Cenozoic uplift, exhumation and deformation in the north Kuqa Depression, China as constrained by (U-Th)/He thermochronometry

Shun Yu a,b, Wen Chen a,b,⁎, Noreen J. Evans c, Brent I.A. McNees c, Ji Yuan Ying a,b, Jingbo Sun a,b, Jie Li a,b, Bin Zhang a,b

⁎ Laboratory of Isotope Thermochronology, Institute of Geology, Chinese Academy of Geological Sciences, Beijing 100037, China
a National Key Laboratory of Continental Structure and Dynamics, Beijing 100037, China
b John De Laeter Center for Isotope Research, Applied Geology/Applied Physics, Curtin University, Perth, WA 6945, Australia

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A B S T R A C T

Placing spatial and temporal constraints on deformation, uplift and exhumation using thermochronology methods can shed light on Cenozoic orogenic evolution in the Kuqa foreland. New apatite (U-Th)/He and previously published apatite fission track thermochronometry are combined with vitrinite reflectance data and modeling to compile a low temperature, multi-stage thermal history of tectonic uplift/thrust and exhumation. A rapid uplift and exhumation event originated in South Tianshan during the Eocene (~46 Ma), with systematic younging of mean apatite (U-Th)/He ages from north to south (from the margin towards the interior). Uplift and exhumation south edge of the Biyoulebaoguzi anticline in the northern monocline belt at ~36 Ma with more than 3400 m of stratum denuded. Subsequently, deformation and uplift south edge of the Biyoulebaoguzi anticline in the northern monocline belt at ~36 Ma with more than 3400 m of stratum denuded. Subsequently, deformation and uplift extended to the northern edge of Kelausu-Yiqikelike at ~10 Ma and then at ~6 Ma, the Kanyaken anticline formed and uplifted resulting in 3000–3700 m of overburden erosion. The data support sequential southward propagating deformation and uplift (inferred exhumation) in the north Kuqa Depression during the Cenozoic, probably as a result of the collision of India with Asia far to the south of the Tianshan.

1. Introduction

The Tianshan Orogen, extending east–west for ~2500 km from NW China to Kazakhstan and Kyrgyzstan, comprises the southwestern part of the Central Asia Orogenic Belt (CAOB) which is one of the world’s largest, most complex, and long-lasting accretionary orogens (Jahn et al., 1993; Windley et al., 2007; Xiao et al., 2004). The original Tianshan Orogen was created in the Paleozoic by subduction–collision processes (Allen et al., 1993; Charvet et al., 2007, 2011; Gao et al., 1998, 2011; Wang et al., 2011; Windley et al., 1990; Xiao et al., 2009), and since then, the Tianshan Orogen has been subjected to repeated structural reactivation (Windley et al., 1990).

Present-day Tianshan was formed by contraction and uplift in response to the collision of India with Asia, which began in the early Tertiary and continues today as the Himalayan orogeny (Avouac et al., 1993; Kloo t v i j k et al., 1992; Molnar and Tapponnier, 1975; Patri at and Achache, 1984; Sobel and Dumitru, 1997). The Tianshan range is flanked by sedimentary basins, most prominently the Kuqa Depression north of Tarim and the Southern Junggar Basin (Fig. 1). Geologic investigation suggests that Tianshan Cenozoic tectonics was concentrated in the northern and southern margins of the range and dominated by thrusting on roughly E-W striking faults and by folding of Cenozoic sediments (Avouac et al., 1993; Tapponnier and Molnar, 1979; Yin et al., 1998). In recent years, much research has focused on Cenozoic deformation in the Tianshan region, however, the exact timing of deformation, uplift and exhumation, a key to understanding the final orogenic procedures, is still controversial. The varying opinions as to the initial timing of major uplift events in the Cenozoic include: Eocene (Du and Wang, 2007b; Du et al., 2007a), Oligocene (Dumitru et al., 2001; Hendrix et al., 1994; Li et al., 2007; Sobel and Dumitru, 1997; Sobel et al., 2006a; Windley et al., 1990; Yin et al., 1998), and Miocene (Abdrakhmatov et al., 1996; Avouac et al., 1993; Bullen et al., 2001; Charreau et al., 2006; Huang et al., 2006; Sun et al., 2004, 2009).

