densities and isochores of inclusions that showed no evidence of CO2 were interpreted using HokieFlincs (Steele-MacInnis et al., 2012). Compositions and densities of the inclusions showing evidence of CO2 were calculated using the numerical model described by Steele-MacInnis (2018).

### Text S2.2. Results

#### Text S2.2.1. Petrography

All analyzed samples from the South Pamir contain abundant fluid inclusions. The fluid inclusions analyzed here are all hosted in secondary assemblages (i.e., assemblages tracing healed fractures and cross-cutting grain boundaries). The analyzed samples contain at least three different types of inclusions, based on the phase assemblages in the inclusions at room temperature: Single-phase liquid, aqueous liquid + vapor (H2OLiq + H2OVap), and aqueous-carbonic three-phase (H2OLiq + CO2Liq + CO2Vap) inclusions (Figure S4a–c; Table S3). These different inclusion types never occur together in coeval assemblages; each assemblage consistently contains only one type. Three samples were selected for microthermometric analysis: two from the eastern end of the SPSZ (J4614A1 and J4615D1) and one from the central portion of the Alichur Dome (J4707B1). We did not analyze single-phase liquid fluid inclusions. We henceforth refer to “aqueous liquid + vapor inclusions” as “2-phase inclusions” and “aqueous-carbonic three-phase (liquid-liquid-vapor) inclusions” as “3-phase inclusions” for simplicity.

Sample J4614A1 is a mylonite from the SPSZ in the Shakhdara dome, composed primarily of euhedral biotite, quartz, and plagioclase (± potassium feldspar). The analyzed inclusions are hosted in quartz and fall into two categories: 2-phase inclusions showing no evidence of CO2, and 3-phase inclusions with “double-bubbles” (carbonic liquid + vapor) at ambient temperature. The carbonic fraction of these inclusions generally occupies around 65 vol% of the inclusion, although this value ranges from ~50 to 85 vol%. These inclusions are mostly <10 µm in diameter, although a few inclusions are up to 30–40 µm. The inclusions are mostly rounded, and some of the 3-phase inclusions have negative crystal shapes.

Sample J4615D1 is also a mylonite dominated by biotite, quartz, and plagioclase (± potassium feldspar ± calcite) from the SPSZ. Fluid inclusions in this sample are mostly <10 µm and hosted in quartz or calcite. The sample hosts mostly 2-phase inclusions, whereas 3-phase inclusions are less common in this sample and do not contain double-bubbles at room temperature (i.e., *T*h,CO2 is less than room temperature). The volume fraction of (carbonic) vapor in these inclusions is about 55 vol%.

Sample J4707B1 is a mylonitized biotite ± white mica granitoid/leucogranite with a slight chloritic overprint from the ASZ. The 2-phase inclusions are common throughout quartz grains, cross-cutting grain boundaries. Inclusions within these assemblages are hosted in quartz and are typically sub-rounded to angular. Several of these inclusions show distinct re-equilibration morphologies that suggest partial decrepitation as a result of deformation, accompanied by the formation of smaller angular neonate inclusions surrounding the larger relict inclusions (Diamond and Tarantola, 2015). The 3-phase inclusions show clear double-bubbles at ambient conditions, with negative-crystal or rounded shapes. Inclusions of both types are mostly <20 µm in diameter. The carbonic fraction of the inclusions occupies about 60‒75 vol% of the inclusions, mostly around 65 vol%.

#### Text S2.2.2. Microthermometry

Temperature measurements are consistent within each analyzed fluid inclusion assemblage, for both 2-phase inclusions and 3-phase inclusions. Deviations from the average value within each assemblage is generally on the order of ~1 °C for low-temperature measurements, and ~15 °C for total homogenization temperatures. Average values for each analyzed assemblage are reported in Table S3.

Microthermometry of 2-phase inclusions shows bimodal distributions in samples J4707B1 and J4615D1. In each of these samples, at least one assemblage showed *T*m,ice values of about -1 to -2 °C and *T*h,tot of about 200 to 240 °C. Only one assemblage of 2-phase inclusions was analyzed in sample J4614A1, and this assemblage shows ice-melting and homogenization temperatures consistent with these latter assemblages. However, in both samples J4707B1 and J4615D1, at least one assemblage of inclusions shows lower *T*m,ice and higher *T*h,tot values: in sample J4707B1, one assemblage shows *T*m,ice of about -6 to -7 °C and *T*h,tot of about 265 to 280 °C; in sample J4615D1, one assemblage shows *T*m,ice of about -3 °C and *T*h,tot >295 °C (Table S3).

