Mesozoic building of the Eastern Tianshan and East Junggar (NW China) revealed by low-temperature thermochronology

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1. Introduction

The Central Asian Orogenic Belt (CAOB), is the largest intra-continental system in the world, incorporating the mountainous zone between the Siberian Craton in the north and the North China-Tarim Cratons in the south (Fig. 1a). The CAOB was formed by Neoproterozoic-Paleozoic amalgamation of a number of continental terranes, island arcs, seamounts and accretionary wedges (e.g., Sengör et al., 1993; Jahn et al., 2000; Xiao et al., 2003; Windley et al., 2007; Wilhem et al., 2012). Following its amalgamation, the CAOB was reactivated several times during the Mesozoic-Cenozoic in response to accretion and collision at the southern Eurasian margin (e.g., Molnar and Tapponnier, 1975; Avouac et al., 1993; Dunitz et al., 2001; De Grave et al., 2007; Jolivet et al., 2013; Glory and De Grave, 2016; Kääbner et al., 2017; Rolland et al., 2020). As a consequence, the CAOB basement was subjected to large-scale intra-continental deformation.

The Tianshan and Junggar orogenic collages occupy the southwestern part of the CAOB (Fig. 1b). They are active intra-continental orogenic systems which record the poly-phase exhumation history of Central Asia (e.g., Tapponnier and Molnar, 1979; Yin et al., 1998; Shu et al., 2003; Jolivet, 2017). During the past decades, the reactivation processes of the Tianshan and Junggar have been explored by numerous thermochronological studies (e.g., Hendrix et al., 1994; Dunitz et al., 2001; Wang et al., 2009a, b; Glory et al., 2010, 2011, 2019; Jolivet et al., 2010; De Grave et al., 2011, 2012, 2013; De Pelsmaeker et al., 2015; Jourdon et al., 2018a; Nachtergaele et al., 2018; Yin et al., 2018a; Gillespie et al., 2020), uncovering several distinct periods of exhumation and basement cooling during the Mesozoic-Cenozoic. However, the cooling histories of certain regions turned out to be...
more complex and protracted, and existing data is still insufficient or contradictory to fully explain the thermo-tectonic evolution of the region.

In the Eastern Tianshan, for example, several studies reported Cenozoic rapid cooling phases for the Bogda mountain range based on apatite fission track dating, and a distant effect of the India-Eurasia collision was proposed (e.g., Zhu et al., 2006a; Li et al., 2008; Wang et al., 2008a). However, more recent studies only recognize Mesozoic cooling pulses in the easternmost Tianshan, suggesting that the bulk of the exhumation occurred prior to India-Eurasia collision (Gillespie et al., 2017a; Chen et al., 2020). Along the Kangguer-Yamansu Arc, Yin et al. (2019) carried out both zircon and apatite fission track analyses and proposed that the Tuwu-Yandong porphyry Cu deposits in the Eastern Tianshan experienced protracted slow cooling since the Late Triassic. However, Gong et al. (2021) analysis of the same region argued for a Middle Jurassic reheating event with a subsequent minor phase of exhumation until the Early Cretaceous. The adjacent East Junggar occupies a critical position between the Eastern Tianshan and Chinese Altai in the southern CAOB, but its exhumation history has not been explored extensively by low-temperature thermochronological methods and is therefore poorly understood.

The controversy on the reactivation episodes in the Eastern Tianshan as well as the lack of constraints on the cooling history of the East Junggar are the main issues as to why further investigation into the exhumation history of these regions is needed. In this contribution, we apply apatite fission track (AFT) analysis and associated thermal history modeling in order to reconstruct the upper crustal thermal history of the Eastern Tianshan and East Junggar. Firstly, we re-evaluate the main reactivation events that took place in the Eastern Tianshan based on a set of basement samples collected from the Bogda, Harlik-Dananhu and Yamansu Arcs. Secondly, we present the first AFT dataset for Paleozoic rocks from various parts of the East Junggar, together with detrital AFT data from the Junggar Basin to the south in order to better constrain the thermo-tectonic history of this domain. Finally, with the use of the newly obtained data, integrated with published data from the adjacent tectonic units, an updated and clearer picture of the Mesozo-Cenozoic geodynamic evolution of the southwestern CAOB is reconstructed. In this context we further discuss the intracratonic tectonics from the continental margins through the crustal architecture of Central Asia, with special attention to main inherited structures.

2. Geological background

2.1. The Eastern Tianshan

The Tianshan belt was formed by Paleozoic multi-stage subduction of the Junggar and Paleozoic-Tianshan Oceans and the subsequent collision between the Kazakhstan-Yili block and Tarim Craton (e.g., Allen et al., 1992; Gao et al., 1998; Wang et al., 2008b; Charvet et al., 2011; Xiao et al., 2013). It extends from west to east across Central Asian republics and NW China (Fig. 1). The Eastern Tianshan refers to the eastern segment of the Chinese Tianshan belt that is geographically divided by the Urumqi-Korla line. Tectonically, the Eastern Tianshan is further divided into the South Tianshan belt, Central Tianshan block and North Tianshan accretionary complex based on differences in basement characteristics and tectonic origin (Fig. 1b; Xiao et al., 2004, 2010; Ao et al., 2010; Song et al., 2015). The eastern Central Tianshan block is composed of a Proterozoic metamorphic basement (Lei et al., 2013; He et al., 2015; Huang et al., 2018).
et al., 2015), overlain by arc-related volcanic-sedimentary strata and intruded by Paleozoic granitoids (Xiao et al., 2004; Lei et al., 2011; Zhang et al., 2015; Du et al., 2018). The North Tianshan accretionary complex refers to the region between the Central Tianshan block and Junggar Basin (Fig. 1b), the framework of this domain is characterized by three subordinate magmatic arcs (i.e., the Bogda, Harlik-Dananhu and Kangguer-Yamansu Arcs) (e.g., Xiao et al., 2004; Zhang et al., 2017; Ni et al., 2021), which are mainly composed of Ordovician to Carboniferous volcanic rocks, interbedded clastic sediments and intruding granitoids (e.g., Wang et al., 2006; Han et al., 2010; Shu et al., 2011; Mao et al., 2018; Wali et al., 2018).