As thrusts in the southern Tianshan propagated southwards towards the foreland (Lu et al., 2001), a series of Cenozoic thrust–fold zones, which function as hydrocarbon traps, developed on the northern flank of the Kuqa Depression (KD) (Dumitru et al., 2001) (Fig. 2). The oil/gas in the KD is mainly accumulated in these thrust–fold zones (Ma et al., 2003; Xu et al., 2004), and a large number of oil and gas fields have been discovered (e.g., Kela2, Dina, Dabei and Touziliouke; Fig. 2). However, the timing of Cenozoic deformation and thrusting onset still lacks consensus and the timing and magnitude of Cenozoic deformation, uplift and
exhumation in these thrust-fold zones are also poorly understood. Previous research discussing the timing of thrusting onset includes: (1) a 21–24 Ma age based on rough magnetostratigraphic dating of the onset of conglomerate deposition in the KD (Yin et al., 1998). It should be noted, however, that higher resolution magnetostratigraphic data for this conglomerate yielded a middle to late Miocene age (Charreau et al., 2006); (2) an Oligocene age (Wang et al., 2002) was derived from an angular unconformity with underlying deformed strata; and (3) an Miocene age was determined from growth strata which were contemporaneously formed with the tectonic deformation (Lu et al., 2000).

Low temperature thermochronology has proven to be a powerful method to elucidate the timing and magnitude of exhumation in response to uplift, deformation and erosion (e.g., Ehlers and Farley, 2003; Gavillot et al., 2010; Stockli et al., 2000; Wilke et al., 2012), especially apatite fission track (AFT) analysis and apatite (U–Th)/He (AHe) dating. The temperature sensitivity of these chronometers (apatite fission track: 110–60 °C (Gleadow et al., 1986; Green et al., 1989); apatite (U–Th)/He: 85–40 °C (Farley, 2000; Wolf et al., 1998)) makes them suitable for recording the timing and magnitude of removal of 1–5 km of crust. AFT has been utilized in numerous studies to constrain the uplift and exhumation history in the Tianshan region (e.g., Bullen et al., 2001; Chen et al., 2008; Du and Wang, 2007b; Dumitru et al., 2001; Luo et al., 2012; Ren et al., 2009; Sobel and Dumitru, 1997; Sobel et al., 2006b; Xiao et al., 2011; Yang and Qian, 1995; Zhu et al., 2006). However, the AFT method alone cannot provide reliable constraints on cooling below 50–60 °C and, given the restricted Cenozoic exhumation in the Kuqa area, AFT ages can contribute little to our understanding of the thermal history at this time (Dumitru et al., 2001).

Fig. 1. Geological sketch map of the Tianshan belt and main structural elements of the study area. (a) Location of the study area in Asia; (b) local terranes in western Xinjiang, NW China. Modified from Yang and Zhou (2009), Jong et al. (2009) and Qiu et al. (2012).

Fig. 2. Regional topography of the KD and STS, showing tectonomorphic zones, and the approximate locations of thrust faults (based on compilation of published mapping) (modified after He et al., 2009; Jin et al., 2008; Lu et al., 2001; Zeng et al., 2010), a series of linear, west–east striking anticlines, parallel to the STS boundary. White box indicates area mapped in Fig. 5 and the orientation of the cross-section used in Fig. 3.
In this work we briefly review the existing AFT data and present new vitrinite reflectance data and AHe ages on exhumed Triassic, Jurassic and Cretaceous strata in thrust–fold belt of KD and from the pluton in southern part of South Tianshan. In contrast to earlier studies, this multidisciplinary study provides more information on the magnitude and timing of uplift and exhumation related to recent deformational events, and combined with previously published work, allows us to better quantify the Cenozoic uplift and exhumation history in the north of KD, which has important implications for petroleum exploration in the region.

2. Background

2.1. Regional geology

The Chinese Tianshan orogenic belt is usually divided into western and eastern segments with the west segment further sub-divided as North, Central and South Tianshan (NTS, CTS, STS) (Fig. 1). During the Cenozoic, the Paleozoic orogenic belt reactivated and boundaries between NTS, CTS and STS are currently characterized by strike–slip shear zones. STS is regarded as a collisional zone separating the CTS and CTS–STS and eastern segments with the west segment further subdivided as northern monocline structural unit within the northern Tarim Basin. The KD is a Mesozoic–Cretaceous strata deformed parallel to STS (e.g., Jin et al., 2009; He et al., 2009). The Cenozoic Asia–India collision is responsible for the recent southward thrusting of STS onto the Tarim Basin, and for the northward thrusting of NTS onto the Junggar Basin.

The Kuqa foreland located in the piedmont of the STS Range, which connects the STS orogenic belt with the Tarim block, is a secondary structural belt of KD and from the pluton in northern part of the KD during the Mesozoic and Cenozoic periods, and ~5–6 km is assigned to the Cenozoic. The Cenozoic stratigraphic sequences in the KD have been detailed from both outcrop and drill hole investigations (Yin et al., 1998), and are comprised of Paleogene Kumugeliemu and Suweiyi Formations, Neogene Jidike, Kangcun, and Kuqa Formations, and the Neogene–Quaternary Xiyu Formation (Fig. 4). These sedimentary formations not only show distinct lateral changes in lithology and thickness but also contain several regional and local unconformities. Two major regional unconformities in the Cenozoic are revealed (Fig. 4): (1) unconformable contact between the Paleocene–Eocene Kumugeliemu Formation and underlying Cretaceous strata; (2) unconformable contact between the Miocene Kangcun Formation and Pliocene Formation. Cenozoic terrigenous sediments of the KD lack the diagnostic fossil or geological data and aHe ages on exhumed Triassic, Jurassic and Cretaceous strata in thrust–fold belts.

