Low-temperature thermochronology of the Indus Basin in central Ladakh, northwest India: Implications of Miocene–Pliocene cooling in the India-Asia collision zone

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Abstract: The India-Asia collision zone in Ladakh, northwest India, records a sequence of tectono-thermal events in the interior of the Himalayan orogen following the intercontinental collision between India and Asia in early Cenozoic time. We present zircon fission-track, and zircon and apatite (U-Th)/He thermochronometric data from the Indus Basin sedimentary rocks that are exposed along the strike of the collision zone in central Ladakh. These data reveal a post-depositional Miocene–Pliocene (~22–4 Ma) cooling signal along the India-Asia collision zone in northwest India. Our ZFT cooling ages indicate that maximum basin temperatures exceeded 200 °C but stayed below 280–300 °C in the stratigraphically deeper marine and continental strata. Thermal modeling of zircon and apatite (U-Th)/He cooling ages suggests post-depositional basin cooling initiated in Early Miocene time by ~22–20 Ma, occurred throughout the basin across zircon

(U-Th)/He partial retention temperatures from ~20–10 Ma, and continued in the Pliocene time until at least ~4 Ma. We attribute the burial of the Indus Basin to sedimentation and movement along the regional Great Counter thrust. The ensuing Miocene–Pliocene cooling resulted from erosion by the Indus River that transects the basin. An approximately coeval cooling signal is well documented east of the study area, along the collision zone in south Tibet. Our new data provide a regional framework upon which future studies can explore the possible interrelationships between tectonic, geodynamic and geomorphologic factors contributing to Miocene–Pliocene cooling along the India-Asia collision zone from NW India to south Tibet.

Keywords: Indus Basin, exhumation, cooling, thermochronology, India-Asia collision zone, Ladakh

1. Introduction

The India-Asia collision zone developed when the Neo-Tethyan ocean closed following the continent-continent collision between India and Asia in early Cenozoic time (e.g., Searle, 2019; Kapp and DeCelles, 2019). The sedimentary basins along the collision zone present a natural laboratory to test models of deposition and exhumation in the interior of the Himalayan orogenic system. The collision zone in Ladakh, northwest (NW) India exposes the Indus Molasse or the Indus Basin sedimentary rocks (IBSR), which are a linear suite of deformed marine and continental strata that were discontinuously deposited from Late Cretaceous to Pliocene time (Figures 1A–B; Garzanti and Van Haver, 1988; Searle et al., 1990; Clift et al., 2002; Henderson et al., 2010; 2011). Thus, the IBSR present an opportunity to study the pre- and syn-collisional tectono-thermal events associated with the evolution of the intercontinental suture zone between India and Asia. Knowing the timing and extent of suture zone basin exhumation is critical to understanding the surficial-to-lithospheric scale processes triggering it, which are intrinsically linked to the geological evolution of the orogenic hinterland.

Previous studies on the thermal history of the IBSR along the collision zone in NW India and on coeval rocks along the collision zone in south Tibet yield different exhumation histories. Carrapa et al. (2014) present (U-Th)/He detrital zircon (ZHe) and apatite fission-track (AFT) cooling ages from the Late Oligocene–Early Miocene Kailas Formation of the Yarlung suture in south Tibet, which record basin exhumation from ~21–15 Ma. The authors interpret that these cooling ages reflect incision by the paleo-Yarlung River as the Indian plate underthrusted beneath Asia. In addition, Tremblay et al. (2015) and Orme (2019) document Early–Middle Miocene (~21–11 Ma) cooling in the Gangdese batholith and the Xigaze forearc basin in south Tibet, thereby emphasizing that Miocene cooling along the India-Asia collision zone was a regional thermal event. By contrast, in NW India, Tripathy-Lang et al. (2013) report ~52–28 Ma ZHe cooling ages from the Kailas-contemporaneous Late Oligocene Basgo Formation. Unlike post-depositional Miocene cooling as recorded in south Tibet, the ZHe cooling ages of the Basgo Formation in NW India are interpreted to be unreset after deposition and are attributed to exhumation of the source – the rapidly-eroding Indian margin (Tripathy-Lang et al., 2013). The only previously reported evidence of post-depositional Miocene cooling in the IBSR is limited to two AFT ages of ~14–12 Ma (Clift et al., 2002) and a single AFT age of ~7 Ma (Schlup et al., 2003). However, ZFT, ZHe and AFT ages from the Ladakh batholith to the north of the IBSR indicate rapid cooling along the collision zone in NW India at ~26–18 Ma (Kirstein et al., 2006).

To determine if a Miocene cooling signal is present across different formations in the Indus Basin in NW India, we sampled the IBSR across 4 traverses in central Ladakh: Temesgam and Basgo sections in the west, Zanskar Gorge in the center, and Upshi-Lato section in the east (Figure 1A). We present ZFT, ZHe and (U-Th)/He detrital apatite (AHe) data to resolve the thermal history of the IBSR and investigate the underlying causes that contributed to the heating and cooling along the India-Asia collision zone in NW India.

2. Geologic Background

2.1 Tectonic Setting

From south to north, the India-Asia collision zone in NW India (Figures 1B–C) is composed of: a) the Precambrian–Paleocene Greater Indian passive margin metasedimentary and sedimentary rocks of the Tethyan Himalaya with an isolated klippe of the Cretaceous Spongtang oceanic arc (Garzanti et al., 1987; Buckman et al., 2018), b) the Indus Suture Zone containing the Lamayuru Complex – the Mesozoic deep-water slope facies of the Indian margin (Robertson and

Sharp, 1998), and the Dras-Nidar Complexes – an assemblage of Cretaceous ophiolitic mélange, volcanic and volcano-sedimentary units (Ahmad et al., 2008; Walsh et al., 2019; Das et al., 2020), c) the Late Cretaceous-Pliocene IBSR (Garzanti and Van Haver, 1988; Searle et al., 1990), and d) the southern edge of the Early Cretaceous–Early Eocene Ladakh batholith (Weinberg and Dunlap, 2000). The IBSR unconformably overlies the Ladakh batholith to the north and are in fault contact with the Dras-Nidar Complexes to the south (Figures 1A, C; Searle et al., 1990; St-Onge et al., 2010). Pre-collisional deposition of the IBSR initiated in an arc-bounded or forearc marine basin in Late Cretaceous time, and the depocenter evolved into a continental intermontane basin with the onset of India-Asia collision in Early Eocene time (Garzanti and van Haver, 1988; Henderson et al., 2010). Regional IBSR deposition largely ended by Late Oligocene–Early Miocene time (~26–23 Ma) when basin inversion began, although local-scale deposition continued in Pliocene time in patches of western and central Ladakh (Mathur, 1983; Clift et al., 2002, Henderson et al., 2010, 2011; Zhou et al., 2020; Bhattacharya et al., 2020).

Structurally, the IBSR constitutes the footwall of the regional north-vergent Main Zanskar backthrust (Searle et al., 1997), also known as the Great Counter thrust (GCT, Figure 1A). Multiple strike-parallel, north-vergent thrusts belonging to the GCT system deform the IBSR (Steck, 2003). The timing of movement along the GCT in NW India is indirectly constrained to 23–20 Ma on the basis of the age of tectonic and metamorphic processes in the Himalayan orogen. Using $^{40}Ar/^{39}Ar$ hornblende ages, Searle et al. (1992) determine that peak metamorphism (700–750 °C, 8 kbar) and maximum crustal thickening in the Zanskar Himalaya (Figure 1A) south of the GCT occurred at ~28–23 Ma. Sinclair and Jaffey (2001) and Clift et al. (2002) suggest that this episode of crustal thickening and uplift in the Himalayan wedge at ~28–23 Ma provided the mechanical force to initiate movement along the GCT at ~23–20 Ma, thereby inverting the IBSR. Recent studies from south Tibet, based on geochronology-thermochronology datasets and cross-cutting relationships among Neogene intrusive rocks, also indicate that motion along the GCT initiated at ~23 Ma and largely ended by ~15 Ma (Zhang et al., 2011; Carrapa et al., 2014; Laskowski et al., 2018; Orme, 2019).

2.2 Stratigraphy

The IBSR stratigraphy comprises two major rock groups (Table 1, Figures 1C, 2A-C): (a) the southern Late Cretaceous–Early Eocene marine Tar Group (Figures 2B-C), and (b) the northern Early Eocene to Pliocene continental Indus Group (Figure 2A-C). The Tar Group consists of carbonate and siliciclastic rocks that are tectonically bounded to the south by the pre-collisional Dras-Lamayuru-Nidar Complexes and are juxtaposed in the north against the Indus Group. The Indus Group exhibits extreme along-strike variations in siliciclastic fluvial facies that unconformably overlie the Ladakh batholith (Brookfield and Andrews-Speed, 1984; Garzanti and Van Haver, 1988; Searle et al., 1990; Sinclair and Jaffrey, 2001; Clift et al., 2002; Steck, 2003; Wu et al., 2007; St-Onge et al., 2010; Henderson et al., 2010, 2011; Tripathy-Lang et al., 2013; Singh et al., 2015; Zhou et al., 2020; Bhattacharya et al., 2020). The Indus Group is categorized into two sub-groups: (i) the Early Eocene–Early Miocene Lower Indus Group and (ii) the Pliocene Upper Indus Group. The former is regionally present along the India-Asia collision zone, while the latter is localized to central and far-western Ladakh (Mathur, 1983; Henderson, et al., 2010).

