Meso-Cenozoic thermo-tectonic evolution of the Yili block within the Central Asian Orogenic Belt (NW China): Insights from apatite fission track thermochronology

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ABSTRACT

The Yili block in the Central Asian Orogenic Belt (CAOB), forms the easternmost part of the Kazakhstan collage system. Exploring its thermo-tectonic history is important to reconstruct the intra-continental evolution of the Tianshan belt. In this contribution, we report new apatite fission track (AFT) data from the basement rocks from the northern (i.e. the Wenquan complex) and southern (i.e. the Dahalajunshan - Nalati range) margins of the Yili block. Thermal history modeling reveals that the Wenquan complex underwent moderate basement cooling in the Cretaceous, possibly due to far-field effects of the Tethys-deformation and the following Lhasa-Qiangtang collision. These events at the southern Eurasian margin propagated tectonic stress to the northern Yili and triggered localized deformation. Early Triassic-middle Jurassic moderate cooling is also identified in the Dahalajunshan - Nalati range, and is interpreted to be related to the post-orogenic strike-slip motion along the major shear zones and the effects of the Qiangtang and Kunlun-Qaidam collision. Combined with the published thermochronological data, it is suggested that the northern and southern parts of the Yili block experienced different Mesozoic thermo-tectonic evolution. Basement cooling of the northern Yili block generally took place before the Cretaceous, exhuming shallower crustal levels as compared with the southern one. The intermontane Yili basin may have accommodated substantial propagated contraction induced by the Cretaceous collisional events. Based on our new results and the previously published thermochronological data, it is suggested that the intra-continental reactivation of the North Tianshan and Nalati faults probably did not invoke significant regional exhumation during the Meso-Cenozoic. Instead, small-scale brittle faults controlled localized enhanced denudation.

1. Introduction

The Central Asian Orogenic Belt (CAOB) is a composite and immense accretionary and collisional orogenic system. It is composed of seamounts, island arcs, accretionary wedges and micro-continents that were assembled due to long-lived subduction and accretionary processes of the Paleo-Asian Ocean since the latest Neoproterozoic (e.g., Jahn, 2004; Kroner et al., 2007, 2014; Windley et al., 2007; Biske and Seltmann, 2010; Xiao et al., 2010, 2018; Wilhem et al., 2012; Wan et al., 2018) (Fig. 1A). During the Mesozoic, the western part of the CAOB (e.g., the prominent Tianshan belt and Altai-Sayan range) underwent several major periods of basement exhumation in response to a series of Cimmerian collisional events affecting the southern Eurasian margin (e.g., accretion/collision of the Qiangtang, Kunlun-Qaidam and Karakoram-Lhasa blocks) (De Grave and Van den Haute, 2002; De Grave et al., 2013, 2014; Glorie et al., 2010, 2011, 2012; Jolivet et al., 2010, 2013; Kääb et al., 2017; Yang et al., 2017). The subsequent collision between the Indian plate and the Eurasian continent in the Cenozoic also invoked lithospheric deformation (e.g., Delvaux et al., 2013) and surface uplift (e.g., Bullen et al., 2001, 2003; Buslov et al., 2007; De Grave et al., 2014).
In the interior of the Tianshan belt. The western CAOB, especially the Tianshan belt that borders the Tarim craton to the south, is therefore an ideal natural laboratory to explore intra-continental evolution of an ancient orogenic belt.

As an important segment of the southwestern CAOB, the Kazakhstan collage system is composed of several continental blocks with Proterozoic basement, Paleozoic continental/island arcs and accretionary wedges (Windley et al., 2007; Biske and Seltmann, 2010; Buslov, 2011; Su et al., 2021). The Yili block forms the wedge-shaped eastern extremity of the Kazakhstan collage system (Figs. 1 and 2) and constitutes a key region in the interior of the Tianshan belt (Wang et al., 2008). It is a continental block with a Precambrian basement (Wang et al., 2008, 2014a; Zhu et al., 2019a), which was vastly intruded by Paleozoic subduction-related plutons (Wang et al., 2006, 2009a; Cao et al., 2017; Zhong et al., 2017; Su et al., 2018). In the Mesozo-Cenozoic, the Yili basement underwent regional exhumation (Chen et al., 2006; Jolivet et al., 2010). Geographically, the Cenozoic Yili basin covers the center of this block, with elevation and relief rising stepwise towards the Keguqin mountain to the north and the Nalati range to the south (Fig. 1 B and C). Compared to the neighboring South Tianshan, the Yili block is generally characterized by a lower mean elevation (< ~3 km). Therefore, the thermochronological signal of this area is unlikely to record significant Cenozoic deformation of the Tianshan belt, but is expected to preserve Mesozoic or earlier cooling events. In this regard, it is of great importance to study the thermal history of the Yili block as it may open a window for exploring early-stage thermo-tectonic events of the Tianshan belt. A substantial amount of thermochronological data have previously been obtained from the easternmost Yili block, along the Dushanzhi-Kuche (Du-Ku) road (e.g., Dumitrul et al., 2001; Du and Wang, 2007; Jolivet et al., 2010; Yu et al., 2014; Yin et al., 2018; Zhao et al., 2020). However, this section is narrow and thus not representative for the thermal history of the entire Yili block (Fig. 2). In addition, a previous data set has been published from the epithermal deposits in the Tulasu basin (e.g., Wang et al., 2021a; Zhao et al., 2021), but the reported ages only revolved around the localized ore deposits without wider regional significance. Lastly, Glorie et al. (2019) reported limited data from near the lithospheric-scale North Tianshan fault, however, this study was largely focused on the neighboring Junggar Alatau in Kazakhstan and inconclusive on the timing of fault reactivations in the Yili block.

Consequently, additional thermochronological studies are in need to give a more complete and clear picture of the post-orogenic thermo-tectonic evolution of the Yili block. Here we focus on the thermal histories of two Neoproterozoic metamorphic complexes (i.e. the Wenquan and the Dahalajunshan complex) located near the northern and southern margins of the Yili block (Fig. 2), which hitherto have not been studied by low-temperature thermochronology. We apply the apatite fission track (AFT) method that is sensitive to near-surface (<2–4 km) deformation and erosion processes (e.g., Green et al., 1986; Wagner and Van den Haute, 1992). The first part of this study presents new AFT ages and inverse modeling results. Then combined with the published data, a systematic thermochronological overview for the Yili block is discussed. Finally, we try to develop a more updated thermal history of the entire Tianshan belt regarding the reactivation of major inherited structures.