2.2. Previous work

To estimate equivalent depths and/or rates of denudation from thermal histories, we need to know the geothermal gradient and, ideally, the
heat flow and appropriate thermal conductivities. Previous thermal regime studies in the Tarim Basin include measurements of the present-day geothermal gradient, heat-flow distribution characteristics and thermal state of continental lithosphere (Feng et al., 2009, 2010; Li et al., 2000; Liu et al., 2004, 2006; Wang et al., 1995, 2003, 2005a). The present-day geothermal gradient in the Tarim Basin ranges from 17 to 32 °C/km with an average of 23 °C/km. Based on temperature data from exploration wells, heat-flow ranges from 26 to 65 mW/m² with an average of 43 mW/m² (Feng et al., 2009, 2010). The present-day geothermal gradient and heat-flow in the KD range from 18 to 28 °C/km (Wang et al., 2003) and 40 mW/m² and 50 mW/m² (Wang et al., 2005) in which the present-day geothermal gradient and heat-flow gradually decrease from north to south in the KD. All these temperature data provide the basis for our study and will permit a more precise understanding of the thermal history.

Previous studies on the KD thermal history have been based on vitrinite reflectance (VR) in both boreholes and outcrops (Li et al., 2004a; Wang et al., 1999, 2005b; Yang et al., 2005) using the EASY%Ro model (Sweeney and Burnham, 1990). The thermal history of well YN2 in the east of the KYSB has been reconstructed in more detail than the other wells (Gao et al., 2002; Li et al., 2004b) in which the stratigraphic sequences are duplicated as a result of faulting and relationships between the depth and VR is poor (e.g., YX1 and KZ1).

Fig. 4. Stratigraphic chart of Kuqa River in the KD modified from Li et al. (2005). Timescale is in agreement with Huang et al. (2006), Peng et al. (2006) and Zheng and Meng (2006). Two major regional angular unconformities are noted in the Cenozoic: Between the Paleocene-Eocene Kumugeliemu Formation and underlying Cretaceous strata, and between the Miocene Kangcun Formation and the Pliocene Formation.
Dumitru, 1997), and a rapid uplift event in the Miocene (Bullen et al., 2001; Yang et al., 2003) given by AFT data. Based on AHe data in the Tarim Basin, Qiu et al. (2012) suggest that the STS experienced rapid uplift in the Miocene. The Tianshan uplift during the Neogene is also evidenced by depositional characteristics, subsidence centers, composition of clastic sediments and heavy minerals (Fang et al., 2004; Li et al., 2003, 2004c, 2006a, 2007; Wu et al., 2005) and geomagnetic chronology (Charreau et al., 2006, 2009; Chen et al., 2002; Huang et al., 2006; Sun et al., 2004, 2009).

2.3. Methods

The study area is characterized by thrusts and folds, suggesting that exhumation driven by contractional deformation and erosion was the primary mechanism for Cenozoic cooling. In this setting, AHe thermochronometry can be employed to constrain the timing and magnitude of cooling through the 40–80 °C temperature window (Stockli et al., 2000; Wolf et al., 1998) and provides particularly useful information on onset and duration of accelerated thrust-related exhumation.

![Fig. 5. Simplified geologic map of the Kuqa River area, with (U–Th)/He and fission-track sample localities. Map modified from Wang et al. (2004). (a) Location of this map is outlined as a white box in Fig. 2, showing Mesozoic-Cenozoic stratigraphy. Black filled squares, unfilled squares, unfilled circles are AFT sample locations from Du et al. (2007a, 2007b), Luo et al. (2012) and Dumitru et al. (2001), respectively. (b) Cross section of the sedimentary succession (location is indicated in subpanel AA′) exposed in the Kuqa River area showing major stratified units and the distribution of sampling sites (red filled circles with AHe ages, from Triassic to Cretaceous deposits). The mean AHe ages are systematically younging in a southward direction.](image-url)
lost from the grain by alpha-ejection within a 20 μm outer rim of the mineral grain (Farley et al., 1996; Wolf et al., 1996). The measured AHe ages have to be corrected (Ft correction; Farley et al., 1996) according to size and morphology of the crystal prior to dating (Farley et al., 1996; Gautheron et al., 2009; Ketcham et al., 2011) or this process can be allowed for explicitly during thermal modeling (Gautheron et al., 2012; Meesters and Dunai, 2002).