2.3 Previous Low-temperature Thermochronometric Studies

Low-temperature thermochronologic data and other thermal proxies from the IBSR are limited to a few local studies with conflicting interpretations, leaving the regional thermal history undetermined. K/Ar mica ages from phyllites of the Indus Basin indicate a low-grade anchizonal metamorphic event along its southwestern margin in Middle–Late Eocene time, when fold-thrust deformation occurred in the Tethyan Himalaya (Van Haver et al., 1986; Steck, 2003). Using illite crystallinity and vitrinite reflectance, Van Haver (1984) determined peak basin temperatures of ~280 °C in the uppermost Tar Group (Nummulitic Limestone Formation, Figure 2B) and ~155 °C in the Lower Indus Group. Clift et al. (2002) report 14–12 Ma AFT ages from two Lower Indus Group samples and interpret that these ages reflect cooling following basin inversion associated with regional counterthrusting along the GCT at ~23–20 Ma. Illite crystallinity estimates by Clift et al. (2002) in central Ladakh suggests temperatures did not exceed 200 °C in the Indus Group. Another paleo-geotemperature study from the Indus Group in eastern Ladakh by Schlup et al. (2003), which is also discussed in Clift et al. (2004), reveals an illite crystallinity index of 0.36 (°$\Delta 2\theta$) from a single Lower Indus Group sandstone sample. This illite crystallinity value translates to a lower anchizone grade burial temperature of ~239°C using the index-temperature equation of Zhu et al. (2016). Schlup et al. (2003) also report a ZFT central age of 23 ± 2 Ma and an AFT age of 7.4 ± 0.7 Ma from the same sandstone sample. The 23 ± 2 Ma ZFT age is interpreted to reflect source cooling and is attributed to the exhumation of the Ladakh batholith, while the 7.4 ± 0.7 Ma AFT age suggests post-depositional cooling in the basin. Tripathy-Lang et al. (2013) report unreset ZHe ages of ~52–28 Ma in the Lower Indus Group Late Oligocene Basgo Formation and attribute them to the exhumation of source regions on the Indian plate.

3. Sampling and Analytical Methods

3.1 Sampling

We sampled medium-grained sandstones from four N-S to NNE-SSW trending sections across the IBSR in central Ladakh (Figures 1A, 2A-C). These sections are: a) Temesgam (Figure 2A), b) Basgo, (Figure 2A), c) Zanskar Gorge (Figure 2B) and d) Upshi-Lato (Figure 2C). We collected eight samples from the Zanskar Gorge for ZFT analyses (Figure 2B). Low yield of good quality dateable apatite in most samples and zircon in several samples limited our AHe (two samples; Figures 2A, 2C) and ZHe datasets (six samples; Figures 2A-C).

Zircon and apatite concentrates were separated from each 8-10 kg sample using conventional mineral separation techniques involving a rock crusher, water table, Frantz magnetic separator and heavy liquids. Only samples DZA23TM from the Temesgam Formation (Figure 2A) and DZA08UL (Figure 2C) from the Lower Upshi Formation produced apatites suitable for AHe dating. Zircon yield in sample DZA08UL was low.

3.2. Zircon fission-track thermochronology

The zircons were mounted, polished and etched with KOH–NaOH at 220 °C for 12–36 hours following standard procedures of the London Fission Track Research Group. Mounts were then irradiated with muscovite external detectors and dosimeter glass CN-5 and CN-2 at the thermal neutron facility of the Risø reactor, Denmark. Fission-track densities were measured using an optical microscope at 1250x magnification with an oil objective. Ages ($\pm 1\sigma$) were calibrated by the zeta method (Hurford and Green, 1983), using a zeta factor of 127 ± 5 that was determined from multiple analyses of zircon standards following the recommendations of Hurford (1990).

ZFT ages indicate cooling through the 240 ± 40 °C temperature window depending on their U-concentrations (Hurford, 1986). Ideally, if all the ZFT ages are younger or older than depositional age of the basin, they indicate cooling in the basin or source, respectively. A mixture of older and younger ages, spanning pre- and post-deposition ages, likely suggests a case of partial fission-track annealing (or partial resetting) in zircon that indicates basin temperatures were within

240±40 °C. Partial annealing of zircon fission tracks begin at ~185–200 °C and the annealing is complete above ~280–300 °C (Bernet and Garver, 2005).

3.3 (U-Th)/He Zircon and Apatite Thermochronology

At the Arizona Radiogenic Helium Dating Laboratory, 3–5 mostly inclusion-free zircon and apatite grains with angular crystal faces were hand-picked from each sample (if available) and packed into Nb tubes. Applying the standard procedures of He extraction using coupled laser heating, the He content was measured on a quadrupole mass spectrometer, and subsequently Th and U contents were measured using ICP-MS following the methods of Reiners (2005). Raw ages were obtained by solving the combined radioactive decay-diffusion equation with known analytical concentrations of U, Th and He. These raw ages were then corrected by applying the alpha-ejection protocols of Farley et al. (1996). If the ZHe and AHe ages are younger than the depositional age of the formation, this implies basin burial temperatures of >140–200 °C and >40–90 °C, respectively, and the ages are interpreted as thermally reset. ZHe or AHe ages that are older than the depositional age of the sample are unreset and reflect cooling of the source before deposition.

3.4 Thermal Modeling

The ZHe and AHe ages from each sample were inverse modelled in the thermal modeling program HeFTy v.1.9.1 (Ketcham, 2005) to determine the time-Temperature (*t-T*) paths using the diffusion model of Guenthner et al. (2013). The forward model in HeFTy predicts the expected grain age data distribution for a given *t-T* path. The inverse algorithm solves for a family of *t-T* paths that a sample could have experienced for a fixed input dataset that include cooling ages, U-Th-Sm concentrations, grain size and zonation parameters. For each resultant *t-T* path, HeFTy calculates the statistical fit between measured and the predicted cooling ages. Acceptable-fit paths have a Kolmogorov-Smirnov probability ≥ 0.05, while good-fit paths have a Kolmogorov-Smirnov probability ≥ 0.5. A weighted mean path and a best-fit *t-T* path are also generated from the inversion process. The weighted mean path is an overall summary of the inversion process with weights based on goodness of fit statistics associated with the acceptable and good-fit paths; it may or may not have an acceptable or a good fit to the data. The best-fit path has the highest goodness of fit and represents the most reasonable thermal history of a sample under the assigned constraints.

4. Results

Our ZFT, ZHe, and AHe results are summarized in Table 2 and Figure 3 (data available in the supporting information, Tables S1–S3). All ages are reported at 1σ uncertainty level. For previous studies that used the youngest single grain age (e.g., youngest single detrital zircon or muscovite grain age) to constrain the maximum depositional ages (MDAs) of a unit, we recalculated the MDA by estimating the weighted mean age of the youngest cluster with overlapping uncertainties (i.e., YC1σ(2+) and YC2σ(3+) ages; Table 2, Dickinson and Gehrels, 2009). If true depositional age (e.g., biostratigraphic or geochronologic tuff ages) is not available for a formation, the YC2σ(3+) age is adopted as a conservative estimate of its MDA (Coutts et al., 2019). Therefore, unless specified, a MDA reported in this study refers to the YC2σ(3+) age, which is the weighted mean age of the youngest cluster of 3 or more grains with overlapping 2σ uncertainties.

The individual ZFT ages span from Cretaceous to Middle Miocene time, 182.15 ± 50.20 – 13.95 ± 2.98 Ma. Although the objective was to date 50–100 grains per sample for ZFT, low yield of zircon resulted in 17–65 grains per sample. All eight samples from the Zanskar Gorge (Figures

2B, 3A) fail the χ^2 test ($P(\chi^2) < 5\%$) indicating the presence of some overdispersion amongst the population of measured grain ages. However, levels of overdispersion expressed as % dispersion of the central age are not always high, suggesting that in some cases, the overdispersion is not significant or poorly developed in terms of defining discrete age components. The ZFT data were decomposed into statistical grain-age components or modes using RadialPlotter (Vermeesch, 2009; Table 2); however, these do not necessarily capture the true age modes if represented by only a few grains. In some cases, a few higher precision ages may be identified as an age mode rather than a population of grains that capture the true Poisson age distribution. To help determine the significance of the component ages, the data are also plotted as Abanico diagrams that combine a radial plot and a probability density estimate (supporting information, Figure S1). These plots help to visualize the distribution of ages in each sample in terms of age modes or groups, like the youngest age mode, the secondary age mode and the oldest age mode.

The individual ZHe ages are all Miocene, 19.04 ± 0.54 – 8.57 ± 0.11 Ma (Table 2, Figure 3B). The AHe ages range from Late Miocene–Pliocene, 6.77 ± 0.40 – 3.94 ± 0.17 Ma (Table 2, Figure 3B).

5. Interpretations

5.1 Tar Group and Lato Formation

The Tar Group, which has a biostratigraphically-determined depositional age limit of ~55–50 Ma (Green et al., 2008; Henderson et al., 2010), is partially reset with respect to the ZFT system, with ages from Zanskar Gorge yielding 130.92 ± 31.87 to 21.53 ± 4.61 Ma for the lowermost Jurutze Formation (sample ZG45), 76.79 ± 14.40 to 13.95 ± 2.98 Ma for the Chogdo Formation (sample ZG55) in the middle, and 182.15 ± 50.20 to 22.60 ± 4.57 Ma for the topmost Nummulitic

Limestone Formation (sample ZG62). The zircon populations (or modes), which are younger than the depositional ages in Chogdo (ZG55) and Nummulitic Limestone (ZG62) Formations confirm partial resetting (Table 2, Figure 3A). Although sample ZG45 from the Jurutze Formation contains a single mode of 65.2 ± 3.1 Ma, which is older than its 54.7 ± 0.3 Ma U-Pb detrital zircon MDA (Table 2), this ZFT age likely reflects partial resetting within the PAZ whereby the older, inherited zircons within the Jurutze Formation were not thermally reset to take them below the MDA. Our data suggest that the burial temperatures in the Tar Group exceeded the ZFT lower partial annealing temperatures of ~185-200 °C. However, basin temperatures did not exceed the higher annealing temperatures of ~280-300 °C above which ZFT ages are completely reset.

The ZHe ages from the Tar Group Sumdo Formation (sample DZA20ZV; 15.42 ± 0.20 - 8.57 ± 0.11 Ma) in the Zanskar Gorge are all younger than its biostratigraphic age of ~55-51 Ma (Henderson et al., 2010), indicating post-depositional temperatures exceeded 180-200 °C (Table 2, Figure 3B). The Lato Formation (possibly Cretaceous in age) within the Upshi-Lato transect is older than the youngest units of the Tar Group and has ZHe ages (sample DZA12UL; 12.62 ± 0.26 - 10.05 ± 0.20 Ma) that are all considerably younger than its stratigraphic age (Table 2, Figure 3B). Therefore, the Lato Formation is also reset.