The 3-phase inclusions analyzed in samples J4707B1 and J4614A1 consistently show values of *T*m,CO2very close to the triple point of pure CO2 (-56.6°C). The homogenization temperature of the carbonic liquid and vapor (*T*h,CO2) of these latter inclusions is consistently very close to the critical point of CO2 (31.1 °C), although the inclusions can all be seen to homogenize to the vapor phase (Table S3). Clathrate dissociation in these two samples occurs at temperatures (*T*m,clath) around 6 to 8.5 °C. The micro­thermometric properties of the 3-phase inclusions in sample J4615D1 differ somewhat from the other two samples. In sample J4615D1, the temperature of melting of CO2 (*T*m,CO2) is slightly depressed down to -58 to -60 °C. Clathrate dissociation in inclusions within this sample occurs at 10.0 °C. Homogenization of the carbonic liquid and vapor (*T*h,CO2) occurs at about 19 °C, which explains why these inclusions do not show “double bubbles” at room temperature (Table S3).

#### Text S2.2.3. Fluid Compositions and Homogenization Temperatures

Petrographic observations indicate two broad compositional categories of inclusions in the three samples analyzed here: those containing CO2, and those without. As noted above, these two compositional types occur only in separate fluid inclusion assemblages, and no evidence of coeval trapping of aqueous and aqueous-carbonic inclusions was observed. Within each of these two broader categories, microthermometric data provide more detailed information on the fluid compositions, and indicate some additional variability in compositions analyzed within each sample.

Firstly, with regards to the 2-phase inclusions, microthermometric data indicate that the fluid salinities are generally low, although systematic variations in salinity are also observed on an inter- and intra-sample basis. In sample J4614A1, only one assemblage of 2-phase inclusions was analyzed, and this assemblage has extremely low salinity (lowest of all analyzed assemblages of 3-phase inclusions) and also low homogenization temperatures. Ice-melting temperatures in this assemblage indicate salinities of <1 wt% in all inclusions (Table S3, Figure S4d). In each of samples J4707B1 and J4615D1, at least one assemblage also showing low salinities (2-3 wt%) and low homogenization temperatures (190‒230 °C) was also analyzed (Figure S4d). However, these two latter samples also contain assemblages of higher salinity, higher temperature inclusions. In sample J4707B1, one assemblage shows salinities of about 9.0‒10.5 wt% NaCl and homogenization temperatures up to 280 °C (Figure S4d). Sample J4614A1 contains the assemblage of 2-phase inclusions with the greatest homogenization temperatures, which exceed 295 °C (Table S3). These latter inclusions are also somewhat high, although not as high as those in sample J4707B1, broadly around 5 wt% NaCl.

Besides the 2-phase inclusions, all three analyzed samples also contain assemblages of 3-phase inclusions, and each of these samples shows different compositional ranges within this latter category. Broadly speaking, 3-phase inclusions in samples J4707B1 and J4614A1 share a more similar fluid composition, compared to J4615D1, at least in terms of CO2 contents (mostly between ~20 to 40 mol%) and absence of other gases. However, it is important to note that sample J4614A1 shows some inclusions ranging up to about 70 mol% CO2, the highest gas content of all fluids analyzed here. Sample J4614A1 also shows the highest-density 3-phase inclusions, up to 0.8 g/cm3. The salinity of 3-phase inclusion fluids in sample J4614A1 is intermediate, about 3 wt% NaCl in general (Figure S4e). In contrast, 3-phase inclusions in sample J4707B1 are significantly more saline at 7-8 wt% NaCl (Figure S4e), and show lower bulk densities of 0.5-0.6 g/cm3 (Table S3). Sample J4615D1 shows notably different compositions compared to these latter two samples. Firstly, the salinity of 3-phase inclusions in sample J4615D1 is approximately 0 wt% NaCl, as indicated by clathrate dissociation at almost exactly 10.0 °C in the presence of carbonic liquid and vapor (i.e., no depression of the *Q*2 temperature below that in the salt-free system H2O-CO2 (Bakker, 1997)). Secondly, 3-phase inclusions in sample J4615D1 show markedly higher concentrations of gases other than CO2—likely CH4 and/or N2—as indicated by the notable depression of *T*m,CO2below the triple point of pure CO2 (<-56.6 °C; Table S3). Although the identities of minor gases in the inclusions cannot be identified from microthermometric data, the maximum concentrations of minor gases can be estimated using data for CH4 and N2. Based on the diagrams of (Van den Kerkhof and Thiery, 2001), the maximum concentration of CH4 is about 10 mol% (relative to CH4+CO2) and the maximum concentration of N2 is about 20 mol% (relative to N2+CO2) in these inclusions. The total gas content of these inclusions is also somewhat lower than that of 3-phase inclusions in the other two samples, generally <20 mol%.