The thermal history of a sedimentary basin can be recovered by integration of data from multiple paleothermometers and chronometers. Integration of thermochronological data (e.g., AHe and AFT data) with mineral grain (Farley et al., 1996; Wolf et al., 1996). During the decay of U and Th, alpha particles (He) are emitted with high kinetic energy and travel significant distances before stopping (approximately 20 μm in apatite, Farley et al., 1996). Therefore, in addition to diffusive controls on He loss, He can be lost from the grain by alpha-ejection within a 20 μm outer rim of the mineral grain (Farley et al., 1996; Wolf et al., 1996). The measured AHe ages have to be corrected (Ft correction; Farley et al., 1996) according to size and morphology of the crystal prior to dating (Farley et al., 1996; Gautheron et al., 2009; Ketcham et al., 2011) or this process can be allowed for explicitly during thermal modeling (Gautheron et al., 2012; Meesters and Dunai, 2002).

The thermal history of a sedimentary basin can be recovered by integration of data from multiple paleothermometers and chronometers. Integration of thermochronological data (e.g., AHe and AFT data) with maximum paleotemperature indicators like VR is particularly useful in basin analysis. VR is the measure of the coalification rank of organic matter, and is used as an indicator of thermal maturity which is mainly dependent on temperature and time (Sweeney and Burnham, 1990). VR data provide a direct estimation of maximum paleotemperatures across the same temperature range as AFT and AHe.

### 3. Samples and analysis

In the KD, the dominant outcrop rocks are Mesozoic and Cenozoic sedimentary rocks. We limited the study area to the north of the KD, where Cenozoic activity is most obvious, and surveyed a transect perpendicular to the general E–W trend of the Tianshan from STS to KD, along the Kuqa River (Fig. 5). It is the same stratigraphic profile along which Du et al. (2007a) and Dumitrut et al. (2001) conducted the AFT studies that we have integrated with our new thermochronology data. Six samples from the Triassic to Cretaceous deposits of the Kuqa River section in KD and 1 sample from the Oxidaban pluton in STS were collected for AHe analysis. The samples were located in the northern KD margin (both from the hanging wall and foot wall of the KBT fault), Biyoulebaoguzi anticline of the NMB and KYSB. Detailed sample locations are marked in Fig. 5. Apatite crystals were separated using the sample preparation procedure described by Donellick et al. (2005) and 3–5 crystals were handpicked based on morphology, clarity, and lack of inclusions. Where possible, only good quality, euhedral grains were selected for analysis, and these were measured and digitally photographed in 3 different orientations. Every effort was made to select grains with a diameter larger than 70 μm in order to maximize helium gas values and minimize the Ft correction. In practice, an AHe age is obtained using a two-stage analytical procedure which includes measuring radiogenic He released from apatite grains during laser heating, and measuring the amounts of U and Th in the same crystal by isotope dilution solution ICP-MS. The analyses were done at the John De Laeter Center for Isotope Research, Curtin University, following the procedures described by Evans et al. (2005).

Measured and photographed grains were loaded into platinum microtubes. Helium was thermally extracted from single crystals using a 1064 nm Nd:YAG laser and ⁴He abundances determined by isotope dilution using a pure ³He spike, calibrated daily against an independent ⁴He standard tank. Following outgassing, a re-extract hot blank was added to correct for the blank.

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**Fig. 6.** Outcrop photographs of the southern limb of the Biyoulebaoguzi anticline. (a) Topography of the south limb of the Biyoulebaoguzi anticline from Google Maps, showing the sample locations. (b) Sketch map from the core of the anticline (modified from Wang et al., 2004), showing the thrust fault (location is indicated in subpanel a) in the core of the anticline. The thrust fault cut across the upper Triassic Talique Formation. (c) Location of sample KY1106. The dashed line marks the boundary between the Qiaokemake and Kezilenuer Formations. (d) Location of sample KY1101. The dashed line marks the boundary between the Huangshanjie and Talique Formations. The upper Triassic and Jurassic are composed of sandstone and interbedded mudstone, and the latter were collected for vitrinite reflectance analysis.
performed to verify complete outgassing, and 4He results were blank corrected. The uncertainty in the sample 4He measurement was <1%. U and Th contents were determined using isotope dilution inductively coupled mass spectrometry. Crystals in Pt microvials were dissolved in 25 μl of a 50% (by volume; approximately 7 M) HNO3 solution containing approximately 15 ppb 231U and 5 ppb 230Th. The apatite was digested in the spiked acid for at least 12 h to allow the spike and sample isotopes to equilibrate. Standard solutions containing the same spike amounts as the samples, in addition to 25 μl of a standard solution containing 27.6 ppb U and 28.4 ppb Th, were treated identically, as were a series of unspiked reagent blanks. 250 μl of Milli-Q water was added prior to analysis on an Agilent 7500CS mass spectrometer. U and Th isotope ratios were measured to a precision of ~2%. Overall the apatite Curvin (U–Th)/He thermochronology method has a precision of 2.5% forapatite, on multiple age determinations (n = 26) of Durango standard which produce an average age of 31.1 ± 1.0 (2σ) (U–Th)/He ages from the Kuqa River section.