5.2 Indus Group

In the Lower Indus Group at Zanskar Gorge, the 50.3 ± 3.3 Ma ZFT modal age of the Nurla Formation (sample ZG42) is within error of its U-Pb detrital zircon MDA of ~51 Ma (Table 2, Figure 3A; Bhattacharya et al., 2020). The Choksti Conglomerate (sample ZG38), which overlies the Nurla Formation and is the basal member of the Choksti Formation, has two ZFT modes, 40.3 ± 2.1 and 68.6 ± 4.1 Ma (Table 2, Figure 3A). These two age modes are approximately equal to or older than the U-Pb detrital zircon MDA of the Choksti Formation, which is 41.5 ± 0.2 Ma (Wu et al., 2007). The Upper Choksti member (sample ZG30), which is the topmost member of the Chokski Formation, has four ZFT modes: 26.6 ± 2.2 (M1), 37.8 ± 3.8 (M2), 49.5 ± 4.4 (M3) and 83 ± 8.4 Ma (M4; Table 2, Figure 3A). The Upper Chokski Member is stratigraphically correlatable to the Hemis and Lower Upshi Formations that have U-Pb detrital zircon MDAs of 37.8 ± 0.2 and 38.3 ± 0.2 Ma, respectively (Table 2; Sinclair and Jaffey, 2001; Henderson et al., 2011; Bhattacharya et al., 2020). The Chokski Formation is also older than the Basgo Formation, which has a Late Oligocene biostratigraphic age (Bajpai et al., 2004; Tripathy-Lang et al., 2013). The M1 mode of Upper Chokski is thus younger than its depositional age, reflecting partial resetting of sample ZG30. Interestingly, partial resetting is not detected in samples ZG42 and ZG38 from the underlying Nurla Formation and Chokski Conglomerate member. This is because these two samples probably contained older zircon populations, which remained above their corresponding MDAs, despite partial resetting. The youngest M1 mode from the Lower Nimu Formation (sample ZG21) is 25.5 ± 3.1 Ma, which is younger than its ^{40}Ar/^{39}Ar detrital muscovite MDA of 32.3 ± 0.2 Ma. In terms of true depositional age, the Lower Nimu Formation is at least older than the biostratigraphically-dated Late Oligocene Basgo Formation (Bajpai et al., 2004; Buckman et al., 2018). The M1 mode of the Lower Nimu Formation thus indicates partial resetting. The upper Indus Group Upper Nimu Formation (ZG16) is unreset, with ZFT modes older than its corresponding ^{40}Ar/^{39}Ar detrital muscovite MDA of 9.5 ± 0.5 Ma (Table 2, Henderson et al., 2010). Overall, like the Tar Group, the Lower Indus Group is also partially reset with respect to the ZFT system, whereas the Upper Indus Group is unreset.

Along the Upshi-Lato traverse, the Lower Indus Group Lower Upshi Formation (sample DZA09UL) has ZHe ages from 17.79 ± 0.26 – 13.63 ± 0.21 Ma (Table 2, Figure 3B). The Lower Upshi Formation and its stratigraphically correlatable Hemis Formation both have detrital zircon and muscovite MDAs of ~38 Ma (Table 2; Henderson et al., 2011; Bhattacharya et al., 2020). The ZHe ages in the Lower Upshi Formation are thus younger than its inferred MDA. Along the Basgo traverse, the Lower Indus Group Basgo Formation (sample DZA07SA) ZHe ages are from 19.04 ± 0.54 – 9.90 ± 0.27 Ma, which are younger than its Late Oligocene depositional age based on ostracods (Bajpai et al., 2004). From the Temesgam traverse, the Lower Indus Group Temesgam Formation (sample DZA23TM) exhibits ZHe ages from 18.91 ± 0.52 – 12.81 ± 0.18 Ma, which are younger than its U-Pb detrital zircon MDA of 26.8 ± 0.1 Ma (Table 2; Bhattacharya et al., 2020). The AHe ages from the Lower Upshi Formation (sample DZA08UL; 6.56 ± 0.10 – 5.22 ± 0.30 Ma) and the Temesgam Formation (sample DZA23TM; 6.77 ± 0.40 Ma – 3.94 ± 0.17 Ma) are younger than their corresponding ZHe ages (Table 2; Figure 3B).

All ZHe ages from the Lower Indus Group are <20 Ma. Deposition in the Lower Indus Group of central Ladakh ended by ~26–23 Ma, after which basin inversion and regional counterthrusting began at ~23–20 Ma (Clift et al., 2002; Zhou et al., 2020; Bhattacharya et al., 2020). Therefore, we interpret the ZHe and AHe ages from the Lower Indus Group formations as thermally reset. This is consistent with our earlier interpretation that the Lower Indus Group is partially reset with respect to the ZFT system, implying peak burial temperatures exceeded 185–200 °C but stayed below 280–300 °C. By contrast, the stratigraphically youngest Upper Indus Group Upper Nimu Formation yields ZHe ages (sample DZA17ZV; 17.39 ± 0.35 – 13.70 ± 0.27 Ma) older than its corresponding ^{40}Ar/^{39}Ar detrital muscovite MDA of 9.5 ± 0.5 Ma (Henderson et al., 2010). The Upper Indus Group is therefore unreset with respect to the ZHe system (Table 2, Figure 3B).

No correlation exists between ZHe or AHe ages and grain size in individual samples. However, compilation of all the ZHe ages reveals a moderate positive correlation between age and grain size, which may contribute to the inter-sample ZHe age dispersion (supporting information, Figure S2). No correlation exists between AHe ages and grain size. Overall, no correlation is observed between effective uranium and ZHe or AHe ages within individual samples, or collectively (supporting information, Figure S2). This suggests radiation damage is not the primary influence of intra-sample ZHe and AHe age variability, and the distribution of ZHe ages are largely geologically controlled. The only exception is sample DZA07SA from the Basgo Formation, which shows strong negative correlation between ZHe age and effective uranium (R^2 = ~0.7) suggesting some control of radiation damage on the observed cooling ages (supporting information, Figure S2).

6. Thermal modeling of (U-Th)/He cooling ages

6.1 Modeling Strategy

Using our ZHe and AHe data in the thermal modeling program HeFTy, we tested two *t-T* modeling approaches to determine the cooling history of the Indus Basin rock samples. The first approach involves considering post-depositional *t-T* constraints based on known regional geologic information, while the second approach lacks any specific post-depositional *t-T* constraints. The purpose of testing the second approach was to check if we can reproduce near-identical cooling histories without imposing particular post-depositional *t-T* constraints in the models, thus reducing bias.

Indus Basin sedimentation began in Late Cretaceous time with the deposition of the marine Tar Group, which continued until ~50 Ma (Henderson et al., 2010). After ~50 Ma, the continental facies of the Lower Indus Group were deposited until Late Oligocene–Early Miocene time (Sinclair and Jaffey, 2001; Clift et al., 2002; Henderson et al., 2011; Zhou et al., 2020;

Bhattacharya et al., 2020). The Indus Basin was inverted at ~23–20 Ma (Clift et al., 2002) and there is no prior evidence of post-depositional basin cooling. Burial temperatures largely remained below 240 °C in the Indus Basin except the Tar Group, where maximum temperatures reached 280 °C (Van Haver, 1984; Clift et al., 2004). In our first approach, to fit the ZHe and AHe data in the context of known regional geologic information, we allow individual models to explore the *t-T* space younger than 23 Ma and colder than 240 or 280 °C (Figures 4A-E). We apply surface depositional temperatures of 0–25 °C and let all the models solve for *t-T* paths from temperatures greater than the closure temperature window of the warmest thermochronometric system modelled. The ZFT, ZHe, and AHe partial annealing/retention temperatures considered are 240 ± 40 °C (Hurford, 1986), 140–200 °C (Reiners, 2005; Guenthner et al., 2013), and 40–90 °C (Ehlers and Farley, 2003), respectively. Based on the knowledge of regional thermal history, a temperature constraint of 0–280 °C was applied only to the Tar Group Sumdo Formation (Sections 2.3, 6.1.2), while a 0–240 °C constraint was imposed on the *t-T* models of the Lato, Lower Upshi, Basgo and Temesgam Formations (Sections 6.1.1, 6.1.3–6.1.5). The input *t-T* constraints are shown by hollow rectangles in Figures 4A-E and are detailed for each formation in sections 6.1.1–6.1.5. For a given sample, simultaneous modelling of individual ZHe ages, or a mix of individual ZHe and AHe ages (2–3 grains or more), yielded no good or acceptable-fit paths with the known input data. This is a common problem with HeFTy as noted in multiple previous studies (e.g., Carrapa et al., 2014); the program could not satisfy all input parameters for a single sample simultaneously and produce acceptable results. Therefore, mean ZHe and AHe ages were calculated and incorporated as input data for *t-T* model extraction in HeFTy using the diffusion model of Guenthner et al. (2013). Inverse modeling produced a set of possible *t-T* paths for a given sample based on the user assigned *t-T* constraints. We ran the models until at least 100 good fit *t-T* paths were generated. The best-fit *t-T* path of each model represents a statistically robust thermal history of the corresponding sample (Figures 4A-E).

In the second approach of *t-T* modeling, we constrain only the depositional age of the sample and its surface depositional temperatures (0–25 °C). This approach allows HeFTy to explore maximum area in the post-depositional *t-T* space and generate a family of *t-T* paths that do not depend on known geologic information from the region. Similar to first approach, at least 100 good fit *t-T* paths were produced (supporting information, Figure S3). Although the best-fit *t-T* paths from our second approach show cooling beginning approximately within the same age range as in the first approach, not all the resultant *t-T* paths yield a geologically meaningful thermal history. Several acceptable and good-fit paths demonstrate *t-T* histories that are unrealistic considering the available data on the timing of basin sedimentation, burial, inversion and cooling. Thus, not all statistically acceptable or good-fit *t-T* paths obtained in our second approach are representative of the post-depositional cooling history of the basin. We examine the causes of rejection for individual models in supporting information, Text S1. The second approach is not discussed henceforth and the following sub-sections 6.1.1-6.1.5 focus on the *t-T* constraints imposed by regional geologic data as per the first approach.