Following the eventual amalgamation, the Eastern Tianshan was reworked by Permian to Early Triassic activity of several near E-W trending large-scale strike-slip faults (e.g., Main Tianshan shear zone; Kangguer-Huangshan shear zone) (Shu et al., 2002; Wang et al., 2008c, 2010, 2014; Cai et al., 2012), with associated emplacement of syn-kinematic plutons (e.g., Wang et al., 2009a,b, 2014). In the mid-Permian, the Bogda and Harlik mountains experienced early-stage uplift and associated erosion recorded by clastic sedimentation in the adjacent basins (Wang et al., 2018; Chen et al., 2019). The Mesozoic history of the Eastern Tianshan is characterized by reactivation episodes in response to distant tectonic events (e.g., collision of continental blocks or island-arcs). To the south, the Beishan belt experienced three distinct phases of exhumation (~225–180 Ma, ~130–95 Ma and ~75–60 Ma) during the Mesozoic (Gillespie et al., 2017b). In the north of the Balikun Basin, comparable Mesozoic cooling episodes during ~222 Ma, ~138–113 Ma and ~68–57 Ma were reported from the Moqing-wula range (Chen et al., 2020). Near the Kangguer-Huangshan shear zone, fast cooling of the Tuwu-Yandong porphyry Cu deposits mainly occurred before the Late Triassic (~255–200 Ma), and a minor cooling pulse took place during the latest Jurassic to Early Cretaceous (Gong et al., 2021). Cretaceous exhumation events were also widely recognized in Bogda (Zhu et al., 2006a; Tang et al., 2015) and Harlik mountain ranges (Gillespie et al., 2017a). In contrast, Cenozoic rapid basement cooling seems to be less extensive in the Eastern Tianshan. Wang et al. (2008a) presented a set of Oligocene-Miocene AFT ages for the Bogda and Balikun mountain ranges, but these data were recently questioned by some studies that reported much older basement AFT ages (Cretaceous) from the same area (e.g., Gillespie et al., 2017a; Chen et al., 2020).

2.2. The East Junggar

The East Junggar is located between the Altai range and Eastern Tianshan, bounded by the Irtysh shear zone to the north and the...
Kalamaili fault to the south (Fig. 1b; Xiao et al., 2008; Zhang et al., 2009; Li et al., 2017). This belt is dominated by a series of Paleozoic accretionary complexes formed by subduction-accretion during the closure of the Paleo-Asian Ocean (e.g., Coleman, 1989; Xiao et al., 2009; Long et al., 2012; Xu et al., 2013). The East Junggar is tectonically made up of the NW-striking Dulate and Yemaquan Arcs and Jiangjunmiao domain, which are separated by the highly deformed and dismembered Aermantai and Kalamaili ophiolite mélanges (Figs. 2 and 3; Xiao et al., 2004; Zhang et al., 2013; Xu et al., 2020). The Dulate Arc is mainly composed of Devonian-Carboniferous volcanic and sedimentary rocks (Li et al., 1990; Zhang et al., 2005, 2008, 2009), as well as granitoids with ages of 390–370 Ma and 330–320 Ma (Tong et al., 2014; Tang et al., 2017; Song et al., 2019). The Yemaquan Arc extends along the Kalamaili ophiolite and borders the Harlik Arc in the east (Fig. 2). It mainly consists of Ordovician to Carboniferous clastic rocks and carbonates, with minor volcaniclastic rocks (XBGMR, 1993; Xiao et al., 2009; Long et al., 2012; Li et al., 2013; An et al., 2021). Granitoid batholiths of the Yemaquan Arc largely yielded late Paleozoic emplacement ages (~390–370 Ma and ~320–300 Ma) (e.g., Yang et al., 2011; Liu and Liu, 2013), and several Silurian intrusive rocks were also found in its eastern part (e.g., Guo et al., 2009; Li et al., 2009). The Jiangjunmiao domain is located in the south of the Kalamaili ophiolite, the majority of this accretionary complex is covered by Meso-Cenozoic strata of the Junggar Basin (Fig. 3). The exposed section is represented by a succession of mid-Devonian to lower Carboniferous clastic sediments and Permian volcanic rocks (XBGMR, 1966; Xiao et al., 2009).

During the Permian (~290–252 Ma), intensive ductile shearing took place along the sinistral Irtysh shear zone, associated with a strong contractional component (Laurent-Charvet et al., 2003; Briggs et al., 2009; Li et al., 2015, 2016). The latter corresponds to the collision between the Altai range and East Junggar (e.g., Li et al., 2017; Hu et al., 2020) and resulted in regional uplift in the southern Chinese Altai (Li et al., 2015). In the contiguous eastern Junggar Basin, Mesozoic sedimentary sequences are well preserved and exposed (Fig. 3). The up to ~1500 m thick Jurassic sediments are mainly composed of coarse-grained upward sequences deposited in an alluvial fan environment (e.g., Vincent and Allen, 2001). Conglomerates are widely recognized at the bottom of the lower Cretaceous strata, indicative of an unconformity at the base of the Cretaceous sediments (Fig. 3b; Yang et al., 2017; Wang et al., 2021).

3. Samples and methodology

3.1. Sampling sites

In this contribution, we present new apatite fission track (AFT) ages obtained on 14 Paleozoic basement rocks from the Eastern Tianshan, and 6 Paleozoic basement samples and 7 Mesozoic sandstones from the East Junggar. We collected samples as widely as...
possible throughout the study area, and care was taken for sampling across different tectonic boundaries. Sample descriptions including their locations can be found in Tables 1 and 2.

In the Eastern Tianshan, representative Paleozoic granitoids were taken from the Yamansu (T28–32), Dananhu (T26), Harlik (Q25, T34–37, 42 and 48) and eastern Bogda (T49) Arcs from south to north (Fig. 2). Among them, samples T34–37 constitute a vertical profile with elevations from 1479 m to 2160 m in the Balkin mountain range (Table 1). From the East Junggar, Paleozoic granitic rocks were collected from several plutonic bodies of the Dulate and Yemaquan Arcs (Figs. 2 and 3), while sample sites E44 and E46 are located near the boundary between the East Junggar and Tianshan belt. Sandstone samples were mainly taken from the lower Triassic to lower Cretaceous strata on the eastern margin of the Junggar Basin (Fig. 3).