In order to constrain the reheating post-depositional history, we collected 4 coal samples and 6 mudstone samples in the Biyoulebaoguzi Jurassic, and were comprised of sandstone and interbedded mudstone over the timescale of interest, samples ranged in age from Triassic to Jurassic, and were in excellent agreement with the reference Durango (U–Th–Sm)/He age of 31.02 ± 1.01 Ma (McDowell et al., 2005).

### 4. Results and modeling

#### 4.1. Results

Table 1 gives the AHe results from the 3–5 single crystals analyzed from each sample. The uncorrected ages range from 3 Ma to 34 Ma, while the Ft corrected ages range from 4 Ma to 57 Ma. Fig. 7 shows the AHe data plotted versus stratigraphic age, along with the AFT data as taken from Dumitru et al. (2001), Du et al. (2007a) and Luo et al. (2012). Horizontal error bars represent 2σ uncertainty on the mean age based on single-grain replicate ages. The samples from sedimentary rocks have AFT central ages ranging from 28 Ma to 118 Ma (Du et al., 2007a) and for each sample, the uncorrected AHe ages are younger

<table>
<thead>
<tr>
<th>No.</th>
<th>Sam.</th>
<th>Str.</th>
<th>⁴He (ncc)</th>
<th>U (ppm)</th>
<th>Th (ppm)</th>
<th>Th/U</th>
<th>Ft</th>
<th>eU (ppm)</th>
<th>Mass (μg)</th>
<th>Radii (μm)</th>
<th>Unc. age (Ma)</th>
<th>Cor. age (Ma)</th>
<th>±1σ (Ma)</th>
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<tbody>
<tr>
<td>1*</td>
<td>KY1101</td>
<td>T3n</td>
<td>0.21</td>
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<td>66.7</td>
<td>3.7</td>
<td>0.61</td>
<td>34.1</td>
<td>1.4</td>
<td>41.9</td>
<td>34.8</td>
<td>57.2</td>
<td>1.3</td>
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<td>0.67</td>
<td>29.9</td>
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<td>48.8</td>
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<td>16.8</td>
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<td>21.3</td>
<td>2.1</td>
<td>41.1</td>
<td>22.0</td>
<td>35.3</td>
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<td>6.9</td>
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<td>53.1</td>
<td>7.1</td>
<td>10.3</td>
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<td>0.9</td>
<td>0.6</td>
<td>69.4</td>
<td>1.3</td>
<td>39.1</td>
<td>15.6</td>
<td>25.8</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Table 1: Apatite (U–Th)/He ages from the Kuqa River section.
than the corresponding AFT age (Fig. 7). Most corrected ages are both significantly younger than the unit’s depositional age and the corresponding AFT ages. The mean ages for each sample were calculated by combining single-grain ages (Table 1).

Geologic constraints suggest that these detrital samples were all buried to depths greater than 3 km (as indicated by stratum in drilling wells located near to collected samples) and subsequently exhumed. Assuming a geothermal gradient of 26 °C/km [Wang et al., 2003] and standard Durango apatite diffusion kinetics, all samples were completely thermally reset during burial, indicating significant post-depositional He loss from the apatite crystals. Therefore, all grain-age populations are taken into account for interpretation, as they represent cooling ages.

Cooling of these samples most likely reflects erosional exhumation or deformation driven by uplift above subjacent or deeper thrusts. Substantial stratigraphic thickness has been eroded in the study area.

Some samples are characterized by a large spread in single AHe ages, so much so that within one sample, the variations in most single grain AHe ages exceeds the analytical error (e.g. sample KY1107, Table 1). Thermal models by Wolf et al. (1998) showed that long residence within the HePRZ can lead to different single grain AHe ages for different grain radii, however, all analyzed grains exhibit only a very weak correlation between AHe age and radius (Fig. 8). The scatter of AHe ages from four individual rock samples systematically varies with effective uranium concentration (eU = U + 0.235Th) (Shuster et al., 2006) (Fig. 9). The old ages correspond to high eU apatite, indicating that these crystals may have more radiation damage. Samples subjected to reheating after accumulation of substantial radiation damage will be more retentive than previously expected (Shuster et al., 2006). It follows that higher degrees of radiation damage increased He retentivity, raised the effective closure temperature (Tc) and resulted in older AHe ages. In contrast, the young ages in low eU crystals indicates less radiation damage, suggesting that they were thermally reset during burial. Thus, the older populations are not considered for modeling purposes, and the younger populations are interpreted to record the most recent signal of exhumation. We have excluded some ages from the mean calculations because the measured AHe ages were older than the depositional age (e.g., sample KY1107) or corresponding AFT age, and the AHe ages are distinctly different from other ages from the same samples (“fliers”). Undetected, He-bearing mineral inclusions are the likely reason for these anomalous ages. A plot of mean age vs. depositional age shows that sample AHe ages generally increase with depositional age (Fig. 7), suggesting a remarkable southward younging trend among the mean AHe ages (Fig. 5b).