6.1.1 Lato Formation

The Indian margin unit Lato Formation was deposited on the surface at 0–25 °C in possibly Cretaceous time (Figure 4A). The Lato Formation is speculated to be correlatable to the Mesozoic Lamayuru Complex or the Mesozoic Chilling Formation in the Zanskar Gorge (Henderson et al., 2011), both of which are Indian margin units that are older than Early Eocene. Henderson et al. (2011) obtained two ~51 and ~77 Ma U-Pb detrital zircon grain ages and a ~67 Ma $^{40}Ar/^{39}Ar$ detrital muscovite grain age from the Lato Formation; all other detrital grains are >350 Ma. The 3 youngest grain ages do not overlap within 2σ; therefore, instead of taking a weighted average, we consider the ~77 Ma grain age as a conservative estimate of MDA for the Lato Formation. The Lato Formation is older than, or coeval with, the youngest Tar Group units that were deposited between 55 and 50 Ma (Henderson et al., 2010, 2011). Therefore, in our HeFTy model, we constrain the depositional age of the Lato Formation from ~77–50 Ma, which is consistent with regional stratigraphic correlations.

Cooling is constrained through 0–240 °C after ~23 Ma. Despite being older than the Tar Group, there is no evidence of burial temperatures exceeding 240 °C in the Lato Formation, and the depositional setting of the Lato Formation relative to Tar Group is undetermined. The Tar Group, which experienced temperatures >240 °C, has blue-grey phyllite (Van Haver, 1984; Clift et al., 2002; Henderson et al., 2010) and was probably deposited just north of the Lato Formation that contains relatively unaltered sandstone.

6.1.2 Sumdo Formation

The Tar Group Sumdo Formation was deposited at the surface (0–25 °C) at ~55–51 Ma (Figure 4B; Henderson et al., 2010). ZFT ages from the overlying Chogdo Formation and the underlying Jurutze Formation are partially reset, which suggest peak burial temperatures between 200–280 °C in the Sumdo Formation. Van Haver (1984) calculated a maximum burial temperature of ~280 °C using illite crystallinity from the overlying Nummulitic Limestone Formation. Therefore, we constrain cooling in the Sumdo Formation after 23 Ma through 0–280 °C.

6.1.3 Lower Upshi Formation

The Lower Indus Group Lower Upshi Formation (Figure 4C) is correlatable to the Hemis Formation, and both have detrital zircon and muscovite MDAs of ~38 Ma (Henderon et al., 2011;

Singh et al., 2015; Bhattacharya et al., 2020). The $^{40}Ar/^{39}Ar$ detrital muscovite MDA of the Upper Upshi Formation, which overlies the Lower Upshi Formation, is ~25 Ma (Table 2; Henderson et al., 2011). Because true depositional ages can be younger than MDAs, we relax the depositional age for the Lower Upshi Formation in our HeFTy model to be from ~38–23 Ma. The upper age of ~23 Ma is based on the ~26–23 Ma cessation of Lower Indus Group deposition in central Ladakh, after which regional counterthrusting began at ~23–20 Ma (Clift et al., 2002; Zhou et al., 2020; Bhattacharya et al., 2020). Our ZFT results indicate that the Lower Indus Group is partially reset with respect to the ZFT system, indicating peak burial temperatures >185–200 °C. In addition, paleo-geotemperature estimates from the Lower Indus Group based on illite crystallinity also suggest maximum burial temperatures of ~239°C (Schlup et al., 2003; Clift et al., 2004). Hence, we allow the model to cool through 0–240 °C after ~23 Ma.

6.1.4 Basgo Formation

The Lower Indus Group Basgo Formation is ~10–200 m thick (Garzanti and Van Haver, 1988) and is biostratigraphically dated as Late Oligocene in age (Bajpai et al., 2004). The formation has a youngest single zircon MDA of ~27 Ma (Bhattacharya et al., 2020). The Basgo Formation is conformably overlain by the Temesgam Formation, which was deposited from 26–23 Ma (Bhattacharya et al., 2020). In our *t-T* model, we constrain the depositional age of the Basgo Formation at ~28–26 Ma (Figure 4D). Because Lower Indus Group temperatures did not exceed 240 °C, we constrain model cooling through 0–240 °C after ~23 Ma.

6.1.5 Temesgam Formation

The Lower Indus Group Temesgam Formation has a U-Pb detrital zircon MDA of ~27 Ma and was deposited conformably on top of Basgo Formation from 26–23 Ma (Table 2, Bhattacharya et al., 2020). Therefore, in our *t-T* model, we constrain the depositional age of the Temesgam Formation from ~26–23 Ma (Figure 4E). An upper age limit of ~23 Ma is imposed from the estimated age of inversion of the Indus Basin (Clift et al., 2002). Like other formations of the Lower Indus Group, we allow model cooling through 0–240 °C after 23 Ma.

6.2 Model Results

All the *t-T* models demonstrate cooling from above or within the ZHe partial retention zone temperatures of 140–200°C through at least 100 good and ≥188 acceptable-fit paths (Figures 4A–E). The best-fit *t-T* model paths show the onset of cooling by ~22–20 Ma in the Lower Indus Group Lower Upshi, Basgo and Temesgam Formations (Figures 4C–E), and by ~15–13 Ma in the Lato and Sumdo Formations (Figure 4A–B). It is possible that cooling may have started earlier than the time indicated by the best-fit *t-T* paths in the Lato and Sumdo Formations as well; a number of good-fit paths in each model suggest cooling began before ~15–13 Ma (Figures 4A–B). We interpret the time of initiation of cooling along the best-fit *t-T* path as the minimum time by which cooling was onset in the sample. The best-fit model paths for the Indian margin Lato Formation and the Tar Group Sumdo Formation, demonstrate a peak burial temperatures (235–245 °C) well exceeding the maximum ZHe partial retention zone temperature of ~200 °C, suggesting that the Lato and Sumdo Formations are reset and the ZHe ages reflect post-depositional basin cooling (Figures 4A–B). The Lower Upshi, Basgo and Temesgam Formations are likely reset as well; the best-fit *t-T* model paths record cooling from above 170–190 °C, which indicate burial within the higher side of the ZHe partial retention zone. Our *t-T* modeling is a consequence of using mean ages in each model. If individual ZHe ages are modelled grain by grain, it does not significantly change the results determined by using mean ages, and best-fit paths still indicate cooling beginning between ~22 and 11 Ma. In summary, the *t-T* modeling results presented in this study confirm the presence of a post-depositional cooling signal in the Indus Basin beginning at ~22–20 Ma, and show that burial temperatures in the Indian margin Lato Formation, Tar Group and the Lower Indus Group exceeded 170–190 °C.

7. Discussion

7.1 Post-depositional Thermal Evolution of the IBSR

In general, the IBSR in central Ladakh, excluding the Upper Indus Group, experienced post-depositional cooling from >170–200 °C in Miocene–Pliocene time. The ZFT results suggest that post-depositional peak basin temperatures exceeded 185–200 °C in the Tar and Lower Indus Groups but stayed below 280–300 °C (Table 2). This basin heating resulted in partial resetting of the Tar and Lower Indus Group rocks with respect to the ZFT system. Our ZFT age interpretations are consistent with the 280 °C and 240 °C maximum burial temperatures of the Tar and Lower Indus Group rocks determined using illite crystallinity and/or vitrinite reflectance (Van Haver, 1986; Schlup et al., 2003, Clift et al., 2004). Although best-fit (U-Th)/He *t-T* model paths from the Lower Indus Group suggest burial temperatures of ~170–190 °C, this might be a consequence of relative extent of burial in the sampled sections. The Zanskar section, from where our ZFT samples are collected, exposes more altered sandstones (Tripathy-Lang et al., 2013) compared to the Upshi-Lato, Basgo, and Temsgam sections, from where our Lower Indus Group ZHe and/or AHe samples are collected.

Our ZHe ages range between ~19 and 8 Ma (Table 2, Figure 3B); however, these ages alone cannot be used to estimate when basin cooling began. Thermal modeling results suggest that cooling initiated by ~22–20 Ma in the Lower Indus Group of the Indus Basin (Figures 4C–E) and was occurring throughout the basin by ~15–12 Ma (Figures 4A–B). The majority of the ZHe cooling ages are between ~16 and 10 Ma, and all our thermal models demonstrate steady or rapid cooling through 200–140 °C between ~20 and 10 Ma (Figure 4). Therefore, we suggest that cooling largely occurred through ZHe temperatures in Early–Middle Miocene time. Cooling continued into the Pliocene time until at least ~4 Ma, which is supported by our ~7–4 Ma AHe cooling ages and model paths (Table 2, Figures 4C, E). Our interpretation expands the ~14–7 Ma post-depositional cooling phase previously identified in the Lower Indus Group using three AFT central ages (Clift et al., 2002; Schlup et al., 2003). It is also possible that the timing of initiation of cooling decreases from north to south across the basin. For example, cooling may have begun earlier in the northern Lower Indus Group Formations between ~22 and 20 Ma (Figures 4C–E), and then progressed southwards in the Tar Group and Lato Formation between ~15-12 Ma (Figures 4A–B); however more low-temperature thermochronometric studies are required in the region to check for such age trends across the Indus suture. Overall, this study in the Indus Basin of central Ladakh reveals a post-depositional Miocene–Pliocene cooling phase (~22–4 Ma) that initiated at ~22–20 Ma.

Unreset ~17–14 Ma ZHe ages from the Pliocene Upper Nimu Formation (Table 2; Mathur, 1983; Henderson, 2010) of the stratigraphically youngest Upper Indus Group indicate post-depositional basin temperatures <140 °C. The Upper Indus Group is ~1 km thick (Henderson et al., 2010). Therefore, Pliocene deposition of the Upper Indus Group did not influence the cooling of either the Tar Group or the Lower Indus Group.