3.2. Methods for apatite fission track thermochronology

The AFT method is based on the spontaneous fission of $^{238}\text{U}$ which creates linear damage trails (fission tracks) in the crystal lattice. Using chemical etching, fission tracks in apatite can be revealed for optical microscopic analysis (e.g., Wagner and Van den haute, 1992; Gallagher et al., 1998). The AFT thermochronometer is sensitive to temperature: above ~120 °C, the apatite lattice recrystallizes and fission tracks are rapidly annealed; whereas at temperatures lower than ~60 °C, fission tracks in apatite are considered stable. The ~120–60 °C window is referred to as the apatite partial annealing zone (APAZ). Within this temperature window tracks accumulate but are progressively shortened (i.e., partially annealed) (e.g., Green et al., 1986; Ketcham et al., 2005). The low temperature AFT method is thus particularly useful for evaluating cooling histories of rocks in the upper ~4 km of the crust, depending on the local geothermal gradient.

All the samples in this study were analyzed by the external detector method using thermal neutron irradiation, following the standard procedure set at Ghent University (e.g., Glorie et al., 2010; De Grave et al., 2011; Nachtgerael et al., 2013). Apatite grains were handpicked and mounted in Struers CaldoFix-2 epoxy resin, and sample mounts were ground and polished (by 6, 3, and 1 μm diamond suspension) to expose internal sections. Apatite grains were etched in 5.5 M HNO$_3$ solution for 20 s at 21 °C to reveal the spontaneous tracks (e.g., Donelick, 1991). Irradiation was carried out at the Belgian Reactor 1 (BR1) facility of the Belgian Nuclear Research Centre in Mol (De Grave et al., 2010). The IRMM-540 dosimeter glasses (De Corte et al., 1998) were inserted in the irradiation container to monitor the thermal neutron fluence. Induced tracks were etched in muscovite external detectors with 40% HF for 40 min at 20 °C.

Fission track densities were measured by using the TrackFlow software (Van Ranst et al., 2020) on a fully motorized Nikon Eclipse Ni-E microscope, equipped with a Nikon DS-Ri2 camera. Age
Apatite fission track data for Paleozoic basement rocks from the Eastern Tianshan and East Junggar.

4. Results

4.1. Apatite fission track results

The AFT results for the granitoids rocks from the Eastern Tian- shan and East Junggar are presented in Table 3, and those for the detrital samples of the eastern Junggar Basin are shown in Table 2. At least twenty apatite grains were measured and 1000 spontaneous tracks were counted for the granitoid samples when possible. For sandstone samples, we aimed at measuring 100 grains for each sample, but only one (E54) attained that level. All the granitoids data passed the $\chi^2$ test with very low dispersion, indicative of a single age population (Galbraith, 1981; Green, 1981). For seven sandstone samples, we used the BinomFit software that is based on a binomial peak-fitting approach (e.g., Brandon, 1996; Stewart and Brandon, 2004) to decompose the single-grain AFT ages and determine the statistical age peaks (Fig. 4; original results refer to Supplementary Material 1). Both AFT mean zeta-ages $t(\zeta)$ and central ages are reported for the Paleozoic granitic rocks.

Table 3

| Sample | No. of Grains (n) | Spontaneous | Induced | Dosimeter | $P(\chi^2)$ (%) | Dispersion (%) | Zeta (arb) | Central age (Ma) | Track length and Dpar |
|--------|------------------|-------------|---------|-----------|----------------|---------------|-----------|-----------------|---------------------|
|        |                  | Ni (ps (105 cm$^{-2}$)) |            | Ni (ps (105 cm$^{-2}$)) | Nd (ps (105 cm$^{-2}$)) |                |           |                 | Ni (Length (μm)) |
|        |                  |              |          |            |               |               |           |                 | Length (μm) |
|        |                  |              |          |            |               |               |           |                 | $\tau_{\text{Dpar}}$ (μm) |
|        |                  |              |          |            |               |               |           |                 |         |
| E44    | 15               | 2399 ± 4.0   | 1787 ± 3.15 | 2690 ± 5.27 | 100 ± 0.00 | 110.6 ± 4.1  | 115 ± 13.1 | 1.4 ± 0.5       | 110.3 ± 13.5 |
| E46    | 25               | 799 ± 2.62   | 611 ± 2.85  | 2681 ± 5.26 | 100 ± 0.01 | 107.9 ± 6.2  | 77 ± 12.3  | 1.0 ± 0.5       | 110 ± 13.5  |
| E51    | 20               | 312 ± 2.22   | 210 ± 2.86  | 2674 ± 5.24 | 100 ± 0.01 | 115.7 ± 11.0 | 120.4 ± 11.0 | 1.3 ± 1.9       | 110 ± 13.5  |
| E40    | 20               | 702 ± 6.65   | 508 ± 7.46  | 2749 ± 5.39 | 100 ± 0.00 | 116.0 ± 7.2  | 114.4 ± 7.1 | 1.2 ± 0.5       | 120 ± 13.4  |
| E50*   | 20               | 452 ± 3.95   | 156 ± 1.37  | 2746 ± 5.38 | 100 ± 0.00 | 238.6 ± 22.7 | 237.4 ± 22.6 | 1.3 ± 1.9       | 120 ± 13.4  |
| E46    | 3                | 239 ± 8.06   | 126 ± 4.24  | 2742 ± 5.38 | 99 ± 0.00  | 156.5 ± 17.5 | 156.2 ± 17.5 | 1.5 ± 1.5       | 110 ± 13.5  |

AFT age and length data: $n$ is the number of counted grains; $p_\alpha$, $p_\beta$, and $p_\gamma$ are the density of spontaneous, induced tracks and induced tracks in an external detector irradiated against a dosimeter glass. The $p_\alpha$-values are interpolated values from regularly spaced glass dosimeters (IRMM-540). $p_\beta$ and $p_\gamma$ are expressed as $10^5$ tracks/cm$^2$. $N_s$ and $N_l$ are the number of counted spontaneous, induced tracks and induced tracks in the external detector. $N_s$ is an interpolated value. $P(\chi^2)$ is the chi-squared probability that the dated grains have a constant $\rho_\beta/\rho_\alpha$-ratio. An $\gamma$-value of 310.0 ± 2.7 a cm$^{-2}$ was used for the calculation of the AFT age $t(\zeta)$ (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 μm), 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.
Table 3; zeta-ages are used in the following discussion. Radial plots of AFT ages for Paleozoic rocks can be found in Supplementary Material 2. As to sandstone samples, we present age range and central age for each sample (Table 2).