2. Geological background

2.1. Tectonic architecture of the Chinese Tianshan belt

The Tianshan belt is located in the southwestern CAOB and separates the Tarim craton in the south from the Junggar terrane to the north (Fig. 1A; Gao et al., 1998; Charvet et al., 2007; Wang et al., 2008; Xiao et al., 2013). It extends from east to west across the Xinjiang province (NW China) to the Central Asian countries (Fig. 1B). The ancestral Tianshan was built by multi-stage Paleozoic subduction of the Paleo-Tianshan Ocean and subsequent collision between the Kazakhstan collage system and the Tarim craton (Allen et al., 1992; Gao et al., 2009, 2011; Wang et al., 2011a, 2018a). Within the Chinese territory, the

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Fig. 1. (A) Tectonic sketch map of Eurasia showing the location of the Central Asian Orogenic Belt (modified from Sengor et al., 1993). (B) Simplified topographic map of the Tianshan belt and adjacent areas, showing main tectonic units and major faults. The black dotted rectangle shows the locality of the study area under investigation in this work. (C) Topographic profile generated from 90-m resolution SRTMDEM across the Yili block. Abbreviations: Bay. – Bayinbuluk; R. – range; S. – shan (mountain); CT – Central Tianshan; NT – North Tianshan; ST – South Tianshan; WJ – Western Junggar; YB – Yili block; BF – Baluntai fault; CKF – Central Kazakhstan fault; DF – Dalabute fault; MTSZ – Main Tianshan shear zone; NF – Nalati fault; NTF – North Tianshan fault; WTF – Wusun trust fault.
The Tianshan belt is geologically subdivided into four tectonic units from north to south: (1) the North Tianshan; (2) the Yili block; (3) the Central Tianshan; and (4) the South Tianshan (Fig. 1B; Wang et al., 2008; Lin et al., 2009; Charvet et al., 2011; Zhong et al., 2015). The North Tianshan is interpreted as a late Paleozoic accretionary complex related with the subduction of the Junggar oceanic plate (e.g., Wang et al., 2006; Han et al., 2010; Li et al., 2015a, 2015b). The South Tianshan mainly comprises Paleozoic sedimentary and volcaniclastic sequences, arc-related intrusions and ophiolitic melanges formed by the consumption of the back-arc basins (e.g., Gao et al., 2009; Wang et al., 2011a, 2018a; Alexeiev et al., 2015; Zhong et al., 2017, 2019). The North Tianshan and contiguous Central Tianshan have Precambrian metamorphic basements (Wang et al., 2014a, 2017; He et al., 2015, 2018; Zhu et al., 2019a), they amalgamated to form a continental ribbon along the Terskey Ocean and Paleo-Tianshan Ocean sutures in the early Paleozoic (e.g., Qian et al., 2009; Han et al., 2015). These tectonic units are separated by several suture zones and large-scale shear zones, including the North Tianshan, Nalati and Baluntai faults and the Main Tianshan shear zone (Fig. 1B; Shu et al., 2002; Laurent-Charvet et al., 2003; Charvet et al., 2011; Wang et al., 2018a; He et al., 2021a).

2.2. Pre-Mesozoic basement of the Yili block

As mentioned earlier, the Yili block is a continental block that forms the easternmost part of the Kazakhstan collage system and is superimposed by Paleozoic arcs (Gao et al., 1998; Wang et al., 2008; Charvet et al., 2011; An et al., 2017; Cao et al., 2017). Precambrian basement rocks of the Yili block are mainly distributed in the Dahalajunshan-Qiongkusitai areas on its southern margin (XBGMR (Xinjiang Bureau of Geology and Mineral Resources), 1993; Huang et al., 2019; Xiong et al., 2019), and the Wenquan-Sayram regions on its northern margin (Chen et al., 1999; Hu et al., 2000; Liu et al., 2011; Wang et al., 2014a; Wang et al., 2014b). These Precambrian basement rocks mainly consist of Mesozoic-Neoproterozoic orthogneiss and metasedimentary rocks, overlain by late Neoproterozoic non-metamorphic and undeformed limestones, siltstones and tillites (XBGMR (Xinjiang Bureau of Geology and Mineral Resources), 1993; Hu et al., 2006, 2010; Wang et al., 2014a). In the northern part of the Yili block, Precambrian
rocks were unconformably overlain by, or in fault contact with Cambrian to Silurian marine sequences (XBGMR (Xinjiang Bureau of Geology and Mineral Resources), 1988a; Wang et al., 2008, 2014a, 2014b). Minor early Paleozoic strata and plutonic rocks also occur in the southern Yili block (Gao et al., 2009; Long et al., 2011; Xu et al., 2013; Zhong et al., 2017). Some of these were affected by greenschist-facies metamorphism (XBGMR (Xinjiang Bureau of Geology and Mineral Resources), 1993). Carboniferous volcanic rocks are widespread within the Yili block and have local thicknesses of >3 km, their formation is considered to be related with the closure of the Paleo-Tianshan and Junggar Oceans (Wang et al., 2006, 2007a; Zhu et al., 2009; Cao et al., 2017; Su et al., 2018, 2021).

2.3. Intra-continental deformation of the Yili block

Following the closure of the Paleo-Tianshan and Junggar oceanic basins in the late Carboniferous (e.g., Han and Zhao, 2018; and the references therein), the Yili block was reworked until the earliest Triassic by the activity of prominent strike-slip faults developed along its margins (Zhou et al., 2001; de Jong et al., 2009; Wang et al., 2009a, 2010; Zhong et al., 2017, 2019; Liu et al., 2021). Based on paleomagnetic data, it is suggested that significant relative movement between the Yili block, Tarim craton and Junggar terrane took place along these major strike-slip faults, resulting in hundreds of kilometers’ displacement during the late Paleozoic (e.g., Wang et al., 2007b; Zhu et al., 2018, 2019b). The Meso-Cenozoic history of this continental block was subsequently dominated by reactivation caused by collision and