7.2 Cause of Basin Burial: Sedimentation or Overthrusting

In the Indus Basin, peak burial temperatures exceeded 170–190 °C just before cooling began between ~22 and 20 Ma (Figure 4A–E). This requires the IBSR, excluding the Upper Indus Group, to be progressively buried by sedimentation and/or regional overthrusting. Stratigraphic studies indicate at least ~4.5 km of sediment was deposited in the Indus Basin by Early Miocene time (Henderson et al., 2010; Bhattacharya et al., 2020), which suggests some of the basin heating was the result of this stratigraphic overburden (assuming a geotherm of 20–30 °C/km). We suggest that additional burial was caused by regional overthrusting associated with the GCT. Although the age of the GCT is not well constrained by geochronological methods in NW India, it is thought to have initiated in Early Miocene time at ~23–20 Ma (Sinclair and Jaffey, 2001; Clift et al., 2002; discussed in Section 2.1). Kirstein et al. (2009) support a >20 Ma age for the GCT that led to the burial of the southern edge of the Ladakh batholith. Recent studies from south Tibet also assert that the slip on the GCT initiated at ~23 Ma (Laskowski et al., 2018), and ceased by ~15 Ma in most locations (Zhang et al., 2011; Carrapa et al., 2014; Laskowski et al., 2018; Orme, 2019).

7.3 Implications and causes of cooling

Despite the relatively limited scope of our data, this is the first regionally extensive multi-thermchronometric study from the IBSR and reveals a post-depositional Miocene–Pliocene cooling signal along the India-Asia collision zone in NW India. Deposition continued regionally along the collision zone until Late Oligocene–Early Miocene time (~26–23 Ma; Sinclair and Jaffey, 2001; Clift et al., 2002; Zhou et al., 2020), and there is no unequivocal evidence of cooling beginning in the IBSR until ~22–20 Ma. Using the ZHe and AHe datasets, we calculate the amount of material removed since the onset of cooling at ~22–20 Ma. This requires assuming a paleo-geothermal gradient, which is challenging considering the few studies along the collision zone in NW India. Thermal modeling of ZFT and AFT ages in Kohistan, >350 km west of the study area, reveal Miocene geothermal gradients of ~40 °C/km (Zeitler, 1985). Based on the geothermal gradient calculated by Zeitler (1985), Sinclair and Jaffey (2001) bracket a 30–50 °C/km range for Miocene geothermal gradients in the Indus Basin to estimate exhumation rates of 0.10–0.40

mm/yr. However, a 30–50 °C/km geothermal gradient range is incompatible with recent studies from the region (e.g., Epard and Steck, 2008; Schlup et al., 2011; Langille et al., 2014; Kumar et al., 2017). Using a bootstrapping algorithm, Kumar et al. (2017) modelled a range of geothermal gradients from ~22–33 °C/km for the Early–Middle Eocene evolution of the Ladakh batholith (Figure 1A) in NW India. In the Tso Morari Complex to the south (Figure 1A), Eocene–Oligocene geothermal gradients were 18–22 °C/km, and the geothermal gradient has remained relatively unperturbed since 30 Ma (Epard and Steck, 2008; Schlup et al., 2011). East of the Tso Morari Complex, ~200 km south-east of the study area, Early Miocene geothermal gradients estimated from the Leo Pargil shear zone by analyzing the Barrovian metamorphic pressure-temperature paths vary from ~22–30 °C/km (Langille et al., 2014). Based on these neighboring geotherm estimates, we assume a Miocene geothermal gradient of ~20–30 °C/km for the Indus Basin. It is essential to note that recent works from sedimentary basins along the India-Asia collision zone in south Tibet have all considered Miocene geothermal gradients within 20–30 °C/km (e.g., Carrapa et al., 2014; Li et al., 2016; Orme, 2019; Ning et al., 2019). Assuming a geothermal gradient of 20–30 °C/km, our ZHe cooling ages indicate cooling from a mean temperature of 204 °C that requires removal of at least ~7–10 km of rock since ~22 Ma.

A potential driver of the Miocene–Pliocene cooling is erosion by the Indus River, which has been draining the India-Asia collision zone in NW India since at least Late Oligocene–Early Miocene time (Sinclair and Jaffey, 2001; Henderson et al., 2010, 2011; Bhattacharya et al., 2020). Indus River erosion removed the GCT-overthrusted rocks that buried the Indus Basin, thereby resulting in the observed Miocene–Pliocene cooling. Although Indus River erosion played an important role in removing rocks from the India-Asia collision zone in Miocene–Pliocene time (e.g., Sinclair and Jaffey, 2001; Henderson et al., 2010), we cannot be certain that the river erosion was the primary factor triggering the onset of cooling between ~22 and 20 Ma. There is considerable debate as to whether the Indus River's flow along the suture zone began in NW India in Early Eocene or Early Miocene time (Searle et al., 1996; Sinclair and Jaffey, 2001; Clift et al., 2002; Najman, 2006; Henderson et al., 2010; 2011; Zhuang et al., 2015). If the Indus River first flowed along the suture zone in the Early Miocene, aggressive erosion resulting from its initiation may explain the onset of regional cooling. If the Indus River existed at this location since Early Eocene time, additional tectonic, geodynamic and geomorphological factors were also responsible for the initiation of cooling. Interestingly, along the Yarlung suture of the India-Asia collision zone in south Tibet, a regional Miocene cooling signal from ~21–7 Ma is well documented from low-temperature thermochronometric studies (e.g., Carrapa et al., 2014; Tremblay et al., 2015, Li et al., 2015, 2016, 2017; Ge et al., 2017; Orme, 2019). These studies generally attribute the Miocene cooling signal to GCT activity and/or Yarlung River erosion (Carrapa et al., 2014; Li et al., 2015, 2016, 2017; Ge et al., 2017; Orme, 2019), or intensification of Asian monsoon (Carrapa et al., 2014), while considering the regional uplift caused by the northward underthrusting of the Indian plate following Greater Indian slab break-off in Early Miocene time (DeCelles et al., 2011; Webb et al., 2017). Therefore, it is possible that a similar combination of tectonic, geodynamic, and geomorphologic factors resulted in a tectonic setting that facilitated regional cooling along the India-Asia collision zone in NW India. However, given the limited previously published and new data in this region, it is difficult to test such scenarios. This study therefore provides the foundation to investigate more complex tectono-thermal events in the India-Asia collision zone of NW India and test models that correlate them with the results from south Tibet.

8. Conclusions

Low-temperature thermochronology of the Indus Basin in central Ladakh reveals a post-depositional Miocene–Pliocene (~22–4 Ma) cooling history. Our ZFT and ZHe results confirm that the basin was buried to temperatures >170–200 °C and exceeded 240 °C in the deepest formations. Basin burial is attributed to sedimentation and regional northward counterthrusting by the GCT in Early Miocene time. Thermal modeling of ZHe and AHe ages indicate cooling onset by ~22–20 Ma, occurred rapidly or steadily across the basin through ZHe partial retention zone temperatures between ~20 and 10 Ma, and continued at least until ~4 Ma. This Miocene–Pliocene cooling, which removed ~7–10 km of rock from the India-Asia collision zone, may be linked to erosion by the Indus River that dissects the ISBR. However, more low-temperature thermochronometric data from western and eastern Ladakh are required to confirm if this cooling signal is present along the strike of the India-Asia collision zone in NW India, as documented in south Tibet. If a regional Miocene–Pliocene cooling signal is indeed present both in NW India and south Tibet, it might be indicative of a continental-scale thermal event operating along the India-Asia collision zone driven by a combination of tectonic, geodynamic, and geomorphologic factors rather than Indus river incision alone.

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Figure Captions

Figure 1. A. Geological map of the India-Asia collision zone in Ladakh, NW India showing major tectono-stratigraphic units modified after Buchs and Epard (2019). Studied cross-sections are indicated in red: 1 - Temesgam section; 2 - Basgo section; 3 - Zanskar Gorge; 4 - Upshi-Lato section. **B:** Location of the study area (red) with respect to major terranes of south Asia. Blackened zones contain ophiolites. **C:** Schematic cross-section along AA' through the collision zone in NW India.

Figure 2. Geological maps of **(A)** Temesgam and Basgo sections (numbered 1 and 2 in red respectively; modified after Garzanti and Van Haver, 1988; Tripathy-Lang et al., 2013), **(B)** Zanskar Gorge (modified after Henderson et al. 2010), and **(C)** Upshi-Lato section (modified after Henderson et al. 2011) showing formations, major structures and our sample locations. Abbreviations: Fm - Formation, sh - shale, Conglomerate - cgl, N lst - Nummulitic Limestone, U - upper, M - middle, L - lower, R - river.

Figure 3. A. Plot showing range of ZFT ages from the Zanskar Gorge samples. Vertical black lines specify ZFT age ranges for each sample and contain solid black diamonds that indicate corresponding depositional ages. Mean percentage of grains representing modes M1, M2, M3 and M4, determined from Abanico plots, are shown in parantheses. Abbreviations: Congl. - Conglomerate; Numm. Lst. - Nummulitic Limestone; n - number of grains. Solid black diamonds indicate depositional ages. **B.** Zircon (ZHe) and apatite (AHe) (U-Th)/He ages versus stratigraphic ages of the Indus Basin sedimentary rocks (IBSR). The ZHe ages (2-3 grains per sample) of individual grains are indicated by the horizontal bars on the dark grey rectangles. The AHe ages (5 grains per sample) are represented by light grey box and whisker plots, where the whiskers represent maximum and minimum individual apatite ages. Solid black squares indicate depositional ages. * - The depositonal age of the Lato Formation is Late Cretaceous, which is not shown on the vertical scale. The depositional ages are compiled from Bajpai et al. (2004), Wu et al., (2007), Henderson et al. (2010, 2011) and Bhattacharya et al. (2020).