10 VR samples were analyzed and the results are presented as mean random reflectance values in Table 2. Overall, VR data ranged between 0.55% and 0.94%, which were consistent with reported in Wang et al. (2005b) (Table 2). The samples show a decrease in VR from the Triassic Huangshanjie Formation to the Jurassic Qiakemake Formation.

4.2. Modeling

4.2.1. Modeling of AHe data

The low-temperature thermal history was further revealed using numerical inverse modeling (HeFTy software; Ketcham, 2005). The
HeFTy approach uses constrained Monte Carlo simulations and takes into account the effects of grain size, radiation damage, and cooling rate on the thermal history (Flowers et al., 2009; Ketcham, 2005). Flowers et al. (2009) suggested that nonlinear, positive correlations between AHe age and eU in apatite crystals subjected to the same thermal history are a diagnostic signature of radiation damage accumulation and annealing and developed a model (RDAAM) to treat such data. Samples in this study show a relationship between grain ages and eU (Fig. 9), qualifying them for inverse modeling using RDAAM. For each sample, model constraints based on geologically plausible scenarios were used as input for deposition, burial, and exhumation so as to allow maximum modeling freedom. The model was allowed to run until 100 good paths were found, and if that failed, the model considered 100 acceptable paths. Known constraints on the deposition temperature of the sample were input (15 ± 5 °C) as the boundary condition at the time of deposition. Constraint on the present-day temperature was placed at 12 ± 4 °C (Wang et al., 2003). Constraints on burial were input from the earliest known depositional age to present, and the temperatures during burial utilized the results of burial and thermal history modeling from VR data for reference as described above. Because AHe ages are significantly younger than the unit depositional age and the corresponding AFT age, we assumed that the samples had been heated above the HePRZ and imposed a maximum burial temperature above 90 °C (Yu et al., 2014). All samples were modeled to start at an age double the depositional age; only the most recent, relevant thermal history is shown in Fig. 10. All model results allow relatively wide boundaries on the timing of burial, but show strong, well-constrained paths of the most recent cooling and exhumation. Although thermal models cannot determine the exact path of exhumation, they can provide constraints on a time—temperature window, indicating when the sample began cooling through the HePRZ, and thus expanding our confidence in the interpretation of recent cooling. While AHe thermochronology cannot tell us about events that occurred while the sample was buried beneath the HePRZ, incorporating the data with reasonable assumptions and known geological constraints allows us to make reasonable interpretations.

4.2.2. Burial and thermal history modeling of VR samples

Reconstruction of the thermal evolution and burial history in the structure provided information on maximum paleotemperatures and the relative rates of erosion. VR data provides wider information on the paleotemperature range, especially when the AFTs are totally annealed and only constrain minimum paleotemperature estimates. The Easy%Ro model of VR (Sweeney and Burnham, 1990) was applied in thermal history modeling. The basic geologic data used in thermal modeling included lithologic data, present-day surface temperatures, thermal gradients (or heat flow), paleosurface temperature, thermal conductivity, compaction factors and stratigraphic data. A complete stratigraphic section was measured in the Biyoulebaoguzi anticline, and gross lithologic characteristics were recorded to construct the stratigraphic column (Fig. 4). The thickness of the strata was taken from a measured section of the Kuqa River in the Biyoulebaoguzi anticline. Present day temperatures and thermal gradients (or heat flow),

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**Table 2**

Vitrinite reflectance data in the Kuqa River area.

<table>
<thead>
<tr>
<th>Stratum</th>
<th>Lithology</th>
<th>VR (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T₁h</td>
<td>Mudstone</td>
<td>0.80</td>
</tr>
<tr>
<td>T₁h</td>
<td>Mudstone</td>
<td>0.87</td>
</tr>
<tr>
<td>T₁t</td>
<td>Coal</td>
<td>0.94</td>
</tr>
<tr>
<td>T₁t</td>
<td>Coal</td>
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</tr>
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</tr>
<tr>
<td>J₁e</td>
<td>Oil shale</td>
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<td>0.50–0.67</td>
</tr>
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<td>Mudstone</td>
<td>0.54–0.55</td>
</tr>
<tr>
<td>J₁t*</td>
<td>Coal</td>
<td>0.78</td>
</tr>
<tr>
<td>J₁h*</td>
<td>Coal</td>
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<td>Mudstone</td>
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</tr>
<tr>
<td>J₂q**</td>
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<td>J₂q**</td>
<td>Mudstone</td>
<td>0.78–1.09</td>
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Note that the VR data marked with * are from Wang et al. (2009b); VR data marked with ** from well YX1 (depth from 2240 to 3020 m) and the well location are indicated in Fig. 2.
paleosurface temperature and thermal conductivity were adopted from previous publications (Feng et al., 2009; Liang et al., 2002; Liu et al., 2006; Wang et al., 1995, 2005a). Compaction factors were obtained from the Sclater and Christie (1980) model. The thickness of Cenozoic erosion and the initiated timing of uplift and exhumation in this model were determined by thermochronological data as discussed in the following section. The gross lithology, thickness of units, thickness of erosion, and existing age control were used to create a geohistory diagram for the anticline, and VR data were added to model the thermal history using PetroMod software.