![Fig. 3. Simplified geological map of the northern Wenquan complex based on XBGMR (Xinjiang Bureau of Geology and Mineral Resources) (1988b). The location of our sample sites and the newly obtained apatite fission track ages are indicated.](image-url)
amalgamation of continental and arc fragments along the southern margin of Eurasia (e.g., Jolivet et al., 2013; Jolivet, 2017). These major tectonic events in the south include the Cimmerian orogeny related with the closure of Paleo- and Meso-Tethys Oceans, and the Cenozoic India-Eurasia collision following the closure of the Neo-Tethys Ocean (e.g., Şengör and Natal'in, 1996; Yin and Harrison, 2000; Glorie and De Grave, 2016). According to published thermochronological data from the northern sections of the Yili block, moderate to rapid basement cooling of the Keguqin mountain (Fig. 2) occurred during the Permian and Triassic (Wang et al., 2018b; Glorie et al., 2019). The associated denudation and erosion provided the surrounding areas with abundant sediment supply. For example, in the Tulasu basin, these sediments reach a thickness of ca. 4 km (e.g., Wang et al., 2021a). Along the Wusun mountain (Fig. 2), mainly Cretaceous AFT ages were obtained, and latest Jurassic-early Cretaceous rapid cooling has been documented (Chen et al., 2006; Han et al., 2008; Wang et al., 2018b). To the south, Jurassic basement cooling was reported for the Nalati range (Wang et al., 2018b). Due to good road access, a large set of low-temperature thermochronological ages were reported from the Du-Ku road that cuts through the easternmost Yili block (Fig. 2). These data revealed two main exhumation phases, the first during the Permian-early Jurassic and the second in the late Cretaceous-Paleogene. Younger Neogene cooling ages were also sporadically recognized at some locations and are interpreted to represent the late Cenozoic reactivation of the Tianshan and the CAOB in general (e.g., Dumitru et al., 2001; Jolivet et al., 2010; Yin et al., 2018; Zhao et al., 2020).

3. Samples and methodology

3.1. Sample collection

A total of twelve basement samples were collected from the northern and southern margins of the Yili block (Fig. 2). Four samples were taken from the Proterozoic gneissic granitoids in the Wenquan complex, the other eight were sourced from the Dahalajunshan and the adjoining Narati range (Figs. 3 and 4). Sample details can be found in Table 1.

The Wenquan complex is exposed in the northwestern Yili block and

Table 1

| Sample | Lithology | Latitude ('N) | Longitude ('E) | Elevation (m) |
|--------|-----------|---------------|----------------|---------------|
| W12    | Granite   | 44°56′45″     | 80°37′32″      | 1808          |
| W13    | Migmatite | 44°55′06″     | 80°37′12″      | 2028          |
| W14    | Gneiss    | 44°53′42″     | 80°37′29″      | 2237          |
| W19    | Schist    | 44°53′57″     | 80°37′54″      | 2402          |
| D69    | Granite   | 43°08′27″     | 82°07′17″      | 1841          |
| D70    | Granite   | 43°08′38″     | 82°07′02″      | 2018          |
| D79    | Granite   | 43°10′46″     | 82°15′48″      | 1479          |
| D80    | Granite   | 43°10′05″     | 82°15′08″      | 1723          |
| D81    | Granite   | 43°10′14″     | 82°14′55″      | 1892          |
| D83    | Gneiss    | 43°09′48″     | 82°14′20″      | 2195          |
| N84    | Granite   | 42°54′34″     | 81°59′28″      | 1889          |
| D86    | Granite   | 42°59′48″     | 81°54′42″      | 1269          |

Fig. 4. Simplified geological map of the Dahalajunshan - Nalati range based on XBGMR (Xinjiang Bureau of Geology and Mineral Resources) (1977, 1979). The location of our sample sites and the newly obtained apatite fission track ages are indicated.
The apatite fission track (AFT) method is based on the accumulation of radiation damage in the apatite lattice, resulting from the spontaneous fission decay of $^{238}\text{U}$. AFT age and length data: $n$ is the number of counted grains; $D_{\text{Dr}}$ is an undeformed Carboniferous granite and another coeval granite $N_{84}$ was taken from the northern edge of the complex, sample $W_{12}$ was taken from a leucogranite dyke and the remaining three ($D_{79}$–81 and 83) are from the Neoproterozoic foliated granites, respectively. Collectively, the samples represent a transect spanning ~600 m in elevation (Fig. 3; Table 1; from 1808 to 2402 m).

The Dahalajunshan is located to the north of the Nalati fault (Fig. 2), along this narrow belt, Neoproterozoic granites intruded the Mesoproterozoic meta-sandstone, phyllite, mica schist and marble (e.g., Xiong et al., 2019; Zhu et al., 2019a). Six samples ($D_{69}$–70, 79–81 and 83) from this belt were collected from the Neoproterozoic foliated granites, and four of them ($D_{79}$–81 and 83) make up a vertical profile with elevations from 1479 to 2195 m (Table 1). Sample $D_{86}$ is an undeformed Carboniferous granite and another coeval granite $N_{84}$ was taken from the adjacent Nalati range (Fig. 4).

### 3.2. Methods of apatite fission track thermochronology

The apatite fission track (AFT) method is based on the accumulation of at least 100 confined tracks is therefore suggested to obtain track length distributions are commonly used to determine the cooling paths through the APAZ and thus allow the reconstruction of the time-temperature history of a sample by thermal history modeling (Ketcham et al., 1999, 2007; Gallagher, 2012). Barbarand et al. (2003) found that the mean track length of confined tracks stabilizes between 50 and 120 track measurements, and measurement of at least 100 confined tracks is therefore suggested to obtain restored under the given temperature conditions. The rate of track shortening (also called partial annealing) partly depends on the chemical composition of the apatite (e.g., Gleadow et al., 1986; Green et al., 1986; Barbarand et al., 2003).

Samples were prepared following the standard procedure of the fission track laboratory of Ghent University (e.g., Glorie et al., 2010; De Grave et al., 2011; Nachtergaele et al., 2018). Hereby, apatite grains are etched in a 5.5 mol/L nitric acid solution for 20 s at 21 °C (Donelick, 1993) to reveal the spontaneous or natural tracks for optical microscopic analysis. Samples and inserted U-doped glasses (IRM-540; De Corte et al., 1998) were irradiated with thermal neutrons in the BR1 reactor of the Belgian Nuclear Research Centre (Mol, Belgium), in Channel X26 (De Grave et al., 2010). The AFT analyses were carried out in Nikon NIS-Elements microscopy software on images acquired by the Nikon-TRACKFlow system (Van Ranst et al., 2020). We measured twenty crystals or a minimum of one thousand spontaneous tracks (a.e. ~3%) for each sample (Table 2). Obtained AFT ages were calculated using the overall weighted mean zeta (310.0 ± 2.7 a.cm$^{-2}$; Analyst Z. He) based on multiple Durango (McDowell et al., 2005) and Fish Canyon Tuff (Hurford and Hammerschmidt, 1985) apatite age standards. Both conventional $\zeta$-ages (Hurford and Green, 1983; Hurford, 1990) and central ages (Vermeesch, 2009) are given for all the dated samples.