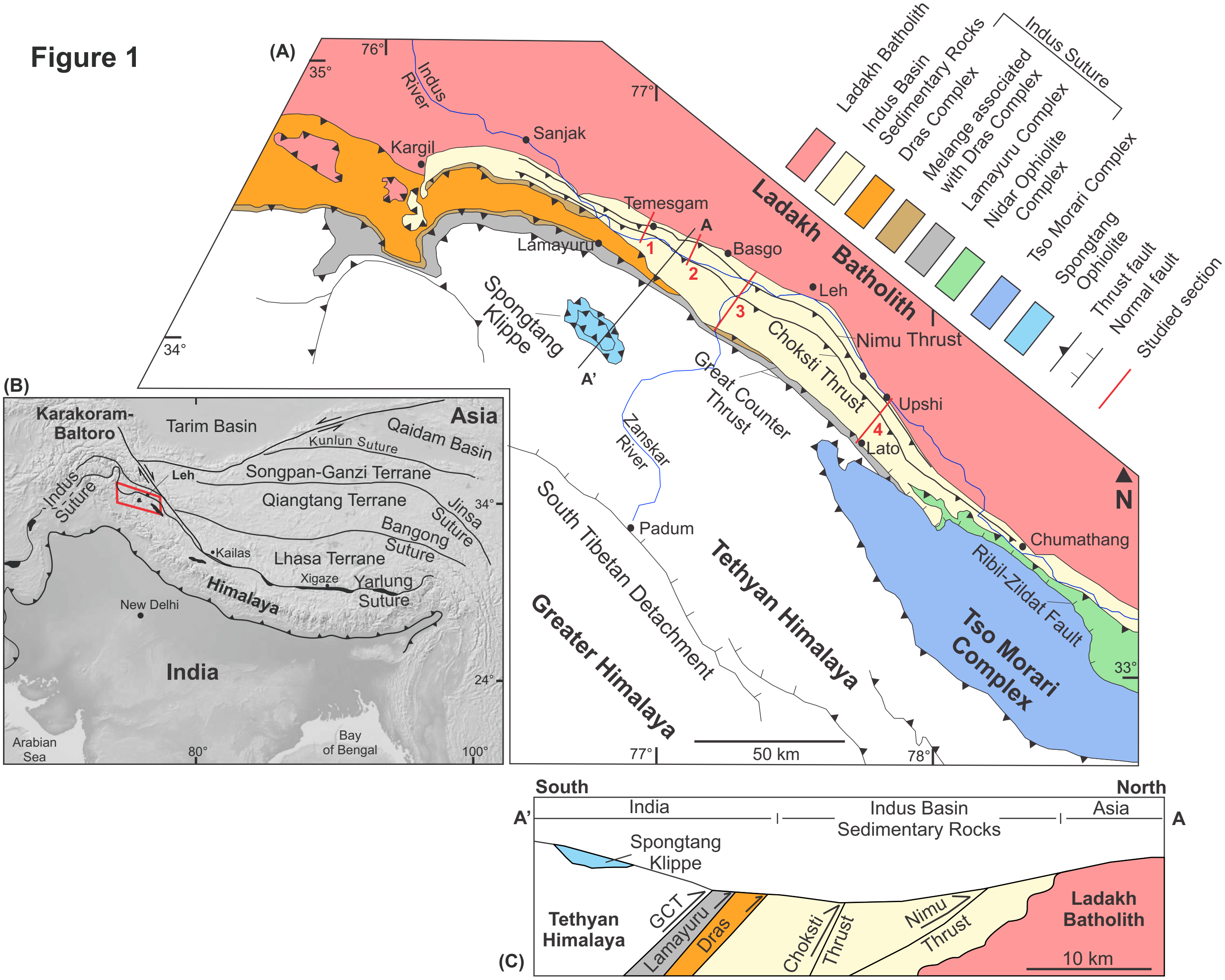
Figure 4. Time-temperature *(t-T)* models of the Indus Basin extracted using the HeFTy program (Ketcham, 2005). **(A)** Lato Formation (Model DZA12UL), **(B)** Sumdo Formation (Model DZA20ZV), **(C)** Lower Upshi Formation (Model DZA09UL), **(D)** Basgo Formation (Model DZA07SA), and **(E)** Temesgam Formation (Model DZA23TM). Abbreviations: PT - paths tried, AP (green) -acceptable paths, GP (pink) - good paths. Solid black line indicates best fit model path. Hollow square boxes demarcate *t-T* constraints.

Table Captions

Table 1. Published stratigraphic schemes compared across the IBSR sections in NW India.

Table 2. Summary of ZFT, ZHe and AHe ages from Zanskar Gorge, Upshi-Lato, Basgo and Temesgam sections.

Figure 1


(A)
Ladakh Batholith
Indus Basin Sedimentary Rocks
Dras Complex
Melange associated with Dras Complex
Lamayuru Complex
Nidar Ophiolite Complex
Tso Morari Complex
Spongtang Ophiolite
Thrust fault
Normal fault
Studied section
Indus Suture
Indus River
Sanjak
Kargil
Temesgam
Lamayuru
Basgo
Leh
Spongtang Klippe
Nimu Thrust
Choksti Thrust
Great Counter Thrust
Upshi
Lato
Zanskar River
Padum
South Tibetan Detachment
Tethyan Himalaya
Greater Himalaya
Tso Morari Complex
Ribil-Zildat Fault
Chumathang
Ladakh Batholith
N
50 km
76°
77°
78°
35°
34°
33°
A
A'
1
2
3
4
(B)
Karakoram-Baltoro
Tarim Basin
Asia
Qaidam Basin
Kunlun Suture
Songpan-Ganzi Terrane
Qiangtang Terrane
Jinsa Suture
Bangong Suture
Leh
Indus Suture
Kailas
Lhasa Terrane
Xigaze
Yarlung Suture
Himalaya
New Delhi
India
Arabian Sea
Bay of Bengal
80°
100°
34°
24°
(C)
South
North
A'
A
India
Indus Basin Sedimentary Rocks
Asia
Spongtang Klippe
Tethyan Himalaya
GCT
Lamayuru
Dras
Choksti Thrust
Nimu Thrust
Ladakh Batholith
10 km