5. Interpretation of AHe ages and HeFly modeling

5.1. Margin of KD

Our most northerly sample (KY1105) is located in the north of the basin boundary fault (hanging wall of KTB fault) and in the southwestern section of STS, where the Oxidaban pluton is exposed. Lithologically, the Oxidaban pluton comprises mainly quartz diorite, granite porphyry and monzonitic granite (Wang et al., 2009b), which is characterized by strong late stage deformation and is in fault contact with the KD (Fig. 5). Zircon U–Pb LA–ICP-MS dating of monzonitic granite yields an age of 421 ± 3 Ma (Wang et al., 2009b) and the age of TIMS U–Pb isotopic dating for the quartz diorite from Oxidaban pluton is 426.3 ± 1.9 Ma (Xu et al., 2006), which represents the emplacement age of Oxidaban pluton. AFT ages for samples from the granite range from 35 Ma to 61 Ma, with a mean age of 46 Ma (Table 3) (Du and Wang, 2007b; Dumitru et al., 2001). Four single AHe ages of K1105 (Oxidaban pluton) range between 23 and 37 Ma with mean age of 32 Ma. All AHe ages are younger than the corresponding average AFT age of 46 Ma. The AFT and AHe ages are younger than the zircon U–Pb ages, and are, therefore, interpreted as cooling ages, recording the passage of the pluton through aptatic partial annealing zone (APAZ: ~110 °C) and HePRZ (~85–40 °C).

For any given sample, all single grains have experienced the same geological history, so their AFT and the corresponding AHe data should reflect the same cooling history. In order to constrain the time–temperature (t–T) history of Oxidaban pluton, we modeled the thermal history using the AHe data and HeFly software (Ketcham, 2005), applying the following external t–T parameter constraints: U–Pb ages, mean AFT ages. The thermal models run for mean grain age start at an age of 421 Ma with only the recent thermal history shown in Fig. 10a. Modeling reveals the three-stage cooling of the Oxidaban pluton, the first stage starting from temperatures >160 °C, followed by rapid cooling through the HePRZ from 46 Ma to 40 Ma and finally, slow cooling to the surface.

Sample K1102 is from Triassic strata exposed on the boundary of the KD (footwall of the KBT fault, ~1 km south of the fault), about 2 km from K1105. K1102 yielded AHe ages of 51, 48, 46, 35, and 24 Ma, with a corresponding AFT age of 42 ± 4 Ma from Du et al. (2007a). Geologic constraints and VR data (Li et al., 2004a; Wang et al., 2005b) at margin of the KD suggest that sample K1102 was buried to maximal depths >5 km and that, subsequently more than 4 km of overburden (Mesozoic stratum) was exhumed during the Cenozoic. This implies that the sample experienced maximum burial temperatures above ~110 °C, resetting the AHe ages. The AHe ages should, therefore, record recent cooling following basin thrust or exhumation, presumably related to deformation. Five grains in sample K1102 cluster into two distinct populations based on the relationship between the AHe ages and AFT ages. The three youngest ages of 46 Ma, 35 Ma and 24 Ma are younger than the corresponding average AFT age of 46 Ma. All AFT and AHe ages are younger than the zircon U–Pb ages, and are, therefore, interpreted as cooling ages, recording the passage of the pluton through aptatic partial annealing zone (APAZ: ~110 °C) and HePRZ (~85–40 °C).

...
than the corresponding AFT age and correlate with exhumation, but two other grains (with high eU) yield ages older than the AFT age.

The three youngest ages of K1102 were chosen for thermal history modeling, which suggests that Cenozoic cooling likely initiated by ~40 Ma, with a period of rapid cooling between 40 Ma and 35 Ma marking the transition from deep burial, through the APAZ and HePRZ and then to the surface (Fig. 10b). Modeling results also indicated that this sample had experienced a maximum temperature of >140 °C, suggesting removal of at least 4500 m of overburden (geothermal gradient, 28 °C/km; surface temperature, 12 °C), consistent with Wang et al. (2005b) and Li et al. (2004a).