In addition to AFT ages, track length distributions are commonly used to determine the cooling paths through the APAZ and thus allow the reconstruction of the time-temperature history of a sample by thermal history modeling (Ketcham et al., 1999, 2007; Gallagher, 2012). Barbarand et al. (2003) found that the mean track length of confined tracks stabilizes between 50 and 120 track measurements, and measurement of at least 100 confined tracks is therefore suggested to obtain

### Table 2

Apatite fission track analytical data for the samples from the Yili Block.

| Sample          | No. of Grains (n) | Spontaneous $N_{s}$ | Induced $N_{i}$ | Dosimeter $N_{d}$ | $P_{(2)}$ (%) | Dispersion (%) | Zeta ($\zeta$) (Ma ± 1SE) | Central age (Ma ± 1SE) | Track length and $D_{\text{Dr}}$ |
|----------------|------------------|---------------------|----------------|-----------------|--------------|----------------|----------------------|-------------------|---------------------|
| *Wenquan Complex* |                  |                     |                |                 |              |                |                      |                   |                     |
| $W_{12}$        | 20               | 962                 | 612            | 4.80            | 2866         | 5.62           | 100                  | 0.00              | 113.5 ± 7.5         |
| $W_{13}^*$      | 20               | 969                 | 860            | 4.78            | 2862         | 5.61           | 99                   | 0.00              | 98.5 ± 5.1          |
| $W_{14}^*$      | 20               | 847                 | 575            | 3.44            | 2859         | 5.60           | 98                   | 0.00              | 121.7 ± 7.4         |
| $W_{19}$        | 20               | 1275                | 749            | 6.82            | 2855         | 5.60           | 87                   | 0.33              | 152.0 ± 7.7         |
| *Dahalajunshan - Nalati Range* |          |                     |                |                 |              |                |                      |                   |                     |
| $D_{69}^*$      | 20               | 1236                | 697            | 4.92            | 2852         | 5.59           | 100                  | 0.00              | 152.4 ± 7.9         |
| $D_{70}$        | 20               | 1525                | 734            | 4.70            | 2848         | 5.58           | 100                  | 0.00              | 178.0 ± 8.8         |
| $D_{79}$        | 20               | 307                 | 185            | 1.34            | 2845         | 5.58           | 100                  | 0.00              | 153.5 ± 14.6        |
| $D_{80}$        | 20               | 1176                | 647            | 3.65            | 2841         | 5.57           | 98                   | 0.00              | 159.7 ± 8.5         |
| $D_{81}$        | 20               | 435                 | 198            | 1.47            | 2838         | 5.56           | 100                  | 0.00              | 183.5 ± 16.2        |
| $D_{83}$        | 15               | 2380                | 973            | 12.27           | 2834         | 5.56           | 95                   | 0.00              | 207.5 ± 20.7        |
| $N_{84}^*$      | 20               | 948                 | 684            | 3.42            | 2831         | 5.55           | 100                  | 0.00              | 170.3 ± 10.2        |
| $D_{86}^*$      | 20               | 1777                | 900            | 5.43            | 2827         | 5.54           | 100                  | 0.00              | 167.2 ± 7.7         |

AFT age and length data: $n$ is the number of counted grains; $P_{(2)}$, $P_{(i)}$, and $P_{(d)}$ are the density of spontaneous, induced tracks and induced tracks in an external detector irradiated against a dosimeter glass. The $P_{(2)}$ values are interpolated values from regularly spaced glass dosimeters (IRM-540). $P_{(2)}$, $P_{(i)}$, and $P_{(d)}$ are expressed as $10^5$ tracks/cm$^2$. $N_{s}$, $N_{i}$, and $N_{d}$ are the number of counted spontaneous, induced tracks and induced tracks in the external detector. $N_{s}$ is an interpolated value. $P_{(2)}$ is the chi-squared probability that the dated grains have a constant $P_{(2)}$/$P_{(d)}$ ratio. $\zeta$-value of 310.0 ± 2.7 a.cm$^{-2}$ (analyst Z. He) was used for the calculation of the AFT age ($\zeta$) (in Ma), AFT central ages (in Ma) are also given. AFT length data are reported as a mean track length with standard deviation $\sigma$ (in $\mu$m), obtained from the measurement of a number of natural, horizontal confined tracks. Samples with no reported length data generally yielded less than 10 measurable confined tracks. *Samples benefited from $^{252}$Cf irradiation.
a representative track length population. In this study, we aimed at measuring 120 horizontal confined tracks (both length and angle between track and crystallographic c-axis) where possible (Table 2). In some occasions, $^{252}$Cf irradiation was conducted at The University of Adelaide on samples displaying low spontaneous track densities to increase the number of observable confined tracks (Donelick and Miller, 1991).

Thermal history modeling with QTQt (Gallagher, 2012) was used for the estimation of time-temperature paths. This software applies the Markov-Chain Monte-Carlo approach (Gallagher et al., 2009) to predict a thermal history based on the age and length data. We adopted the annealing model of Ketcham et al. (2007), with $D_{\text{par}}$ as the kinetic parameter. Inverse modeling was conducted on eight samples that produced sufficient numbers (all $>$70, mostly $= 120$) of confined tracks (Table 2). The prior for temperature was set as time = central age $\pm$ central age, temperature $= 70 \pm 70 ^\circ C$. The present surface temperature was set as $15 \pm 10 ^\circ C$, which is realistic for recent climate conditions in the study areas. We first ran the algorithm for 10,000 burn-in and 50,000 post-burn iterations to find the appropriate search parameters, after that 200,000 iterations were run as burn-in and post-burn-in iterations for each modeled sample data set.

![Fig. 5.](image-url)

(A) AFT age-elevation relationship for the northern Wenquan complex. (B) Integrated thermal history models for two samples from the northern Wenquan complex generated in QTQt (Gallagher, 2012) based on AFT data. Confined fission track length distributions for each sample are shown.
4. Results

4.1. Results from apatite fission track analysis

The analytical results are summarized in Table 2. All dated twelve samples passed the $\chi^2$ test of homogeneity, indicating that the single-grain ages belong to a statistically single population (Galbraith and Green, 1990; Green, 1981). Zeta-ages $\zeta(t)$ are used in the following discussion. Radial plots generated by IsoplotR (Vermeesch, 2018) for each basement sample are presented in Supplementary Information 1.