4.1.1. Eastern Tianshan

From the Yamansu Arc, five neighboring samples (T28-32) display mid-Cretaceous apparent AFT ages ranging from 126 ± 6 Ma to 90 ± 7 Ma, and sample T26 from the adjacent Dananhu Arc yields a comparable AFT age of 119 ± 13 Ma (Fig. 2; Table 3). Among them, T30 shows a short mean track length of ~12.1 μm and T32 has a mean track length of 12.5 μm with a standard deviation of 1.2 (Fig. 5), suggesting clear track shortening within the APAZ. Whereas T28 yields a relatively higher mean track length of ~13.5 μm as well as a larger average Dpar value of 1.82 μm (Fig. 5; Table 3), probably indicating that this sample has stronger annealing resistance property (e.g., Donelick et al., 2005).

Along the eastern Bogda-Harlik Arc, AFT analysis of eight granitoid samples produced Late Cretaceous AFT ages ranging from ~103 Ma to ~69 Ma (Fig. 2). Therein four samples (T34-37) collected from the Balkun mountain constitute a vertical profile with a ~700 m elevation span (Table 1), and yield a narrow extent in AFT ages from 87 ± 5 Ma to 69 ± 6 Ma (Table 3). These four AFT ages, with a normal age-elevation relationship, suggest an apparent denudation rate of approximately ~38.5 m/Ma (R² = 0.96) during the Late Cretaceous (Fig. 6a). It should be noted that the latter value can be an overestimation as the low-temperature isotherms (within the window of AFT sensitivity) tend to be compressed in the upper crust when denudation rates are high (e.g., Braun, 2002). Due to limited number of apatite grains and/or poor crystal quality, only two samples (T34 and T37) provided a sufficient number (both > 80) of measured confined tracks, with mean track lengths of ~12.6 μm and ~12.9 μm, respectively (Fig. 5). Few confined tracks were found in samples T36 and T49, and their mean track lengths are listed for reference only (Table 3).

4.1.2. East Junggar

Three granitic samples (T44, 46 and 51) taken from the Yemaquan Arc exhibit similar mid-Cretaceous AFT ages from ~120 Ma to ~108 Ma (Table 3). Adequate numbers of confined tracks (all > 70) were measured, with relatively high mean track lengths varying between ~13.5 μm and ~13.1 μm (Fig. 7). Regarding the Dulate Arc to the north, the AFT ages from this domain vary in a wide range from 237 ± 23 Ma to 114 ± 7 Ma (Fig. 3). After 252Cf irradiation, a total of 120 confined tracks were measured for sample EJ05, giving a mean track length of 13.4 μm and a standard deviation of 1.3 μm (Fig. 8). While for the other two samples, track length data are lacking due to their very limited apatite grains.

As for seven Mesozoic sandstone samples collected from the eastern Junggar Basin and inside the Yemaquan Arc, the central age of each sample is almost coeval with or older than their stratigraphic ages (Fig. 4). Furthermore, the central age of the lowermost Triassic Cangfanggou Formation (sample E55) was determined as latest Permian, suggesting that even the bottom sequences of the studied strata were not buried deeply enough to completely reset the AFT clocks. This is consistent with the fact that the whole Meso-Cenozoic sedimentary sequence is less than 3 km thick (Fig. 3b). Therefore, the obtained detrital AFT ages should largely reveal the thermal history of the source areas (i.e., possible basement of the East Junggar). The BinomFit plotting for the Triassic sample E55 yields a single age peak at 257 ± 15 Ma (Fig. 4). Lower Jurassic sample E56 presents 62 AFT single grain ages with a central age of 195 ± 8 Ma, and two age populations of ~174 Ma (59.3%) and ~232 Ma (40.4%) are observed by BinomFit decomposition (Fig. 4; Table 2). All three Middle Jurassic samples (E54, 57 and 45) display single age peaks, indicating three provenances with cooling ages of ~228 Ma, ~201 Ma and ~173 Ma, respectively (Fig. 4). The upper Jurassic sample E50 exhibits comparable age
peaks at \(\sim 179\) Ma (71.3%) and \(\sim 202\) Ma (28.7%) (Fig. 4). As to the lower Cretaceous sample E59, results of decomposition show two distributed age populations of \(\sim 183\) Ma (53.6%) and \(\sim 237\) Ma (46.4%) (Fig. 4).

4.2. Thermal history modeling

In this section we present the expected temperature–time paths of all the modeled samples, they will also be used in the discussion for representing the most probable cooling history (Gallagher et al., 2009; Gallagher, 2012). Individual sample length distribution histograms and temperature–time plots are detailed in Supplementary Material 3, in which the 95% credible intervals of cooling phases are generally consistent in time with the expect paths. For a more accurate description in our further discussion, we define rates 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. Eastern Tianshan

The thermal history of the Yamansu Arc is reconstructed by the modeling results of samples T28, 30 and 32. Therein, the samples T28 and 32 display similar cooling paths, they record rapid cooling through the APAZ at \(\sim 150–120\) Ma, and the accelerated cooling lasted until the Early Cretaceous (Fig. 5). By contrast, the cooling pulse of sample T30 initiated slightly earlier at the Middle Jurassic (\(\sim 170\) Ma), it rapidly cooled through the APAZ at the earliest Cretaceous, followed by moderate cooling until the mid-Cretaceous (Fig. 5). It is noted that a final increase in cooling, outside the APAZ window, during the late Cenozoic is observed in all the modeled samples, and that this cooling step may be associated with a well-known modeling artifact (e.g., Ketcham et al., 1999). Hence, the final cooling step is excluded from further discussion.