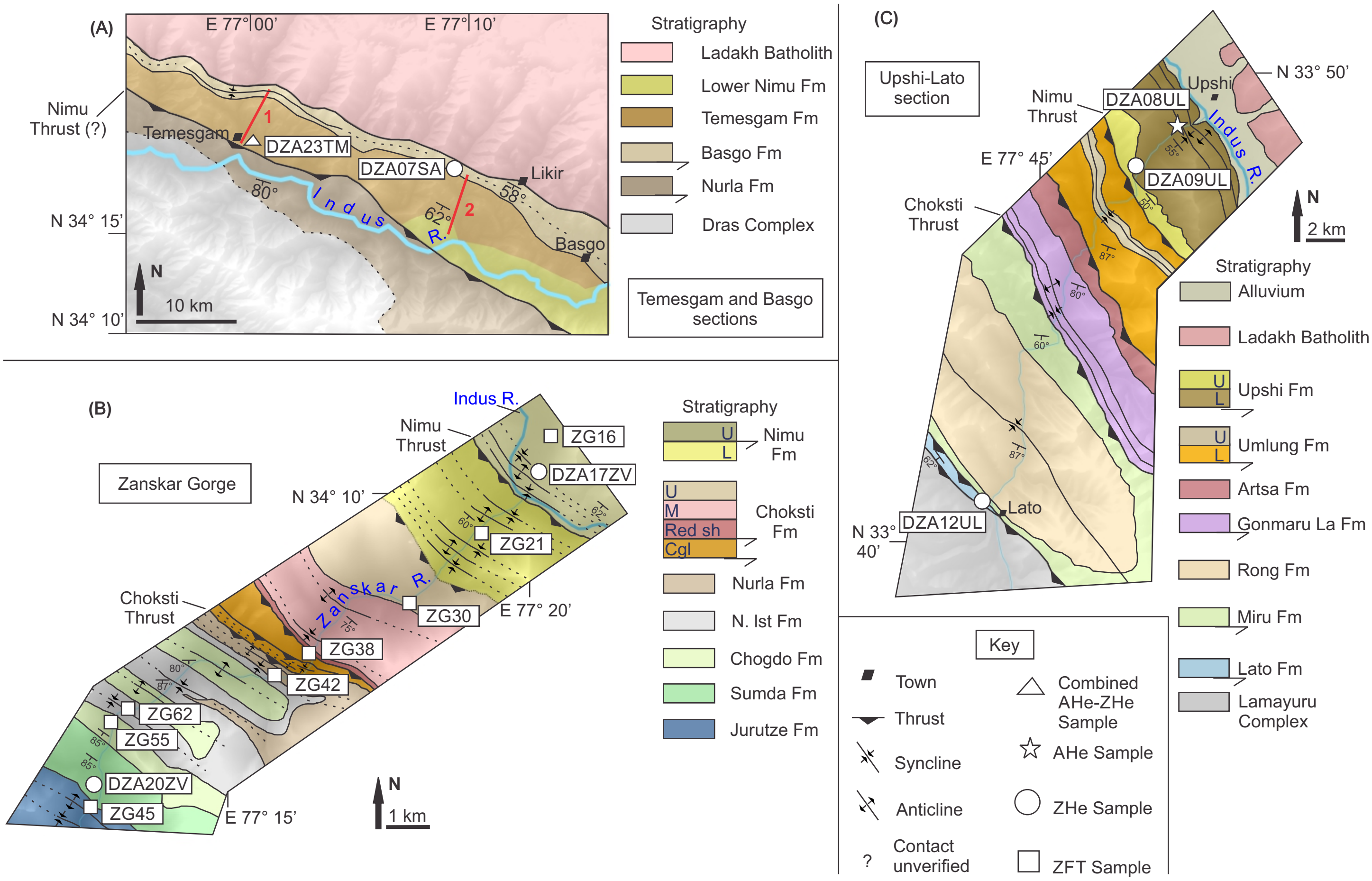
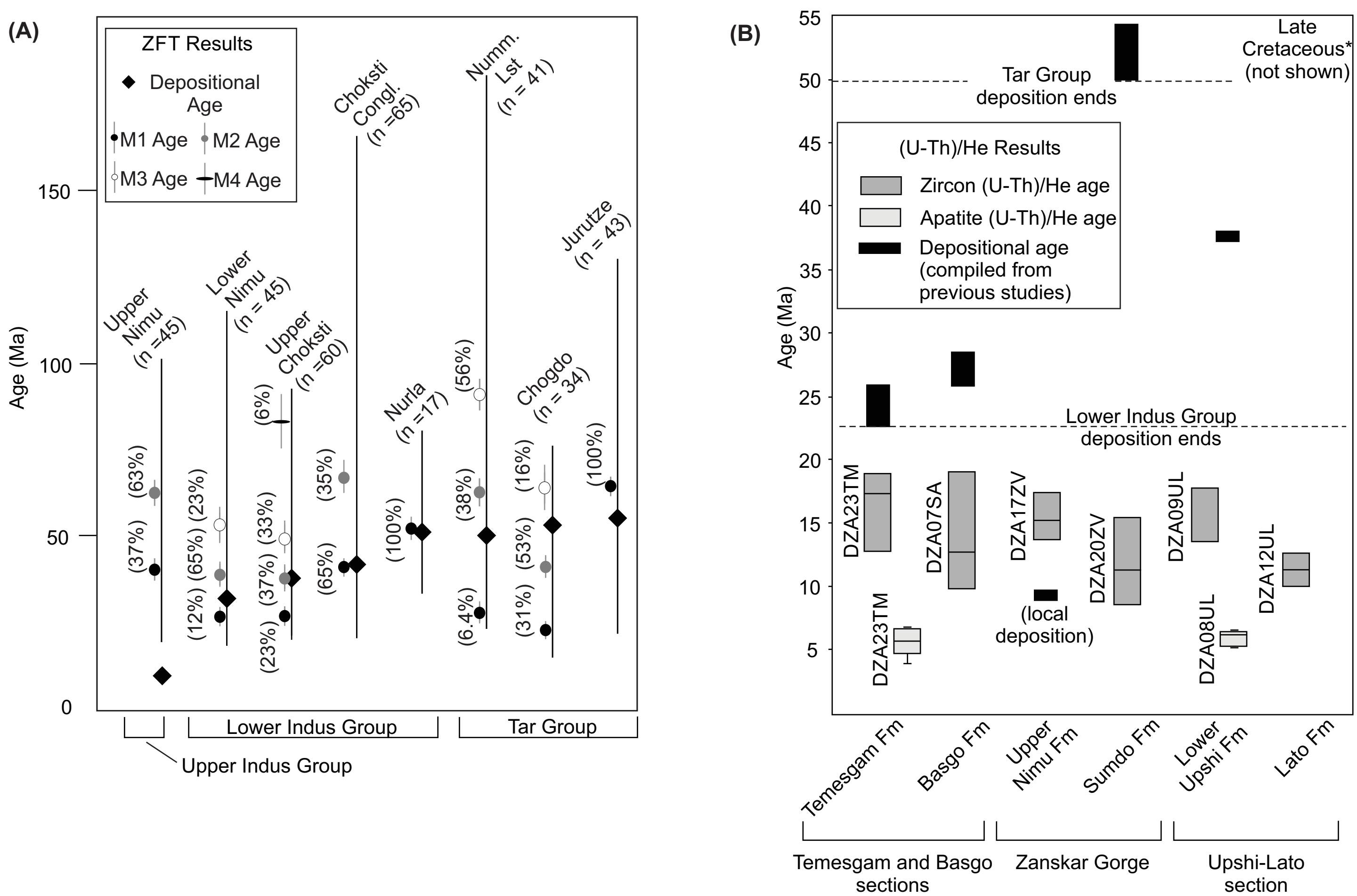
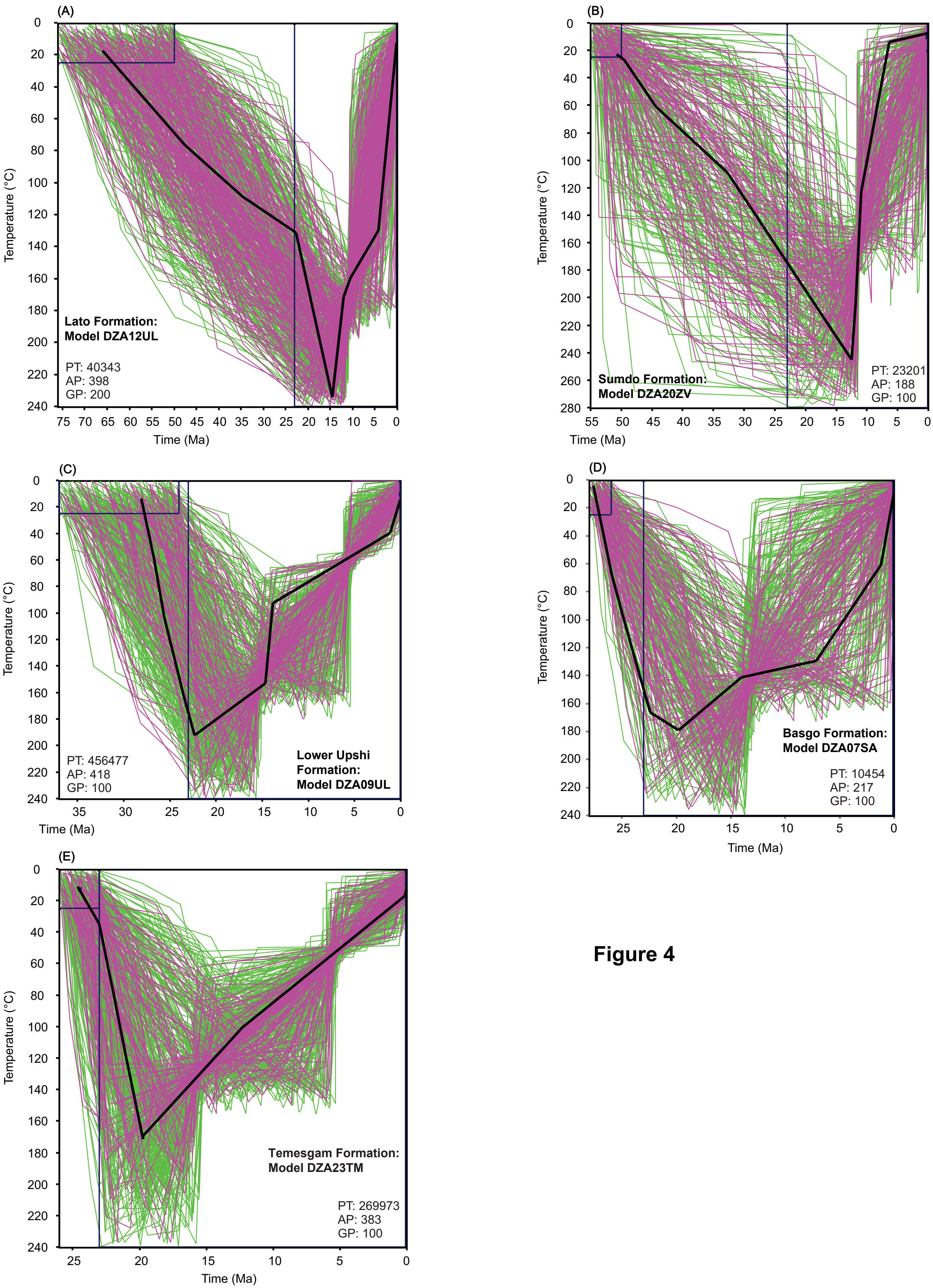

(A)
E 77° 00'
E 77° 10'
Nimu Thrust (?)
Temesgam
DZA23TM
DZA07SA
Likir
Indus R.
Basgo
N 34° 15'
N 34° 10'
10 km
Stratigraphy
Ladakh Batholith
Lower Nimu Fm
Temesgam Fm
Basgo Fm
Nurla Fm
Dras Complex
Temesgam and Basgo sections
(B)
Zanskar Gorge
Indus R.
Nimu Thrust
N 34° 10'
ZG16
DZA17ZV
ZG21
Zanskar R.
ZG30
E 77° 20'
Chokski Thrust
ZG38
ZG42
ZG62
ZG55
DZA20ZV
ZG45
E 77° 15'
1 km
Stratigraphy
Nimu Fm
Chokski Fm
Red sh
Cgl
Nurla Fm
N. Ist Fm
Chogdo Fm
Sumda Fm
Jurutze Fm
(C)
Upshi-Lato section
Nimu Thrust
DZA08UL
Upshi
N 33° 50'
E 77° 45'
DZA09UL
Indus R.
Choksti Thrust
2 km
Lato
DZA12UL
N 33° 40'
Stratigraphy
Alluvium
Ladakh Batholith
Upshi Fm
Umlung Fm
Artsa Fm
Gonmaru La Fm
Rong Fm
Miru Fm
Lato Fm
Lamayuru Complex
Key
Town
Thrust
Syncline
Anticline
Contact unverified
Combined AHe-ZHe Sample
AHe Sample
ZHe Sample
ZFT Sample

Figure 2



(A)
ZFT Results
Depositional Age
M1 Age
M2 Age
M3 Age
M4 Age
Age (Ma)
Upper Nimu (n =45)
Lower Nimu (n = 45)
Upper Chokski (n =60)
Choksti Congl. (n =65)
Nurla (n =17)
Numm. Lst (n = 41)
Chogdo (n = 34)
Jurutze (n = 43)
Lower Indus Group
Tar Group
Upper Indus Group
(B)
Tar Group deposition ends
Late Cretaceous* (not shown)
(U-Th)/He Results
Zircon (U-Th)/He age
Apatite (U-Th)/He age
Depositional age (compiled from previous studies)
Lower Indus Group deposition ends
(local deposition)
Age (Ma)
DZA23TM
DZA07SA
DZA17ZV
DZA20ZV
DZA09UL
DZA08UL
DZA12UL
Temesgam Fm
Basgo Fm
Upper Nimu Fm
Sumdo Fm
Lower Upshi Fm
Lato Fm
Temesgam and Basgo sections
Zanskar Gorge
Upshi-Lato section