4.1.1. Wenquan complex

From the Wenquan complex, four samples yield latest Jurassic–Cretaceous AFT ages ranging from $152 \pm 8$ Ma to $99 \pm 5$ Ma (Table 2). Except for sample W12, the age-elevation relationships for these samples displays a normal trend (i.e. samples with higher elevations exhibit older AFT apparent ages) (Fig. 5A). As sample W12 was taken close to a fault, its AFT age might be offset with respect to the other samples (Fig. 3). However, considering that the slope of an age-elevation curve usually does not represent the true exhumation rate (e.g., Braun, 2002; Valla et al., 2010; Fitzgerald and Malusà, 2019), the slope and regression coefficient ($R^2$) given by the age-elevation relationships (Fig. 5A) are for reference only and will not be discussed in function of absolute cooling and exhumation rates. After $^{252}$Cf irradiation, samples W13 and 14 were found to have $>70$ confined tracks with mean track lengths of $\sim 12.6 \mu$m and $\sim 12.5 \mu$m, respectively. Due to a small number of apatite grains, samples W12 and 19, however, exhibit insufficient numbers of confined tracks ($<15$), and their mean values are only listed for reference and comparison (Table 2).

4.1.2. Dahalajunshan - Nalati range

Samples taken from the Dahalajunshan and Nalati range dominantly...
display Jurassic AFT ages (Fig. 4). Four granitic samples (D79–81 and 83) from the northern Dahalajunshan constitute a vertical profile spanning ~700 m of elevation (Table 1), and yield AFT ages from 208 ± 9 Ma to 154 ± 15 Ma (Table 2). The age-elevation diagram shows a clear and positive correlation (Fig. 6A). As mentioned above, slope usually over/underestimates rates of exhumation due to topographic effects, the estimated exhumation rate given by the age-elevation plot is also for reference only (Fig. 6A). Two samples (D80 and 83) from this profile yielded 120 confined tracks with comparable mean track lengths of ~12.3 μm and ~12.2 μm, respectively (Table 2), indicating clear signals of track shortening within the APAZ. The remaining three samples from the central and southern Dahalajunshan show similar Jurassic AFT ages of ~178–152 Ma, and sample N84 from the adjoining Nalati range also displays an apparent Jurassic AFT age of ~170 Ma (Fig. 4). They all yield sufficient (=120) measurable confined tracks (Table 2) for thermal history modeling.

4.2. Results from thermal history modeling

All samples that yield adequate (> 70) numbers of confined tracks were withheld for thermal history modeling. The expected time-temperature paths generated by QTQt (Gallagher, 2012) are shown in Figs. 5-7, full thermal history data for each sample are presented in Supplementary Information 2. It needs to be pointed out that several modeling results indicate late Cenozoic ‘re-heating’ and ‘accelerated cooling’ phases. This is often a modeling artifact that occurs as the program would require a late ‘cooling event’ to bridge the gap between the present-day surface temperature and considerable higher temperature required by the model for the observed amount of annealing (e.g., Ketcham et al., 1999). Without additional and independent geological evidence, these parts of the thermal history model are geologically meaningless and will not be discussed. In addition, for a more quantitative interpretation, we define and qualify rates (in our study area’s intra-continental context) of <0.5 °C/Ma, ~0.5–2 °C/Ma and >2 °C/Ma as slow, moderate and rapid cooling, respectively, based on empirical values.

4.2.1. Wenquan complex

For the Wenquan complex, samples W13, 14 and 19 are situated within a single fault wall bordered by two brittle thrust faults (Fig. 3) and their thermal histories can thus be derived by an integrated modeling. AFT data of samples W13 and 14 were used as they yield sufficient (>70) numbers of confined tracks. The expected models provided by the QTQt record evident Cretaceous cooling pulse, the samples cooled through the APAZ in the early Cretaceous (~150–110 Ma) at a rate of ~1.25 °C/Ma, followed by moderate cooling until the early Paleogene (Fig. 5B). The subsequent ‘re-heating’ and the late Cenozoic ‘enhanced cooling’ that quickly brought the sample to near the surface, however, are clearly outside the APAZ temperatures and considered to be a modeling artifact as indicated above.

Fig. 7. Thermal history models for four samples from the Dahalajunshan and Nalati range generated in QTQt (Gallagher, 2012) based on our new AFT data. Confined AFT length distributions for each sample are shown.
4.2.2. Dahalajunshan - Nalati range

Similar as for the Wenquan complex, based on the positive age-elevation relationships of the northern Dahalajunshan profile without evidence of intermittent faults in the horizontal tract of the profile (Fig. 4), the thermal history of this vertical profile was reconstructed by integrating AFT data of samples D80 and 83. The integrated modeling results reveal a multi-stage cooling history with moderate cooling during the early-middle Triassic, and subsequent slow cooling until the late Cenozoic (Fig. 6B). In the central and southern Dahalajunshan and Nalati range, the modeled four samples display highly comparable Cenozoic (Fig. 6B). In the central and southern Dahalajunshan and Nalati range, the modeled four samples display highly comparable cooling paths. Samples D70 and N84 cooled through the APAZ (< 60 °C) in the earliest Jurassic, followed by very limited exhumation since the Jurassic (Fig. 7). Although the cooling curve of sample D69 initiated high up in the APAZ, it predicts the occurrence of protracted slow cooling episode since the late Jurassic. Similarly, moderate cooling is also observed to have occurred in the Jurassic for sample D86, followed by a Cretaceous-Cenozoic slow cooling phase (Fig. 7).

5. Interpretations and discussion

5.1. Thermochronological interpretations

The studied sections cover two key areas in the northern and southern margins of the Yili block where old basement rocks are exposed (Fig. 2). Over the geographic extent, the acquired AFT ages generally show a younger trend from south to north. More specifically, four samples from the Wenquan complex display Cretaceous ages, while Jurassic ages are more abundant in the Dahalajunshan and Nalati range (Table 2). In addition, the thermal history modeling reveals that these two regions underwent quite different Mesozoic cooling phases. As the final closure of the Paleo-Tianshan Ocean and several associated back-arc basins took place in the latest Carboniferous (e.g., Han and Zhao, 2018; Wang et al., 2011a, 2018a, 2018c), the Mesozoic cooling events in the Yili block must have occurred in an intra-continental setting.