#### Text S2.2.4. Fluid-Inclusion Isochores

No evidence of liquid-vapor immiscibility was observed in any of the analyzed fluid-inclusion assemblages, and therefore isochores were constructed to project from the measured homogenization temperature to higher pressure and temperature to help constrain trapping conditions. Constructed isochores for the 2-phase inclusion assemblages show a large scatter in slope, particularly in the case of higher- and lower-temperature assemblages in samples J4707B1 and J4615D1 (Figure S4f). The lower salinity, lower temperature inclusions in samples J4707B1 and J4615D1, along with the one analyzed fluid inclusion assemblage in sample J4614A1, all cluster as isochores extending from ~200–250°C at relatively steep slopes. In contrast, the higher salinity, higher temperature inclusions in samples J4707B1 and J4615D1 reflect isochores that extend from higher temperatures (~280 and 300+ °C, respectively) at more modest slopes (Figure S4f)—thus, projecting to higher temperatures at equivalent pressures, compared to the former isochores.

The isochores for the 3-phase inclusions are more consistent within each sample compared to the 2-phase inclusions, and project at lower *dP/dT* slopes—thus, projecting to higher temperatures at equivalent pressures. Isochores of sample J4614A1 record the highest pressures, followed by J4707B1 and J4615D1 at lower pressures. The petrographic observations of microstructures for the studied samples suggests that these rocks experienced different ductile deformation regimes, from grain-bulging to mainly subgrain rotation (e.g., Passchier and Trouw, 2005). Therefore, the quartz crystals recrystallized during deformation at temperatures between ~300‒450 °C (Figure S2). Because the inclusions occur as secondary assemblages decorating healed fractures that crosscut grain boundaries, we deduce a maximum temperature limit of the trapping conditions of fluid inclusions at ~450 °C.

### Text S2.3. Discussion

When analyzing and interpreting fluid inclusions formed at temperatures and pressures such as those inferred here, modification of fluid inclusions by post-entrapment processes must be considered. In particular, mechanical re-equilibration (“stretching” and/or “decrepitation”) of the inclusions may occur and would result in spurious bulk densities, homogenization temperatures and isochores (Bodnar and Bethke, 1984; Bodnar et al., 2003). Although the 2-phase inclusions, in particular, show somewhat scattered isochores, the data for these inclusions do not seem to indicate that densities have been modified by stretching, because the observed phase ratios and measured homogenization temperatures are consistent within each individual assemblage (Figure S4d; Table S3) (Bodnar et al., 2003). The variation in isochore slopes between inclusions rather reflects differences between assemblages. Thus, these data indicate multiple generations of fluids recorded by fluid inclusions, and good evidence that the compositions and densities of the inclusions faithfully record the properties of fluids trapped at different pressures and temperatures. Mechanical re-equilibration under weak ductile shearing is observed in some of the assemblages of sample J4707B1 (Figure S4c). Petrographic analyses show some small angular neonate inclusions surrounding larger irregularly shaped relict inclusions, indicating decrepitation where the internal pressure of the inclusions was higher than the confining pressure.

Although no petrographic evidence of immiscibility was observed, one may speculate as to whether the 3-phase inclusions may represent an aqueous fluid coeval and immiscible with an aqueous-carbonic fluid (but perhaps simply segregated from this latter fluid prior to trapping). The microthermometric data strongly argue against this possibility (Figure S4d; Table S3). According to (Duan et al., 1995), a saline-aqueous fluid immiscible with an aqueous-carbonic fluid of 40-50 mol% CO2 at conditions similar to those reported here would generally contain >20 wt% NaCl. In contrast, the aqueous liquid-vapor inclusions analyzed here all contain <10 wt% NaCl, and in some cases are less saline than the 3-phase inclusions in the same sample (e.g., the low-salinity aqueous inclusions in samples J4707B1 and J4615D1). Aqueous fluids of such low salinity are incompatible with immiscibility from an aqueous-carbonic fluid at the geologically reasonable pressure-temperature conditions for these samples. Alternatively, the evidence for modest ductile deformation in some of the fluid-inclusion assemblages might suggest that the diversity in densities and CO2 concentration might be enhanced by H2O selectively escaping through dislocations under the dynamic setting (Hollister, 1988, 1990).