Along the Harlik Arc, two samples from the top and bottom sites of the vertical profile were suitable for modeling (T34 and 37; Fig. 6). They provided reliable constraints on the thermal history of the \(\sim 3,300\) m-high Balikun mountain. The prior for the paleo-temperature difference for these two samples was set to 30 °C/km, representing the present-day normal geothermal gradient. The integrated modeling results reveal moderate cooling during the mid-Cretaceous to Eocene (\(\sim 105–45\) Ma; Fig. 6b). During this stage, a total cooling of \(\sim 70\) °C is exhibited by the model, corresponding to a mean cooling rate of \(\sim 38.9\) m/Ma. This is almost identical with the cooling rate given by the age-elevation relationship (Fig. 6a).

4.2.2. East Junggar

Thermal history models for the Yemaquan Arc record comparable Cretaceous cooling events. In the southern part of this domain that borders the Bogda Arc, the thermal history model for the sample E44 shows a short-lived rapid cooling episode during the Early Cretaceous. Subsequently, the t-T paths indicate a moderate to slow cooling since \(\sim 120\) Ma (Fig. 7). Another sample (E46) in this area rapidly cooled through the APAZ in the Early Cretaceous (\(\sim 130–110\) Ma), with this cooling phase lasting until \(\sim 90\) Ma as predicted by the modeling (Fig. 7). To the northwest, sample T51 exhibits cooling into the APAZ in the Late Jurassic, followed by a moderate cooling until the mid-Cretaceous (\(\sim 90\) Ma; Fig. 7).
Concerning the Dulate Arc, one sample (EJ05) from its interior domain is suitable for modeling (Figs. 3 and 8). The inverse modeling result indicates a two-stage thermal history. A moderate cooling is predicted to have occurred during the Permian to Triassic, when slow cooling eventually brought the sample to present-day ambient surface temperatures (Fig. 8).

5. Interpretations and discussion

5.1. Thermo-tectonic history of the Eastern Tianshan

Since the Mesozoic, the Precambrian-Paleozoic basement units of the Eastern Tianshan (see Section 2) have experienced several tectonic events. Here we discuss the basement exhumation history of these units, and attempt to link it to regional geodynamic processes.

Our data dominantly comes from the North Tianshan accretionary complex (Figs. 1 and 2). In the Yansansu and Dananhu Arcs, all six dated rocks yielded comparable apparent mid-Cretaceous AFT ages (~126–90 Ma), and the modeling of three samples displays similar Cretaceous cooling paths, suggesting synchronous exhumation during the late Mesozoic. Based on the occurrence of widespread Jurassic sandstones in this area, Gong et al. (2021) suggested that the Yandong orebody (in the Yansansu Arc) underwent Jurassic burial and reheating before the Early Cretaceous exhumation. Whereas Yin et al. (2019) alternatively proposed an early Permian to Late Triassic burial, on the basis of the thermal history of a late Paleozoic conglomerate that displayed a reset zircon fission track age of ~197 Ma. Thus, the final exhumation of the Yansansu Arc occurred no later than the early Cretaceous. Thermal history modeling by Gong et al. (2021) indicated minor cooling from the Middle Jurassic to Early Cretaceous (around 20–30 °C in total), but this cooling phase involves low temperatures outside the APAZ (Fig. 5 in Gong et al., 2021) that might be affected by modeling artifacts. Hence, this cooling ‘event’ is less convincing. Our results, however, imply that the Early Cretaceous exhumation in the Yansansu Arc was much more intensive, it lasted until the mid-Cretaceous (~100 Ma) with a total of ~70–80 °C cooling.
In addition, Yin et al. (2019) recognized a moderate cooling episode (1.45–2.21 °C/Myr) from the Late Triassic to the Paleogene, but the timing and duration of this cooling was only roughly constrained based on questionable track length distributions with less than 30 measured confined tracks. In general, moderate cooling in the Yamansu Arc since the Early Cretaceous transpired, and it probably lasted until the mid-Cretaceous.

The mechanism for the Early Cretaceous accelerated cooling episode can be related with the regional contraction in response to the far-field effects of the subduction of the Meso-Tethys oce-
nic plate (Yan et al., 2016; Zahirovic et al., 2016); or the closure of the Mongol-Okhotsk Ocean in Siberia (Zorin, 1999; Jolivet et al., 2009; Metelkin et al., 2012). It was unlikely that the collision between the Qiangtang and Lhasa blocks triggered the intra-continental deformation of the Yansansu Arc. In recent years a growing number of studies argued that the ‘hard’ (continent–continent) collision between the Lhasa and Qiangtang blocks took place no prior to ~130–120 Ma based on structural (Kapp et al., 2007), sedimentary (Lai et al., 2019; Li et al., 2020), palaeomagnetic (Bian et al., 2017) and geochronological-geochemical (Zhu et al., 2016) evidence, which postdated the Early Cretaceous cooling phase indicated in this study. Although far-field effects of the Mongol-Okhotsk orogeny cannot be excluded, the scissors-like closure of the Mongol-Okhotsk Ocean was more likely to have impact on the regions like the Transbaikalia, North Mongolia and interior North China Craton in the east (e.g., Yang et al., 2015a; Arzhannikova et al., 2020), and the Eastern Tianshan is too remote for having been subjected to exhumation and cooling at that time. Moreover, debate still exists whether the closure of the Mongol-Okhotsk Ocean involved a true compressional orogeny (e.g., Jolivet et al., 2013; Jolivet, 2017). Therefore, we favor the interpretation that the localized Early Cretaceous signals found in the Yansansu Arc was more likely related with the closure of the Meso-Tethys Ocean (e.g., Yan et al., 2016; Zahirovic et al., 2016), a low-angle plate subduction beneath the Asian continental lithospheric mantle generated considerable crustal shortening within the continental interior (e.g., Chapman et al., 2018a, 2018b). The reactivation of the nearby ~E-W-striking Kangguer-Huangshan shear zone (Wang et al., 2008c, 2014) controlled the exhumation at that time in a regional compressional or transpressional setting.