As illustrated by the temperature-time paths, the modeled two samples from the Wenquan complex recorded clear moderate cooling phase during the Cretaceous (Fig. 5B). This latest cooling pulse brought the sampled rocks to temperatures at near-surface levels. It is noted that sample W12 does not fit the linear relationship between the AFT age and elevation for this sampling profile (Fig. 5A). Considering that several subordinate near-E-W-striking faults crosscut the northern Wenquan complex (Fig. 3), the activity of these intermittent faults probably has resulted in differential exhumation of this region, and sample W12 thus may display a distinct different thermal history compared to the other three.

Enhanced basement cooling in the Cretaceous has been widely recognized throughout the entire Tianshan belt, including the Talas-Fergana region (Nachtergaele et al., 2018), the Issyk-Kul and Song-Kul regions (De Grave et al., 2011, 2013), the trans-Ilı-Balkhash (De Pelsmaeker et al., 2015), the central Chinese Tianshan (Dumitru et al., 2001; Wang et al., 2009b), the Balkun-Harlik range (Gillespie et al., 2017a; He et al., 2022) and the Beishan belt (Gillespie et al., 2017b) from west to east. Some previous interpretations relate this cooling event to the late Jurassic to mid-Cretaceous Lhasa and Qiangtang micro-continents collision in the south (e.g., Yin and Harrison, 2000). However, in recent years a growing number of studies suggested that the ‘hard’ collision between the Lhasa and Qiangtang blocks occurred no prior to ~130–120 Ma based on structural (Kapp et al., 2007), sedimentary (Lai et al., 2019; Li et al., 2020a), palaeomagnetic (Li et al., 2016; Biao et al., 2017) and geochemical-geochronological (Zhu et al., 2016) evidence. In addition, the distinct effects in a compressional regime usually result in surface uplift, an erosion process is then needed to create exhumation and renew the thermochronological clocks (e.g., Glorie and De Grave, 2016). Hence, a distinct time-lag (up to several tens of million years delay) is often observed between the timing of a distant continental collision and the timing of onset of intra-continental cooling. As a result, the early Cretaceous cooling pulse occurring along the Tianshan belt might not (solely) be induced by the far-field effects associated with the Lhasa-Qiangtang collision. Alternatively, the late Jurassic-early Cretaceous moderate cooling phases could be interrelated with the contemporaneous closure of the Meso-Tethys Ocean (e.g., Yan et al., 2016; Zahirovic et al., 2016). In this case, the regional contraction caused by northward low-angle subduction of the Meso-Tethys oceanic plate (Chapman et al., 2018a, 2018b) was able to trigger earlier (i.e. late Jurassic-early Cretaceous) faults reactivation and reveal contemporary thermochronological indicators (e.g., He et al., 2022). Moreover, a compressional setting within the Yili block is also supported by structural evidence, such as the occurrence of large-scale thrust faults (e.g., the Wusun thrust fault) (Figs. 1 and 2). As accelerated cooling of the studied profile initiated in the earliest Cretaceous (~150 Ma; Fig. 5b), we thus favor the interpretation that distant effects triggered by the Tethys-deformation and the subsequent collisional effects (e.g., Lhasa-Qiangtang collision) led to localized (i.e. the northern Wenquan complex) Cretaceous cooling pulse in the northern margin of the Yili block.

For the Dahalajunshan and Nalati range in the south, thermal history modeling results for the vertical profile and two single basement rocks (D70 and N84) indicate moderate Triassic cooling (Figs. 6B and 7). This process brought the rocks to the shallow crust (< 60–80 °C) in the early Mesozoic with very limited basement exhumation in the following ca. 200 Ma. These samples were collected from near the prominent Nalati strike-slip fault (Figs. 2 and 4). The Nalati fault is a shear zone that reworked the Carboniferous suture zone formed by the closure of the Paleo-Tianshan Ocean (e.g., Lin et al., 2009; Wang et al., 2009a, 2010; Zhong et al., 2019). Its dextral motion occurred in the Permain (~285–245 Ma based on mica 40Ar/39Ar data (Zhou et al., 2001; Wang et al., 2007c; de Jong et al., 2009)). Subsequently, less intensive fault activity may have still persisted for a period of time after the closure of mica Argon system (~450–350 °C), resulting in continuous denudation. In view of the fact that there was no coeval distant major tectonic event providing far-reaching deformation, the early Triassic cooling phase in the Dahalajunshan and Nalati range was likely to be related with the N-S-directed compression generated by transpressional deformation along the Nalati fault.

The late Triassic-Jurassic moderate cooling is exhibited by the cooling curve of sample D86 (Fig. 7). Although the cooling path of D69 started at the upper APAZ, its shape predicts a similar cooling history compared with that of D86 (Fig. 7). In the late Triassic-early Jurassic, renewed tectonic activity in response to the Qiangtang and Kunlun-Qidam accretions along the southern Eurasian margin was well documented across the Tianshan belt by thermochronological data (De Grave et al., 2011; Jepson et al., 2018; Glorie et al., 2019), and in the sedimentary record (containing coeval coarse clastic sediments including conglomerates) (Hendrix et al., 1992; Vincent and Allen, 2001; Wang et al., 2021b).

5.2. Thermo-tectonic history of the Yili block

Recent studies have demonstrated the occurrence of several early Paleozoic suture zones in the western Kazakhstan collage system (e.g., Windley et al., 2007; Alexeev et al., 2011; Konopelko et al., 2012; Kroner et al., 2012), they may extend eastwards into the Yili block but are covered by the overlying Cenozoic sediments (i.e. the Yili basin; Fig. 2) (Wang et al., 2014b). The Yili Basin is an intramontane basin that formed in the Mesozoic based on the widespread Jurassic sandstones exposed along its margins (Fig. 2; XBGMR (Xi’anxiang Bureau of Geology and Mineral Resources), 1993), and accumulated sediments through most of the Cenozoic. It is hence an important Mesozo-Cenozoic feature in the intra-continental evolution of the area, but obscures the underlying basement architecture. Therefore, the northern (i.e. Wenquan complex - Keguqin mountain - Boroboro range) and southern (Wusun mountain - Dahalajunshan - Nalati range) parts of the Yili block may have different pre-Mesozoic basement origins. Hence, in the following we separately...
discuss the thermo-tectonic histories of the northern and southern Yili block.