The most reasonable interpretation is that the differing fluid compositions represent different fluid pulses during exhumation, accompanied with modest degrees of post-entrapment re-equilibration under weak ductile–brittle shearing. In Figures S4h‒j, ellipses outline the pressure-temperature space given by both the 2- and 3-phase fluid inclusions; they signify the pressure-temperature range for multiple entrapment events recorded by the various inclusions. For all samples, the actual pressure-temperature range is likely at the lower limit indicated by the ellipses because dynamic recrystallization must have reset most of the fluid inclusions formed at higher pressure-temperature. Interestingly, isochores for both the 2-phase and 3-phase inclusions generally intersect in the vicinity of the upper temperature limit constrained by the microstructural analysis (Figure S4h-j), and indicate broadly higher pressures for sample J4614A1 (Figure S4h) versus lower pressures for samples J4707B1 (Figure S4i) and J4615D1 (Figure S4j). It should be stressed that no petrographic evidence directly indicates that these assemblages of 2-phase versus 3-phase inclusions are coeval; nevertheless, the isochore intersections are at least consistent with the inference that the inclusions all reflect post-mylonitization conditions during exhumation. The most reasonable interpretation is that the 3-phase inclusions and the higher salinity 2-phase inclusions represent fluids derived from metamorphic devolatilization, whereas the lower-salinity 2-phase inclusions may record dilution by incursion of meteoric water during exhumation. The higher salinity 2-phase inclusions in samples J4615D1 and J4707B1 project to higher temperatures owing to their lower *dP*/*dT* slopes, whereas the lower salinity inclusions project to lower temperatures which again seems reasonable in light of the interpretation that these inclusions record influx of cooler meteoric water. The lack of petrographic constraint notwithstanding, intersections of isochores yield crude pressure-temperature ranges of 200–250 °C and 0.5–1.5 kbar for sample J4615D1 for the low-salinity inclusions versus 450–500 °C and 2 kbar for the higher-salinity inclusions, the latter being close to the maximum temperatures deduced from microstructural analysis (Figure S2). The projected intersection of isochores for sample J4707B1 suggest that entrapment occurred 300–400 °C and 1–2 kbar. The isochores for sample J4614A1 project to the highest trapping pressures among all three samples, with temperatures from 300 °C to greater than 500 °C and pressures of 1.5 up to at least 4 kbar.

The overall trends—with highest pressures for sample J4614A1, followed by J4615D1 and J4707B1—are broadly consistent with previous work on the Shakhdara dome (e.g., Hacker et al., 2017). These data are consistent with decreasing exhumation depths from southwest to northeast. The overall ranges of temperatures and compositions of fluid inclusions provide insight into hydrothermalism and variations in fluid properties during the exhumation and cooling of these rocks. The 3-phase inclusions, present in all three samples, are rather typical saline-aqueous-carbonic fluids as generally associated with metamorphic devolatilization (Bodnar et al., 2014), whereas the dilute 2-phase inclusions give the plausible suggestion of incursion of deeply circulating meteoric water. Evidence for modest CH4 and/or N2 concentrations in sample J4615D1 also suggest fluid sourcing from specific (likely reducing) lithologies. Thus, the results broadly suggest that as these rocks were exhumed, they witnessed variable fluid fluxes from different sources. Circulation of cool, dilute water into these rocks may have provided a mechanism to promote cooling during exhumation.

## Text S3. (U–Th)/Pb analysis: Zircon, Titanite, Rutile, and Monazite

We fragmented rock samples using both mechanical and high-voltage discharge separation with the Freiberg SELFRAG® facility. Prior to mounting in epoxy, mineral concentrates were enriched with a Frantz® magnetic separator, wet and dry shaking tables, wet and dry sieving, wet panning, heavy liquids, and handpicking. Cathodoluminescence images were used to ensure that ablation pits did not overlap multiple age domains or inclusions. The two samples dated at UCSB (see below) were analyzed in-situ in thin section. For Zrn, we used *Isoplot* (Ludwig, 2008) to calculate, depending on context, the most geologically meaningful Concordia, weighted-mean, and lower-intercept ages possible with common-Pb-corrected and/or non-common-Pb-corrected data. We computed lower-intercept-age calculations for Ttn and Rt, and a weighted-mean age calculation for Mnz. To ensure reproducibility of the reference material, we report all <2% calculated 2σ crystallization-age uncertainties as 2%.