Cretaceous-Paleogene moderate cooling was recognized in the Balikun mountain of the Harlik Arc, albeit somewhat younger compared to this study. The integrated modeling results of the vertical profile constrains the main episode of denudation and orogenic uplift between ~105 and ~45 Ma, with a cooling rate consistent with that deduced from the age-elevation plot (Fig. 6). Adjacent to this profile, similar enhanced cooling that initiated at ~90 Ma was recognized from a tilted erosional surface in the Harlik mountain (Gillespie et al., 2017a), suggesting Late Cretaceous regional exhumation along the Harlik Arc. In the north of the Balikun Basin, Chen et al. (2020) identified a cooling phase of ~113–92 Ma in the Moqingwula range. Based on field structural analysis and AFT dating results of modern river sand samples, these authors also suggested Late Cretaceous-Paleocene regional exhumation in this area under a N-S-directed compressional setting. Furthermore, other samples from the southern Harlik Arc (Q25), southern Balikun Basin (T42 and 48) and eastern Bogda Arc (T49) in this study also exhibit fairly comparable mid- to Late Cretaceous cooling ages (Fig. 2; Table 3). Hence, published data and our new results confirm widespread basin cooling along the eastern Bogda and Harlik Arcs since the mid-Cretaceous, that probably lasted until the Paleocene.

Mid- to Late Cretaceous cooling events have been widely recognized in the Tianshan belt (e.g., Dumitru et al., 2001; Wang et al., 2009b; De Pelsmaeker et al., 2015; Tang et al., 2015; Nachtergaele et al., 2018; Glorie et al., 2019; Rolland et al., 2020), and were generally interpreted as a response to the far-field effects of the Lhasa-Qiangtang collision (~120–90 Ma) and/or Kohistan-Dras Arc collision (~90–70 Ma) (Yin and Harrison, 2000; Rolland, 2002; Rehman et al., 2011; Kapp and DeCelles, 2019). A compressional regime in the mid-Cretaceous (~120–100 Ma) is documented by coeval tectonic inversion of the Turpan-Hami Basin (e.g., Zhu et al., 2004, 2006b). Furthermore, final suturing between the Lhasa and Qiangtang blocks in western Tibet at ~110–100 Ma resulted in foundering of the Meso-Tethys slab and high-flux magmatic events (see Kapp and DeCelles, 2019 for a review). Such events may have led to lithosphere thinning and deep-level denudation in Central Asia, influencing regional topographic evolution (e.g., relief generation and orogenic erosion).

Our study also favors this interpretation for the case of the Balikun mountain (Harlik Arc), as there was a clear time-lag between uplift and erosion (~15 Ma) from the onset of the Lhasa-Qiangtang collision to the starting of the Cretaceous cooling (Fig. 6b). In addition, structural observations indicate ~N-S compression deformation around the Balikun Basin (Chen et al., 2019, 2020), which was more likely driven by collisional events to the south. Approximate E-W-striking faults are widely distributed along the Bogda and Harlik Arcs (Fig. 2), through faults reactivation, the ongoing tectonic processes along the Asian continental margins triggered continuous regional exhumation until the Paleocene. For the Central Tianshan block and South Tianshan belt (Beishan) in the south (Figs. 1 and 2), published low-temperature thermochronological data are mainly from the Xingxingxiao fault, the vicinity of Liuyuan town and near Dunhuang (Gillespie et al., 2017b). From there, thermal history modeling shows Early to mid-Cretaceous (~130–95 Ma) fast cooling events indicating widespread coeval exhumation throughout the Central Tianshan block and Beishan belt (Gillespie et al., 2017b).

Based on our new data and a synthesis of the literature, it is clear that the entire Eastern Tianshan was dominated by moderate to rapid regional exhumation throughout the Cretaceous, as a series of major tectonic events to the south continuously triggered the intra-continental exhumation along reactivated major or basin-bordering faults. During the Early Cretaceous, the low-angle subduction of the Meso-Tethys (i.e. Bangong-Nujiang) oceanic plate installed a compressional tectonic regime within the Eastern Tianshan, creating distant reactivation of inherited structures in the Beishan belt, Central Tianshan block and Yansansu Arc. The subsequent Lhasa-Qiangtang and (intra-oceanic) Kohistan-Dras Arc collisions probably continued to trigger the far-field effects in a compressional regime, as a result, the basin-bordering faults along the Bogda and Harlik Arcs were reactivated and enhanced basinment cooling took place during the mid- to Late Cretaceous. It is noted that this later phase of exhumation was only recognized in the northern part of the Eastern Tianshan (north of the Turpan-Hami Basin), it may explain the relatively high elevation and relief of the current Bogda and Harlik Arcs compared with the areas in the south (Fig. 1b). Meanwhile, it cannot be excluded that the Bogda and Harlik Arcs may have also experienced an Early Cretaceous cooling episode (Gillespie et al., 2017a), but the older thermochronological signals in the basement were removed by later reactivation and associated erosion events.

5.2. Thermo-tectonic history of the East Junggar

This study presents the first low-temperature thermochronological data from various parts of the East Junggar. In the following section we discuss the Mesozoic intra-continental evolution of this domain based on the newly obtained AFT data.

The Kalamaili fault is a key tectonic boundary between the East Junggar and Tianshan belt (Fig. 1), three Paleozoic granitic samples of the Yemaquan Arc were collected from different localities along this fault zone (Figs. 2 and 3). These samples present relatively long mean track lengths (~13.5–13.1 μm; Table 3), and their thermal history modeling shows clear signals of moderate to slightly rapid cooling during the Cretaceous (Fig. 7). Moderate cooling is represented by the sample E51 that is also located near the Kalamaili suture zone (i.e. Kalamaili ophiolite belt) (Fig. 3a). One sample (E46) at the border of the eastern Bogda Arc shows a more rapid cooling path since the Early Cretaceous. Adjacent to the northern Balikun Basin, the sample E44 displays short-period initial rapid
cooling followed by moderate cooling during the Cretaceous (Fig. 7). These cooling episodes lasted until the Late Cretaceous and are highly comparable with the thermal events that occurred in the Eastern Tianshan. It is thus reasonable to propose that the distant effects corresponding to major tectonic events from the south (e.g., regional deformation related to the Tethys tectonics) also reached the Junggar area since the Early Cretaceous. The cooling was controlled by the Kalamaili thrust fault (Fig. 1b) (probably in a compressional/transpressional regime like the case of the Yansamu Arc). It is noted that base Cretaceous unconformities were identified in the eastern margin of the Junggar Basin (e.g., Vincent and Allen, 2001; Yang et al., 2015b, 2017; Wang et al., 2021), indicating renewed erosion in the Early Cretaceous. This is in accordance with coeval regional reactivation in the southern East Junggar revealed by our AFT results.