Thermal history modeling reported here and available published results reveal that the southern Yili block underwent continuous exhumation during the Mesozoic. In the Dahalajunshan, moderate to slightly rapid basement cooling took place during the Triassic-middle Jurassic (Figs. 6 and 7), corresponding to early Mesozoic deformation. Along the neighboring Nalati range, Wang et al. (2018b) identified successive early Jurassic to early Cretaceous accelerated cooling phases based on AFT analyses. Further, the Wusun mountain also recorded late Jurassic to late Cretaceous intensive exhumation (Chen et al., 2006; Han et al., 2008). These cooling events lasted until ca. 80 Ma, indicating that the Cretaceous Lhasa-Qiangtang collision and subsequent Kohistan-Dras arc collision (~90–70 Ma; Rehman et al., 2011) might have produced significant far-field intra-continental deformation in this area. It is thus observed that in the Mesozoic, the southern Yili block showed continuous responses to the post-orogenic convergence and a series of accretion/collision events along the southern Eurasian margin.

In comparison, a large number of thermochronological studies revealed that the northern Yili block preserves comparably older cooling episodes since the late Paleozoic. Near the North Tianshan fault, Glorie et al. (2019) recognized Triassic fast cooling and interpreted it to be a record of the accretion of the Qiangtang block in the south. In the southern Wenquan complex, these authors identified Carboniferous-Permian rapid cooling and Triassic-middle Jurassic moderate cooling phases (Fig. 4 in Glorie et al., 2019), indicative of Paleozoic-early Mesozoic thermal events. Early Mesozoic cooling events also occurred in the Tulasu basin (Wang et al., 2021a; Zhao et al., 2021) and Keguqin mountain (Wang et al., 2018b; Glorie et al., 2019). All the published data imply that no Cretaceous nor later large-scale regional exhumation occurred in the northern Yili block. The lack of younger exhumation in this area also accounts for the preservation of several epithermal deposits there (e.g., Wang et al., 2018b, 2021a; Zhao et al., 2021). Our AFT analyses document that Cretaceous enhanced cooling did take place locally in the northern Wenquan complex (Fig. 5B). However, this exhumation is quite localized and was controlled by the activity of small-scale brittle faults as discussed above.

In order to better reflect the differential thermo-tectonic histories inside the Yili block, we compiled the literature data (published both in English and Chinese) and our newly obtained AFT ages, as well as mean track lengths by using a boomerang plot (Fig. 8). This distinctive distribution of data is generally interpreted to imply that the samples experienced coeval cooling at a range of paleo-depths, samples with short mean track length usually have resided in the APAZ for quite a long period before cooling to above the APAZ (Green et al., 1986; Gallagher et al., 1998; Hendriks et al., 2007). The compiled data from the southern and northern Yili block are indicated by yellow and red boxes, respectively, and reveal two different ‘boomerang blades’ (increase in mean track lengths) (Fig. 8). For the northern Yili block, the mean track lengths are characterized by relatively higher values in the early Jurassic, indicating more rapid cooling rates during this period. This boomerang blade is generally coincident with the Qiangtang and Kunlun-Qidam collision, implying that the northern Yili responded to this distant tectonic event. Whereas the plotting for the southern Yili block exhibits a younger boomerang trend in the late Cretaceous (~90 Ma), coinciding with the timing of the Lhasa-Qiangtang collision and the subsequent Kohistan-Dras arc collision (Fig. 8). Therefore, compared with the southern Yili block, the northern Yili is characterized by an older boomerang blade in the Mesozoic time. This implies that the northern Yili block probably did not experience significant regional exhumation since the late Jurassic and shows lower-level crust exposure. As a result, the AFT boomerang plot patterns are generally in agreement with the conclusion derived from the inverse thermal history modeling that the northern Yili was less exhumed than the southern Yili block.

Hence, the northern and southern parts of the Yili block display different thermo-tectonic histories, as the basement rocks in the northern Yili only suffered limited exhumation corresponding to the Cretaceous tectonic events from the south. We suggest that the possible
hidden boundary faults below the Cenozoic cover of Yili basin (Figs. 1B and 2) should have played an important role in controlling the intra-continental deformation, they might have largely accommodated the horizontal crustal shortening induced by the far-field effects during the Cretaceous so that the northern Yili block experienced quite limited regional exhumation with respect to the southern Yili.

5.3. Implication for intra-continental evolution of the Tianshan belt

In this section we aim to integrate the thermo-tectonic history of the Yili block into the greater Tianshan belt’s intra-continental evolution. In this study, new thermochronological results obtained for the Dahalajunshan - Nalati range reveal Triassic enhanced cooling (Figs. 6B and 7), similar early Mesozoic cooling episodes have also been reported from the western segment of the Tianshan belt. In the westernmost Tianshan, rapid (> ~5–7 °C/Ma) Triassic-early Jurassic (~225–190 Ma) cooling was for example recognized in the Chatkal-Kurama Terrane (Uzbekistan-Tajikistan) (Jepson et al., 2018). Along the Karatuu-Talas range (Kazakhstan-Kyrgyzstan), these authors recently reported a similar phase of prominent uplift controlled by reactivation of the Talas-Fergana fault (occurring at ~230–190 Ma ago, followed by moderate to slow cooling until the present) (Jepson et al., 2021). On the Song-Kul plateau in the Kyrgyz Tianshan, De Grave et al. (2011) documented late Triassic-early Jurassic (~230–180 Ma) enhanced basement denudation using tinate and apatite FT thermochronology. From the Junggar Alatau domain in SE Kazakhstan and NW China, Glorie et al. (2019) identified late Triassic (~230–210 Ma) rapid basement cooling based on apatite-U-Pb and FT data as well. Therefore, late Triassic-early Jurassic tectonic reactivation, recorded in low-temperature thermochronology, is well documented in various parts of the Tianshan, and is generally considered to be related to the collision of the Qiangtang block with the Eurasian margin as indicated above. However, compared with this extensive basement cooling event in the Tianshan belt and neighboring regions, preserved signals from early to middle Triassic (~250–230 Ma) thermo-tectonic events (as in the case of the Dahalajunshan profile in this study) are scarce or lacking.