Six labs were used to collect U, Th, and Pb isotopes for zircon, titanite, rutile, and monazite:

1. The Senckenberg Naturhistorische Sammulungen Dresden in Dresden, Germany (DD) implemented a New Wave UP-193 Excimer Laser System and a Thermo-Scientific Element 2 XR sector field LA-ICPMS to collect U, Th, and Pb isotopes for zircon. The data are not common-Pb-corrected, and were generated using previously outlined protocols (Frei and Gerdes, 2009; Linnemann et al., 2011), with the caveat that data was processed using *Iolite* (Paton et al., 2011). Laser spot size was 25 or 30 µm. GJ-1 zircon was used as a primary standards and Plesoviće zircon as a secondary standard to assess in-run accuracy. The data are presented in Dataset S2a.
2. The Arizona Laserchron Center at the University of Arizona in Tucson, AZ, USA (UA) implemented a Nu Plasma LA-MC-ICPMS to collect U, Th, and Pb isotopes for zircon. The data were generated using previously outlined protocols (Gehrels et al., 2008). Two protocols were executed: (i) For more-simple igneous samples, 30 µm ablation-pit diameter using Faraday detectors for 238U, 232Th, 208Pb, 207Pb and 206Pb and discrete-dynode ion counters for 204Pb and 202Hg (“Faraday” analyses); and (ii) For more-complex igneous samples (particularly leucogranites), a 15 µm ablation-pit diameter using Faraday detectors for 238U and 232Th and ion counters for all Pb isotopes (“ion-counter” analyses). Sri Lanka zircon was used as the primary standard and R33 zircon was used as the secondary standard to assess in-run accuracy; standards were mounted together with unknowns. Faraday and ion-counter analyses were conducted during different sessions, with ablation-pit diameters of unknowns matching those of standards. Data reduction was performed using the Excel macro *AGECALC.XLS*, which applies a common-Pb correction (“206/204 factor”) that modulates the 206Pb/204Pb of the standards to shift the analyses onto Concordia if they are systematically over- or under-corrected for common Pb. Some age calculations used common-Pb-corrected data (“yes” in column E of Table S4); For others, a 206/204 factor of 1000 was applied produce common-Pb-uncorrected data that is more geologically meaningful for some samples (“uncorr.” in column E of Table S4). The data are presented in Dataset S2b.
3. The Key Laboratory of Continental Dynamics at Northwest University in Xi’an, P.R. China (X) implemented an Agilent 7500a ICPMS and a GeoLas 2005 laser-ablation system equipped with a 196 nm Excimer laser (spot size 30 µm) to collect U, Th, and Pb isotopes for zircon. The data are not common-Pb-corrected, and were generated using previously outlined protocols (Yuan et al., 2004); data was processed using *GLITTER* (Van Achterbergh et al., 1999). The data are presented in Dataset S2c.
4. The Center of Isotopic Research, VSEGEI, in St. Petersburg, Russia (SP) implemented a SHRIMP-II ion microprobe to collect U, Th, and Pb isotopes for zircon. Zircon 91500 was used as a reference standard (Wiedenbeck et al., 1995). The spot diameter was 25 µm; the primary-beam intensity was ~2.5 nA; and each analysis consisted of ~5 scans through the mass range. The data were reduced (including common-Pb correction) following (Williams, 1998), using the *SQUID* Excel Macro (Ludwig, 2000). These data are presented in Dataset S2d.
5. The LASS lab at the University of California, Santa Barbara, USA (UCSB) implemented an LA-ICPMS to collect, *in-situ* (in thin section), U and Pb isotopes for titanite and U and Pb isotopes and trace-element concentrations for rutile. The data were generated following previous protocols (Kylander-Clark et al., 2013; Spencer et al., 2013). These data are presented in Dataset S2e.
6. The UCLA SIMS lab at the University of California, Los Angeles in Los Angeles, CA, USA (UCLA) implemented a SIMS to collect Th and Pb isotopes for monazite. The data were generated following previous protocols (e.g., Spear et al., 2008 and references therein). These data are presented in Dataset S2f.

Non-detrital (U–Th)/Pb Zrn, Ttn, and Rt, and Th/Pb Mnz ages are provided in Table S4; detrital-zircon (U–Th)/Pb ages are provided in Table S5. The full analytical dataset is visualized in Dataset S1; isotopic measurements and age calculations are provided in Dataset S2a–f.