Figure 3



(A)
Lato Formation:
Model DZA12UL
PT: 40343
AP: 398
GP: 200
Temperature (°C)
Time (Ma)
(B)
Sumdo Formation:
Model DZA20ZV
PT: 23201
AP: 188
GP: 100
Temperature (°C)
Time (Ma)
(C)
PT: 456477
AP: 418
GP: 100
Lower Upshi
Formation:
Model DZA09UL
Temperature (°C)
Time (Ma)
(D)
Basgo Formation:
Model DZA07SA
PT: 10454
AP: 217
GP: 100
Temperature (°C)
Time (Ma)
(E)
Temesgam Formation:
Model DZA23TM
PT: 269973
AP: 383
GP: 100
Temperature (°C)
Time (Ma)

Figure 4

Table 1: Published stratigraphic schemes compared across the IBSR sections in NW India

Group (Age)		Temesgam and Basgo sections [1]	Zanskar Gorge [2]		Upshi-Lato section [3] (north)	Upshi-Lato section [3] (south)	Composite Indus Group [4]
Indus Group (Early Eocene – Pliocene)	Upper Indus Group (Pliocene)		Upper Nimu Formation (f) [9.5 ± 0.5 Ma]**				Local Pliocene strata (f)
	Lower Indus Group (Early Eocene – Early Miocene)	Temesgam Formation Basgo Formation [~28 Ma]#	Lower Nimu Formation (f) [32.3 ± 0.2 Ma]**		Upper Upshi Formation [24.6 ± 0.1 Ma]**	Rong Formation [50.0 ± 0.2 Ma]**	Temesgam Formation [26.8 ± 0.1 Ma]* Basgo Formation (f)
		(inaccessible)			Lower Upshi Formation (f) [38.3 ± 0.2 Ma]**		Nimu Formation Hemis Formation (f) [37.8 ± 0.2 Ma]*
			Chokste Formation	Upper Chokste Member	Upper Umlung Formation		Chokste Formation (f)
				Middle Chokste Member	Lower Umlung Formation (f)		
				Red Shale Member (f)	Artsa Formation		
				Chokste Conglomerate (f) [41.5 ± 0.2 Ma]*	Gonmaru La Formation (f)		
		Nurla Formation (inaccessible)	Nurla Formation [51.8 ± 0.2 Ma]*		Stratigraphy absent		Nurla Formation (f) [50.7 ± 0.3 Ma]*
Tar Group (Late Cretaceous – Early Eocene)			Nummulitic Limestone [~50 Ma]#		Miru Formation (f) [54.9 ± 0.2 Ma]*		Marine strata
			Chogdo Formation [52.1 ± 0.1 Ma]*				
			Sumdo Formation [~55-51 Ma]#				
			Jurutze Formation (f) [54.7 ± 0.3 Ma]*				
Indian margin (Cretaceous)			Chilling Formation		Lato Formation		

Note: [1] Garzanti and Van Haver (1988), Bajpai et al. (2004), Tripathy-Lang et al. (2013), [2] Wu et al. (2007), Henderson et al. (2010), [3] Henderson et al. (2011), [4] Bhattacharya et al.
Symbols: * - U-Pb detrital zircon maximum depositional age, ** - 40Ar/39Ar detrital muscovite maximum depostional age, # - biostratigraphic age, f - the formation or member has a fault with the unit immediately below or older; bold dashed line indicates unconformity.
Maximum depositional ages are YC2σ(3+) ages, which is the weighted average of youngest 3 or more grain ages with overlapping 2σ uncertainties. All uncertainties are reported at 1σ uncertainty level.

Table 2: Summary of ZFT, ZHe and AHe ages from Zanskar Gorge, Upshi-Lato, Basgo and Temesgam sections

Section	Group	Formation	Member	Maximum Depositional Ages (Ma)			Fossil Age (Ma)	Thermochronometric Ages (Ma)			Interpretation
				YSG	YC1σ(2+)	YC2σ(3+)		ZFT Modes	ZHe Range	AHe Range	
Zanskar Gorge	upper Indus	Upper Nimu		DM: 6.1 ± 2.3	6.7 ± 1.5	**9.5 ± 0.5**		M1: 40.2 ± 3.1 M2: 62.7 ± 3.5 (ZG16)	17.39 ± 0.35 - 13.70 ± 0.27 (DZA17ZV)		Unreset w.r.t ZFT and ZHe
	lower Indus	Lower Nimu		DM: 23.7 ± 0.2	32.3 ± 0.2	**32.3 ± 0.2**		M1: 25.5 ± 3.1 M2: 38.5 ± 2.7 M3: 53.8 ± 5.8 (ZG21)			Partially reset w.r.t ZFT
		Choksti	Upper Choksti*	DZ: 36.8 ± 0.6 (H) DM: 37.6 ± 0.4 (LU)	37.3 ± 0.3 (H) 38.9 ± 0.2 (LU)	**37.8 ± 0.2 (H)** **38.3 ± 0.2 (LU)**		M1: 26.6 ± 2.2 M2: 37.8 ± 3.8 M3: 49.5 ± 4.4 M4: 83 ± 8.4 (ZG30)			Partially reset w.r.t ZFT
			Choksti Conglomerate	DZ: 41.1 ± 0.3	42.0 ± 0.4	**41.5 ± 0.2**		M1: 40.3 ± 2.1 M2: 68.6 ± 4.1 (ZG38)			Partially reset w.r.t ZFT (see text for explanation)
		Nurla		DZ: 51.0 ± 0.5 DZ: 49.5 ± 0.7 (EL)**	51.5 ± 0.2 50.2 ± 0.4 (EL)	**51.8 ± 0.2** **50.7 ± 0.3 (EL)**		M1: 50.3 ± 3.3 (ZG42)			Partially reset w.r.t ZFT
	Tar	Nummulitic Limestone		DZ: 52.5 ± 0.4	89.6 ± 0.3	90.2 ± 0.2	**~50**	M1: 27.8 ± 3.5 M2: 62.6 ± 4.4 M3: 91.1 ± 5.5 (ZG62)			Partially reset w.r.t ZFT (see text for explanation)
		Chogdo		DZ: 50.8 ± 0.5	51.3 ± 0.3	**52.1 ± 0.1**		M1: 22.5 ± 2 M2: 40.3 ± 3 M3: 63.8 ± 6.4 (ZG55)			Partially reset w.r.t ZFT
		Sumdo					**~55–51**		15.42 ± 0.20 - 8.57 ± 0.11 (DZA20ZV)		Reset w.r.t ZHe
		Jurutze		DZ: 53.4 ± 0.7	53.7 ± 0.5	**54.7 ± 0.3**		M1: 65.2 ± 3.1 (ZG45)			Partially reset w.r.t ZFT (see text for explanation)
Upshi-Lato	lower Indus	Upper Upshi		DM: 24.4 ± 0.2	24.4 ± 0.2	**24.6 ± 0.1**					
		Lower Upshi		DM: 37.6 ± 0.4	38.9 ± 0.2	**38.3 ± 0.2**			17.79 ± 0.26 - 13.63 ± 0.21 (DZA09UL)	6.56 ± 0.10 - 5.22 ± 0.30 (DZA08UL)	Reset w.r.t ZHe and AHe
		Umlung/Artsa/ Gonmaru La									
	Tar	Miru		DZ: 54.3 ± 0.4	54.7 ± 0.2	**54.9 ± 0.2**					
	Indian margin unit	Lato		DZ: 51.1 ± 0.4 DM: 67.2 ± 1.13 DZ***: 159.2 ± 2.0 (CF)	481.0 ± 2.5 375.8 ± 1.0 451.6 ± 3.9 (CF)	484.3 ± 1.7 376.3 ± 1.0 456.4 ± 3.4 (CF)			12.62 ± 0.26 - 10.05 ± 0.20 (DZA12UL)		Reset w.r.t ZHe
Basgo and Temesgam	lower Indus	Temesgam		DZ: 26.2 ± 0.5	26.7 ± 0.1	**26.8 ± 0.1**			18.91 ± 0.52 - 12.81 ± 0.18 (DZA23TM)	6.77 ± 0.40 - 3.94 ± 0.17 (DZA23TM)	Reset w.r.t ZHe and AHe
		Basgo		DZ: 27.2 ± 0.5	52.6 ± 0.2	53.4 ± 0.1	**~28-26**		19.04 ± 0.54 - 9.90 ± 0.27 (DZA07SA)		Reset w.r.t ZHe

Note: Maximum depositional ages and fossil ages are compiled from Bajpai (2004), Green et al. (2008), Wu et al. (2007), Henderson et al. (2010, 2011), and Bhattacharya et al. (2020). Youngest cluster ages, i.e., YC1σ(2+) and YC2σ(3+), if unreported in previous studies, were recalculated using detritalPy (Sharman et al., 2018). Details about the methods of maximum depositional age recalculation can be found in Dickinson and Gehrels, (2009).
For thermochronometric interpretations, if fossil ages (bold) are unavailable for a formation, we consider the corresponding YC2σ(3+) age (bold), which is the most conservative estimate of maximum depositional age (Coutts et al., 2019).
Abbreviations: YSG - youngest single grain, YC1σ(2+) - weighted mean age of youngest cluster of at least 2 ages with overlapping 1σ uncertainties, YC2σ(3+) - weighted mean age of youngest cluster of at least 3 ages with with overlapping 2σ uncertainties, DZ - detrital zircon maximum depositional age, DM - detrital muscovite maximum depositional age, w.r.t - with respect to.
*Upper Choksti Member is correlatable with the Hemis (H) and Lower Upshi (LU) Formations, and the corresponding maximum depositional ages are provided (Henderson et al., 2011; Bhattacharya et al., 2020).
**(EL) indicates the maximum depositional ages of the Nurla Formation from eastern Ladakh.
**Lato Formation is also correlatable to the Indian plate Chilling Formation (CF) whose maximum depositional ages are provided (Henderson et al., 2011).

Table 2. Summary of ZFT, ZHe and AHe ages from Zanskar Gorge, Upshi-Lato, Basgo and Temesgam sections. Depositional ages were compiled from stratigraphic works of Bajpai et al. (2004), Green et al. (2008), Wu et al. (2007), Henderson et al. (2010, 2011), Bhattacharya et al. (2020).