In the Dulate Arc, the dated three samples display various apparent Mesozoic AFT ages (Fig. 3a), suggesting different degrees of exhumation. Two samples EJ04 and 06 present younger AFT ages, but their thermal histories could not be derived due to limited apatite grains and measured confined tracks. The inverse modeling results for another sample EJ05 show that it underwent slow to moderate cooling during the Permian and Triassic. Since the Middle Jurassic, it had cooled to near surface temperatures and only very limited exhumation occurred during the later evolutionary stage (Fig. 8). As the final amalgamation of the Altai range, the East Junggar and the Harlik-Dananhu Arc (i.e. the closure of the Ob-Zaisan and Kalamaili Oceans) were welded by the late Carboniferous (~320–310 Ma; See Han and Zhao, 2018 for a review), the geological events that generated the Permian-Triassic cooling of the Dulate Arc must have occurred in an intra-plate setting. The post-orogenic tectonic evolution of the East Junggar was characterized by eastward escape of orogenic material along large-scale strike-slip faults (Wang et al., 2007; Zhu et al., 2018, 2019; He et al., 2021a). For example, the sinistral Irtysh shear zone was active during the Permian (~283–252 Ma, by mica 40Ar/39Ar and zircon U-Pb dating) with transpressional deformation, as a result of the collision between the East Junggar and Chinese Altai (Li et al., 2015; Hu et al., 2020). In this case, the Permian moderate basement cooling within the Dulate Arc probably corresponded to such a compressional tectonism. As the moderate cooling continued in the Triassic, we interpret this signal to be related with the denudation associated with the subsequent Qiangtang and Kunlun-Qaidam accretion since the Early Triassic (e.g., Glorie et al., 2010; De Grave et al., 2011; Macaulay et al., 2014; Jepson et al., 2018). It is noted that the Cretaceous AFT age of sample EJ04 possibly recorded a younger enhanced cooling phase, because this sample is located near the continuation of the Fuyun fault and was likely influenced to a higher degree by fault reactivation (Fig. 3a).

So far, not many late Paleozoic-early Mesozoic AFT cooling ages have been reported from the southwestern CAOB because later multi-phase denudation and exhumation has largely removed evidence for these thermochronological signals. These cooling events, however, could be well preserved in detrital samples. Our detrital AFT data from seven Mesozoic sandstone samples record four distinct age peaks of ~257 Ma, ~237–228 Ma, ~201 Ma and ~183–173 Ma (Fig. 4). According to available paleocurrent indicators (e.g., Hendrix et al., 1992; Vincent and Allen, 2001) and detrital zircon U-Pb ages (Wang et al., 2021), the East Junggar was the only source region of the Mesozoic sequences in the eastern Junggar Basin. Hence, our newly obtained detrital AFT age populations could provide critical evidence for the latest Paleozoic to Mesozoic cooling history and potential tectonic reactivation of the East Junggar. The oldest population P4 yielding a late Permian AFT central age (~257 Ma) provides constraints on the latest Paleozoic denudation in the East Junggar, this is almost coeval with the activity of the Irtysh shear zone (Glorie et al., 2012b; Li et al., 2015; Hu et al., 2020) and other deep-rooted strike-slip faults in the south (e.g., Main Tianshan shear zone) (Shu et al., 2002; Laurent-Charvet et al., 2003; Hu et al., 2020), indicating syn-tectonic exhumation during the eastward tectonic wedging in the southwestern CAOB (He et al., 2021a). The six Jurassic and lower Cretaceous sandstone samples are characterized by Middle Triassic to Middle Jurassic detrital AFT age peaks of ~237–228 Ma (P3), ~201 Ma (P2) and ~183–173 Ma (P1) (Fig. 4), indicating successive upper crustal cooling in the sediment source areas during this period. This latter cooling is interpreted to be a record of the accretion of the Qiangtang block with southern Eurasia (e.g., Glorie and De Grave, 2016) as mentioned above. In addition, upper Triassic to lower Jurassic conglomerates were recognized in the Tarim and Turpan-Hami Basins and eastern margin of the Junggar Basin, also implying significant regional erosion following basement uplift during this period (Hendrix et al., 1992; Vincent and Allen, 1999, 2001; Jolivet et al., 2010; Choulet et al., 2013). It is noteworthy that the upper Cretaceous terrigenous sample E59 yields a relatively old central age of ~206 Ma and age peaks of ~237 Ma and ~183 Ma (Fig. 4). The lack of younger apatite grains probably indicates a period of tectonic quiescence following the collision of the Qiangtang block. This is in agreement with the hypothesis that an extensive penepelaneous surface was developed in the Tianshan belt and the surrounding areas during the Middle to Late Jurassic (e.g., Dumitru et al., 2001; Jolivet et al., 2010; De Grave et al., 2011; Morin et al., 2019; Rolland et al., 2020; He et al., 2021b).

5.3. Boomerang plot and comparison with neighboring regions

The AFT results presented in this study are highly comparable with earlier works in several key areas of the southwestern CAOB. Concerning the Eastern Tianshan and Junggar, we compiled both the published (from Gillespie et al., 2017a, 2017b; Yin et al., 2019; Chen et al., 2020; Gong et al., 2021) and our newly obtained AFT ages and mean track lengths by using a boomerang plot (Fig. 9). The boomerang plot expresses the relationships between AFT age and mean track length for each sample, indicative of cooling rate through the APAZ (Green et al., 1986; Gallagher et al., 1998). More specifically, rapid basement cooling through the APAZ is represented by higher mean track lengths, whereas the lower values stand for the samples that underwent a protracted cooling through the APAZ. The compiled AFT ages in the plot display a boomerang shape throughout the late Paleozoic-Mesozoic (Fig. 9). Initially, rapid cooling was recorded in the Permian and Triassic, indicating rapid exhumation induced by post-orogenic transcurrent movements and the subsequent distant effects of the accretion of the Qiangtang block to Eurasia. These events were followed by slow cooling with longer residence within the APAZ during the Middle to Late Jurassic, fitting well with this period with moderate tectonic activity. The Cretaceous segment is characterized by increasing mean track lengths, defining a period of moderate to rapid cooling and shorter APAZ residence. This final trend might have been caused by a series of subduction-related contractions and collisions at the southern margin of Asia since the Early Cretaceous (Fig. 9).