## Text S4. 40Ar/39Ar Analysis: White-mica, Biotite, and Amphibole

For 40Ar/39Ar analysis, we used the largest grain-size fraction from which we could handpick optically inclusion-free crystals. The SELFRAG® processing yields grain sizes that closely correspond to the size of the crystal prior to separation; additionally, it minimizes the proportion of broken grains (Sperner et al., 2014). We conducted 40Ar/39Ar analysis using the Argus noble-gas mass spectrometer at the Argonlab Freiberg (ALF) at the TU Bergakademie Freiberg in Freiberg, Germany. Pfänder et al. (2014) outlined the analytical procedures for the ALF laboratory, and (Rutte et al., 2015) the irradiation geometry and reactor specifics used for the ALF samples, which employ metallic fluence monitors to correct for horizontal-fluence gradients in some irradiations (Dataset S4). We used the revised, 28.305 ± 0.072 Ma Fish Canyon sanidine age-standard value (Renne et al., 2010; Renne et al., 2011) to calculate ages. We calculated inverse variance weighted mean (WMA) and (inverse) isochron ages (IIA/IA) and their statistical uncertainties (Table S6) with Isoplot (Ludwig, 2008). Most samples yielded well-defined plateau ages, for which we report the WMA. For samples exhibiting argon loss, we used a WMA comprising the steps defining a plateau with atmospheric 40Ar/36Ar isochron intercepts. For samples with a trapped Ar component of non-atmospheric composition, i.e., containing extraneous argon (cf. Dalrymple and Lanphere, 1969; McDougall and Harrison, 1999), we used the least-disturbed steps with atmospheric intercepts or the IIA, in the case of evenly distributed trapped non-atmospheric argon. In the latter case, we also recalculated the WMA using the non-atmospheric 40Ar/36Ar intercept. For a few samples with a variable age spectrum and a weakly disturbed isochron, we report an age that covers the combined uncertainties of the WMA and IIA. The full 40Ar/39Ar dataset is visualized (WMA plots of all analyzed samples and selected isochron plots) in Dataset S3; analytical measurements and calculations are provided in Dataset S4.

## Text S5. (U–Th)/He Analysis: Zircon and Apatite

Zircon (U–Th)/He dating (ZHe) was conducted at four labs that share broadly similar protocols with minor caveats: The Geochronology Center (Gö) in Göttingen, Germany; the lab at the Universität Tübingen, Germany (Tü-EE and Tü-KS indicate samples run at different times), the Arizona Radiogenic Helium Dating Laboratory in Tucson, AZ (UA). The protocols are discussed below with an emphasis on distinguishing caveats.

Clear, 60–200 µm-wide, euhedral zircon crystals with minimal impurities and fractures were selected using a binocular microscope and their geometries were measured for the calculation of the α-ejection correction factor (FT). Whereas a bulk FT correction was calculated for the Gö/Tü-EE/Tü-KS analyses following Farley et al. (1996), individual FT corrections for 238U, 235U, and 232Th were calculated for the UA lab following Hourigan et al. (2005). We analyzed 3–5 zircon aliquots per sample, each of which comprised single zircon grains that were individually packed in Nb foil tubes. FT-based ESR estimates are provided for each grain (UA) or as averages of intra-sample grains for some samples (Gö/Tü-EE/Tü-KS). 4He was extracted from the aliquots by heating them with a 960 nm diode focused laser beam for 10 min at 20 A (Gö/Tü-EE/Tü-KS) or with a 1–2 W laser for 15 min (UA). We re-extracted He from each grain to ensure sufficiently complete degassing in the first step; the re-extracts showed <1% (Gö/Tü-EE/Tü-KS) or <2% (UA) of the signal from the first extract. [U] and [Th] were determined by isotope dilution at the respective labs where 4He extraction was conducted, using a Thermo Fisher iCAP ICP-MS (Gö/Tü-EE/Tü-KS) or a high-resolution single-collector Element2 ICP-MS (UA). Sm concentration was disregarded at all labs. Zircon-grain mass, [U], and [Th], and [eU] were estimated based on the measured [Zr] assuming 49.8 wt% Zr in zircon for the Tü-KS and UA analyses only. Analytical uncertainties for single-grain ages, which are based on analytical uncertainties for He, U, Th, and FT, are reported for the Gö/UA labs only. The uncertainty for intra-sample ZHe single-grain ages are high despite <2% analytical uncertainty for individual aliquots. Therefore, we report ZHe ages and uncertainties for each sample as the non-weighted mean and 2σM of the intra-sample analyses (Table S7).

We conducted apatite (U–Th–Sm)/He dating (AHe) for two samples at UA. Clear, inclusion- and fracture-free apatite grains were handpicked and measured to compute FT following (Farley et al., 1996; Farley, 2002). We analyzed 4 aliquots per sample and report sample ages following our protocol for ZHe sample ages. The AHe results are reported together with the ZHe results in Table S7.