Regarding the Tianshan belt, the mechanism for early Triassic exhumation remains unclear. On the one hand, a large number of studies have demonstrated that the final amalgamation of the Tianshan and Junggar orogenic belt occurred at the late Carboniferous with no Permian or Triassic subduction-accretion events (e.g., Han and Zhao, 2018; Wang et al., 2018a, 2018c; Alexeiev et al., 2019), hence, the Triassic regional cooling was not related with the closure of a certain ancient ocean with an ensuing accretionary orogey in the southern CAOB. On the other hand, the large-scale strike-slip faults (e.g., Karatuu - Talas - Fergana fault; North Tianshan fault - Main Tianshan shear zone; Abatasi - Nalati fault; Baluntai fault) along the Tianshan belt were considered active during the Permian and earliest Triassic based on thermochronological and structural data (Shu et al., 2002; Lauren-Charvet et al., 2003; de Jong et al., 2009; Wang et al., 2009a; Cai et al., 2012; Konopelski et al., 2013; Rolland et al., 2013; Li et al., 2020b; He et al., 2021a). It is suggested that orogenic terranes in the western CAOB extruded eastwards into between the Siberia and Tarim cratons via dextral movements of large-scale strike-slip faults during the latest Carboniferous and Permian (e.g., Wang et al., 2007b; Li et al., 2015b, 2015a; Zhu et al., 2018, 2019b; Hu et al., 2020; He et al., 2021a), resulting in significant intra-continental deformation. Consequently, some areas in the Tianshan belt underwent coeval denudation and surface erosion. In this regard, the early Triassic exhumation was likely induced by transpressional or transtensional deformation of these major fault zones.

It is also noted that a large area of the Yili block seems to have experienced a rather small amount of exhumation (< ~2–4 km) since the Jurassic or throughout the Mesozoic in general, showing relatively old (Permian-early Cretaceous) AFT apparent ages (published AFT ages from the Yili block are summarized in Supplementary Information 3). Widespread Triassic-Jurassic penaneulation surfaces are still preserved in the Yili block and adjacent areas (Morin et al., 2019; He et al., 2021b). Within the neighboring Central Tianshan block, the > ~1500 m Alagou vertical profile only recorded a moderate Cretaceous cooling following the Triassic-Jurassic cooling stagnation. Its basement cooling rate is highly comparable to that of the Wenquan profile in this study (He et al., 2021b). The aforementioned, together with the accelerated early Cretaceous cooling phases recognized in the southern Yili, indicate that enhanced late Mesozoic basement cooling through denudation occurred in the western Chinese Tianshan belt. However, this cooling was only moderate (< ~1–1.5 °C/Ma) and the associated denudation was insufficient to erase the pre-Cretaceous low-relief surfaces. In the meanwhile, the wide occurrence of these particular thermochronological signals in the region could also be related to a long-lasting (but not incessant) arid to semi-arid climate during the Messo-Cenozoic (e.g., Jolivet et al., 2018; Morin et al., 2019) and the lack of internal drainage (e.g., Sobel et al., 2003), hence resulting in limited surface erosion.

Another issue concerns the reactivation of inherited structures in the Tianshan belt. In Central Asia, numerous studies have emphasized the important reactivation of pre-existent suture/shear zones in controlling regional exhumation and relief generation (Glorie and De Grave, 2016; and the references therein). The Yili block is bounded by two deep-rooted strike-slip faults that are near parallel to Paleoasian suture zones as mentioned above. In addition, the Central Kazakhstan strike-slip fault and Wusun thrust fault are also developed within this block (Figs. 1B and 2). In order to better reveal the roles of fault zones in controlling intra-continental deformation, published AFT ages (Supplementary Information 3) were plotted with color-coded annotations in the topographic map (with indication of major faults) (Fig. 9). It is observed that along the prominent North Tianshan and Nalati faults, the rocks do not show distinct younger AFT ages compared with the surrounding areas. Although late Cenozoic thermochronological ages were identified from the Du-Ku road in the easternmost Yili block (Fig. 9), this very recent exhumation was considered to be associated with localized brittle faults movement instead of reactivation of regional strike-slip faults (Dumitrul et al., 2001). Furthermore, thermal history modeling results of the basement rocks from nearby of these two fault zones generally indicate Permian rapid and Triassic-middle Jurassic moderate cooling, followed by limited exhumation until the present (e.g., Wang et al., 2018b; Glorie et al., 2019; and this study). Hence, we deduce that the North Tianshan and Nalati faults were not sufficiently reactivated to produce intensive regional exhumation during the Mesozoic and Cenozoic. Similarly, He et al. (2021b) recently documented that major shear zones (i.e. the Main Tianshan shear zone and the Baluntai fault; Fig. 1B) around the adjoining Central Tianshan were also not significantly reactivated in the Meso-Cenozoic, indicating that only limited vertical displacements occurred along these Paleoasian large-scale strike-slip faults in response to intra-continental crust shortening since the Mesozoic. On the other hand, a set of younger, late Cretaceous-Cenozoic AFT ages ‘cluster’ around the eastern section of the Wusun trust fault (Fig. 9), reflecting comparably younger exhumation events. This indicates that localized brittle faults probably have played important roles in controlling regional exhumation along the Tianshan belt (e.g., Dumitrul et al., 2001; He et al., 2021b), and samples from the Wenquan complex in this study also serve as a typical example.

6. Conclusions

Low-temperature thermochronological investigations on the Wenquan complex and Dahalajunshan - Nalati range shed new light on the Mesozoic thermo-tectonic evolution of the easternmost Kazakhstan collage system in the CAOB. New constraints together with available data lead us to draw the following conclusions:

(1) Cretaceous moderate basement cooling occurred in the northern margin of the Yili block, probably associated with the Tethys-
deformation and subsequent Lhasa-Qiangtang collision along the southern Eurasian margin.

(2) The Dahalajunshan - Nalati range recorded an early Triassic accelerated cooling phase, which was likely induced by short-lived post-orogenic intra-continental transpression between the Tarim and the Tianshan belt.

(3) The northern and southern margins of the Yili block experienced different thermo-tectonic evolution during the Mesozoic, the northern Yili was less exhumed with exposure of a shallower crustal level.

(4) Similar to the Main Tianshan shear zone and the Baluntai fault, the North Tianshan and Nalati faults were not significantly reactivated to generate intense regional exhumation during the intra-continental evolutionary stage. In comparison, locally developed brittle faults have played an important role in controlling small-scale enhanced basement exhumation and cooling.

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Credit authorship contribution statement

Zhiyuan He: Conceptualization, Field investigation, Methodology, Data curation, Writing - original draft. Bo Wang: Field investigation, Writing - review & editing, Funding acquisition. Wenbo Su: Methodology, Writing - review & editing. Stijn Glorie: Methodology, Writing - review & editing. Xinghua Ni: Field investigation, Writing - review & editing. Jiashuo Liu: Field investigation, Validation. Dongxu Cai: Methodology, Validation. Linglin Zhong: Writing - review & editing. Johan De Grave: Supervision, Field investigation, Writing - review & editing, Funding acquisition.

Declaration of Competing Interest

The authors declare that they are not aware of any competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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