The latest Permian to Early Jurassic AFT cooling ages from base- ment rocks and clastic sediments from the East Junggar provide clear evidence for early Mesozoic reactivation in this area. In addition, Early Cretaceous exhumation is also well documented in its southern part (i.e. the Yemaquan Arc). This differs significantly from the thermal history of the Western Junggar that is situated on the opposite (northern) side of the Junggar Basin. Published data suggested that the majority of the basement of the Western Junggar has rapidly cooled to <60 °C since the Permian (~285–260 Ma), followed by limited exhumation during the
Meso-Cenozoic (Gillespie et al., 2020). Therefore, compared with the Western Junggar, this terrane was more significantly affected by the distant effects associated with accretion and collision events at the southern Eurasian margin, producing intra-continental deformation during the Mesozoic. Furthermore, the Cretaceous rapid basement cooling was widespread throughout the southwestern CAOB. In view of the results of this study, Cretaceous reactivation may have extended from the Tianshan belt (including the Beishan) (e.g., Dumitru et al., 2001; Wang et al., 2009b; Jollivet et al., 2010, 2013; Gillespie et al., 2017a, 2017b; Yin et al., 2018b; and this study), through the East Junggar (this study) to the Siberian Altai of the interior Eurasian plate in the north (e.g., Glorie et al., 2012a; De Grave et al., 2014). The role of inherited Paleozoic major fault zones in the strain partitioning was paramount as they were (repeatedly) reactivated and thus controlled the exhumation process (e.g., Rolland et al., 2013; Jourdon et al., 2018b).

Regarding the Cenozoic thermal history, no evidence was found in the Eastern Tianshan and East Junggar for significant exhumation in response to the India-Asia collision. It is evident that most areas in the Eastern Tianshan and East Junggar exhibit low elevations and rather flat topography (Fig. 1b; Gillespie et al., 2017a, 2017b), suggesting that they were relatively stable during the Cenozoic. Although the Bogda and Harlik Arcs display prominent elevation (> ~3–4 km), late Cenozoic reactivation (e.g., Cunningham et al., 2003) failed to produce contemporary thermochronological records due to the low level of denudation and exhumation (Gillespie et al., 2017a). Also, in this study it was found that basement rocks from the Harlik Arc cooled through the APAZ in the Cretaceous (Fig. 6). This hence implies that no more than 60°C of crustal cooling (corresponding to ~2 km of exhumation) has occurred during the Cenozoic. It is noted that Wang et al. (2008a) reported a large set of young Oligocene-Miocene AFT ages from the eastern Bogda Arc, however, recent studies and our data suggested that Cretaceous AFT ages are prevalent along the Bogda and Harlik Arcs (Gillespie et al., 2017a; Chen et al., 2020). Such young cooling ages in this region indicate that significant relief generation took place during the late Cenozoic, resulting in high-relief topography like the present-day South Tianshan-Pamir ranges. However, topographic analyses show a large area of low-relief surface occurring in the Bogda mountain (Morin et al., 2019). We therefore argue that there was no significant uplift in the Eastern Tianshan during the Cenozoic. Available late Cenozoic low-temperature cooling ages mainly come from the southern margin of the eastern Tianshan belt and the northern margin of the Tarim Basin (e.g., Sobel et al., 2006; Chang et al., 2012, 2021; Jia et al., 2015; Rolland et al., 2020; He et al., 2021b), however, compared with Cretaceous exhumation, late Cenozoic reactivation did not result in large-scale deep basement exposure in the southwestern CAOB.

6. Conclusions

New apatite fission track data for Paleozoic granitic rocks and Mesozoic sediments from the Eastern Tianshan and East Junggar belts, putting further constraints on the Mesozoic evolution of the southwestern Central Asian Orogenic Belt, and allow the following conclusions to be drawn:

(1) Regional exhumation occurred in the East Junggar during the late Permian to Early Jurassic, as a result of post-orogenic transpression, and the ensuing far-field effects of the collision of the Qiangtang block with Eurasia.

(2) Moderate to rapid cooling of the basement prevailed in the Eastern Tianshan and southern part of the East Junggar (i.e. the Yemaquan Arc) throughout the Cretaceous. The Early Cretaceous cooling was probably related with contraction of the upper plate triggered by Tethys slab subduction, while the mid- to Late Cretaceous exhumation was likely associated with the compression due to the collision of Lhasa-Qiangtang and Kohistan-Dras Arc. During these processes, reactivation of major faults played key roles in controlling the basement exhumation.

(3) Most areas in the Eastern Tianshan and East Junggar were unlikely to have experienced significant relief generation during the late Cenozoic.

CRediT authorship contribution statement

Zhiyuan He: Conceptualization, Investigation, Methodology, Data curation, Writing – original draft. Bo Wang: Investigation, Writing – review & editing, Funding acquisition. Stijn Glorie: Methodology, Writing – review & editing. Wenbo Su: Methodology, Writing – review & editing. Xinghua Ni: Investigation, Writing
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

We thank Dr. Yann Rolland, Dr. Sabin Zahiriova and an anonymous reviewer for their detailed and constructive comments, together with Associate Editor Prof. Sanghoon Kwon for his efficient editorial handling. We are grateful to Simon Nachtergaele, Ann-Eline Debeer and Jan Jurckea for their assistance in sample preparation in the laboratory of Ghent. We also would like to thank Dr. B. V. Houdt and Dr. G. Vittiglio for help during neutron irradiation at the Belgian Nuclear Research Centre in Mol (SCK-CEN, BR1 facility). This study is partly sponsored by the National Natural Science Foundation of China (42011530146, 41772225, 41390445), the Fund for Scientific Research - Flanders (FWO, Bilateral Project VS06520N). The support provided by the China Scholarship Council (CSC, 201806190214; 201908320260) is appreciated for financing the research stay of Z. He and W. Su in Belgium.

Appendix A. Supplementary material

Supplementary data to this article can be found online at https://doi.org/10.1016/j.gr.2021.11.013.

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