## Text S6. Fission-track Analysis: Zircon and Apatite

Zircon fission-track (ZFT) analyses were conducted at TU Bergakademie Freiberg (TUBAF). ZFT ages were obtained by the ζ-calibration method using the Fish-Canyon tuff age standard and the IRMM-541 standard uranium glass. We embedded the zircons in PFA Teflon® at ~325 °C. For easier grinding and polishing, we encased the Teflon mounts in epoxy. After removal of the Teflon mount from the epoxy, the zircon mounts were stepwise etched with a 7:5 mixture of eutectic melt of NaOH and KOH at 228 °C for 13 to 49 hrs. The mounts were covered with 1 cm2 of 50 μm thick, U-free muscovite external detectors, and the age standards, unknown samples, and IRMM-541 dosimeter glasses were irradiated together in the FRM-II reactor at the TU Munich, Germany. We etched the external detectors 30 min in 40% HF at room temperature. The mounts and the corresponding external detectors were fixed side-by-side, track-side up on glass slides, and the tracks in the external detector and the zircons were counted in transmitted light at 1500× magnification. The counted grains have a prismatic surface and moderate U concentration; we counted 17–46 grains per mount. The ages are reported as pooled ζ-ages; separate ζ-values were determined for each of the two analysts. The ZFT data are provided in Table S8.

Apatite fission-track (AFT) analyses were conducted at TUBAF and at the University of Arizona Fission Track Laboratory (UA). AFT ages were determined with the external detector method (Gleadow, 1981) and the ζ-approach (Hurford and Green, 1983). For the TUBAF samples, the apatite mounts were etched for 20 s in 5.5 M HNO3 at 21 °C (Carlson et al., 1999), covered with 1 cm2 of 50 μm thick, U-free muscovite external detectors, stacked in irradiation containers with three to four age-standard mounts (Durango apatite: 31.4 ± 0.1 Ma, (McDowell et al., 2005); Fish-Canyon tuff apatite: 28.2 ± 0.1 Ma, (Gleadow et al., 2015)), and standard uranium glasses (IRMM-450R), and irradiated in the hydraulic channel of the FRM-II reactor at the TU Munich, Germany. The UA samples were etched for 20 s in 5.5 M HNO3 following (Donelick et al., 1999) and were irradiated at the TRIGA reactor at Oregon State University. The external detectors for the TUBAF samples were etched for 30 min in 48% HF at room temperature and repositioned them track-side down on the apatite mounts (Jonckheere et al., 2003) for the track counts. The external detectors for the UA samples were etched for 15 min in 49% HF at 23 °C following (Donelick et al., 2005). The apatites were polished parallel to their prism faces and between 11 and 60 crystals from each sample were counted by three analysts (J. K., K. S., and A. S.) at 800× magnification. In the case of the availability of two or more sample ages within one outcrop, we calculated an outcrop WMA. The AFT data are provided in Table S9.

# Supporting Information: Figures S1–S4 (separate .pdf files)

## Figure S1. Full structural dataset (10 pages).

Figure S1. (a) Stereonet-station locations for the Alichur-dome region and lower-hemisphere stereonets of structural measurements for all stations in this study and that of Stübner et al. (2013a), whose average s- and c-plane measurements are indicated with blue- and magenta-shaded great circles, respectively. **s**, foliation; **c**, c-plane; **str**, stretching lineation (X-axis of finite strain); **fl**, flow line; **fs**, flow sense; faults, nodal planes and stress directions calculated from fault-slip data, in some cases (few faults) the average fault plane and slickenside lineation are shown; **σ1≥σ2≥σ3**, principal stress directions; **s0**, bedding; **s1-x**, foliation related to deformation event 1–x; **e1≤e2≤e3**, principal strain directions; **B**, fold axis; **l**, average slickenside-lineation orientation. Paleostress calculations: **R**, stress-ellipsoid shape factor; **n**, number of fault-slip data used for calculation and number that do not fit the calculated tensor; **θ**, fracture angle used for calculation; **Chl**, chlorite; rotation: e.g., **100/0/20acw**, trend and plunge of rotation axis, 20° anticlockwise. (b) Revised map and new and published (Stübner et al. (2013a) structural data from the Gunt shear zone.

## Figure S2. Microstructures (7 pages).

Photomicrographs of Alichur shear zone and South Pamir shear zone samples and microstructural interpretations.

## Figure S3. Locations of all samples used for fluid-inclusion analysis and geo–thermochronology (1 page).

(a) Simplified structural map of the South Pamir summarizing exhumation-depth estimates from phase equilibria (Schmidt et al., 2011; Hacker et al., 2017) and integrated microstructure and fluid-inclusion analyses (this study). Exhumation depths for the three samples studied for fluid inclusions in this study were estimated assuming a 2.7 kg/m3 crustal density and geothermal gradients of 30–50 °C/km for the Alichur dome and 40–60 °C/km for the Shakhdara dome (Stübner et al. (2013b)). For the Alichur shear zone sample J4707B1, we calculated a >6–15 km exhumation depth range; this uses as a lower bound fluid trapping at ~1.5 kbar (>6 km) post-dating ductile deformation, and as an upper bound 300‒450 °C (≤15 km) given by the microstructural evidence (subgrain rotation recrystallization in quartz). For eastern South Pamir shear zone sample J4615D1, we calculated a >4–15 km exhumation depth, given by fluid trapping at ~1.2 kbar (>4 km) and ductile deformation at 300‒450 °C (≤15 km). For central-eastern South Pamir shear zone sample J4614A1, we calculated a >11–13 km exhumation depth, given by fluid trapping at ~3 kbar (>11 km exhumation) and ductile deformation at <~500 °C (~13 km). Note where we give single exhumation-depth numbers, these denote maximum exhumation depths, and where we give a range, this gives the depth range provided by the fluid inclusions and the microstructural information. (b) Locations of all samples used for geo-thermochronology and fluid-inclusion analysis.

## Figure S4. Fluid-inclusion results (3 pages).

Fluid-inclusion results. (a–c) Fluid-inclusion photomicrographs. (d) Microthermometric data for 2-phase inclusions. (e) Microthermometric data for 3-phase inclusions. (f) Isochores for 2-phase inclusions. (g) Isochores for 3-phase inclusions. (h) Intersection between isochores for 2- and 3-phase inclusions for central-eastern South Pamir shear zone (SPSZ) biotite gneiss sample J4614A1 (gray band indicates ~500 °C range for the transition between subgrain-rotation and beginning grain-boundary-migration recrystallization in quartz). (i) Intersection between isochores for 2- and 3-phase inclusions for Alichur shear zone (ASZ) orthogneiss sample J4707B1 (gray band indicates 300–450 °C range for subgrain-boundary rotation recrystallization in quartz). (j) Intersection between isochores for 2- and 3-phase inclusions for eastern South Pamir shear zone (SPSZ) biotite + sillimanite gneiss sample J4615D1 (300–450 °C range for subgrain-boundary rotation recrystallization in quartz). The ellipses span the interpreted pressure-temperature (P‒T) space during fluid-inclusion trapping defined by both the 2- and 3-phase inclusions; they, thus, signify the P‒T range and multiple draping events recorded by the various inclusions. The actual P‒T range is likely at the lower limit indicated by the ellipses, as the recrystallization will have reset most of the fluid inclusions formed at higher P‒T.

## Figure S5. Single-sample T-t regressions (3 pages).

Single-sample temperature-time (T-t) weighted regressions.

# Supporting Information: Tables S1–S9 (headings refer to sheet names in separate Excel spreadsheet: “Alichur\_SI\_Tables.xlsx”)

## Table S1. Stations

Station locations and general lithologies. Photomicrographs for relevant samples are provided in Figure S2.

## Table S2. Samples

Summary of all geo-thermochronologic central ages acquired for South Pamir samples reported in this study and cited from: Hubbard et al. (1999); Schmidt et al. (2011); Stübner et al. (2013b); Smit et al. (2014); Stearns et al. (2015); Hacker et al. (2017); Chapman et al. (2018b); Chapman et al. (2018a).

## Table S3. FI

Average microthermometric data from 2-phase (H2O*Liq* + H2O*Vap*) and 3-phase (H2O*Liq* + CO2*Liq* + CO2*Vap*) fluid inclusions.

## Table S4. (U–Th)-Pb

New (U–Th)/Pb geochronologic data.

## Table S5. Detrital U-Pb

New detrital-zircon U/Pb data

## Table S6. 40Ar-39Ar

40Ar/39Ar data from this study, Hubbard et al. (1999), Stübner et al. (2013b), and Hacker et al. (2017).

## Table S7. ZHe AHe

Zircon and Apatite (U-Th)/He data from this study, Stübner et al. (2013b), and Chapman et al. (2018b).

## Table S8. ZFT

Zircon fission-track data from this study and Stübner et al. (2013b).

## Table S9. AFT

Apatite fission-track data from this study and Stübner et al. (2013b).

# Supporting Information: Datasets S1–S4 (separate PDF and .xlsx files)

## Dataset S1 (separate PDF file, 32 pages).

Full (U–Th)/Pb dataset, visualized in Concordia- and weighted-mean-age plots.

## Dataset S2 (separate .xlsx spreadsheet).

Full (U–Th)/Pb analytical dataset.

## Dataset S3 (separate PDF file, 17 pages).

Full 40Ar/39Ar dataset, visualized in age-spectrum and inverse-isochron plots. If multiple age spectra are given in one plot, the primary spectrum based on atmospheric 40Ar/39Ar of 298.56 ± 0.031 is complemented by secondary spectra recalculated based on 40Ar/39Ar inferred from inverse isochron intercepts.

## Dataset S4 (separate .xslx spreadsheet).

Full 40Ar/39Ar analytical dataset.

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