Table 3

<table>
<thead>
<tr>
<th>Number</th>
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<th>n</th>
<th>Tc (Ma) (±1σ)</th>
<th>L (µm) (N)</th>
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<tbody>
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<td>61 ± 4</td>
<td>11.9 ± 1.7 (116)</td>
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<td>54 ± 3</td>
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</tr>
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<td>37 ± 3</td>
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</table>

5.2. NMB

In the Kuqa river section, the NMB mainly consists of the northern jiesidelike anticline and southern Biyoulebaoguzi anticline, where the deformed Triassic and Jurassic Formations are exposed at the surface. The jiesidelike anticline is a fault–bend fold dominated by a thrust fault that cuts across the lower Triassic and upper Permian (Fig. 3BB). The Jiesidelike anticline is a fault and yields discrete AHe ages of ~35 Ma, 25 Ma, 11 Ma, 8 Ma and 5 Ma, (mean of 17 Ma), all of which are significantly younger than the depositional age and are representative of recent cooling. Five apatite crystals from KY1106, located in southernmost limb of the anticline, yielded two distinct age clusters and all ages are younger than the depositional age. The three younger ages are 11 Ma, 11 Ma and 5 Ma, while two other grains yield ages of 26 Ma. All the samples in this anticline experienced peak burial temperature above 100 °C, and have been fully reset during burial. All samples were likely buried to a maximum depth below the HePRZ, while KY1101 was likely subjected to greater temperatures and experienced temperature below APAZ. As described above, due to stratigraphic burial reheating, all samples in the anticline have been completely reset post-deposition and all AHe ages can be interpreted to record rapid cooling through the HePRZ.

Mean AHe ages become systemically younger from the core of the Biyoulebaoguzi anticline (KY1101) to the southern limb (KY1106). This may be attributed to differential uplift and exhumation during Cenozoic. Sample KY1101 was strategically collected from the deepest stratigraphic interval of the anticline, however, AHe ages show for KY1101 are considerably older than the more shallowly burial samples (KY1106 and KY1103) from Jurassic strata. This suggests that KY1101 cooled through the HePRZ earlier than KY1106 and KY1103. Apparently, the amount of exhumation decreases from the core to the southern limb, such that the core sample was exhumed from Triassic strata while the limb sample was exhumed from Jurassic strata. This is in good agreement with the denudation system of the anticline, indicating that the core of the anticline at high altitude had been strongly denuded (leading to Jurassic strata removal), whereas at lower altitude, at least ~1 km of relict Jurassic strata remains.

Based on constrains from burial and thermal history modeling using VR data, we modeled the thermal histories using HeFty software and AHe data (Fig. 10c, d, e), respectively. Results suggest that all samples experienced maximum temperatures above 100 °C, and were fully reset during burial. All three samples yield similar thermal histories, with the timing of cooling onset during the Cenozoic varying by ±10 Ma. KY1101 modeling indicates that the onset of cooling was ~6000 m.
~36 Ma, while the other samples (KY1103, KY1106) suggest that cooling started at ~26 Ma and 18 Ma, respectively. Assuming a geothermal gradient of 26 °C/km (Wang et al., 2003), the thickness of strata denuded during the Cenozoic was calculated by modeling using AHe data from KY1101 and KY1106, ranging from ~3400 m to 5000 m. There must have been 1000–2000 m of rapid Paleocene burial prior to exhumation at ~36 Ma (Fig. 11a) with subsequent unroofing completely removing Paleocene and Cretaceous strata in the area. These results are in good agreement with Du et al. (2007a) who suggested that the thickness of denuded strata was 3100–3500 m in this structure and that the onset of cooling was ~30 Ma during Cenozoic. Overall, these samples imply rapid cooling during the late Eocene to Miocene. The onset of cooling shows younging southward, from the core of the anticline to the southern limb, and the timing of the onset of cooling of sample KY1101 represents the onset of exhumation for this anticline.

5.3. KYSB

The KYSB, which is close to the NMB and bound by thrust faults, consists of two rows of shallow anticlines. Cretaceous outcrops are found in the north of the anticline belt while Paleogene outcrops occur in the south. Surface outcrops reveal several folds trending NEE–EW, intersected and deformed by strike thrust faults. The Kanyaken anticline is a detachment fold (Lu et al., 2000, 2001; Wang et al., 2004) located at the juncture of the KYSB and Kuqa River, and consisting of steep strata in the core and gently dipping strata in the limbs. This anticline exposes the Jurassic Qigu Formation and Cretaceous rocks in the core, and the Paleogene Kumugeliemu, Suweiyi, Neogene Jidike and Kangcun Formations in the limbs (Fig. 12). The core of the anticline is relatively closed, corresponding to a deep, high-angle basement-involved thrust tip (Qi et al., 2009). We collected two samples for AHe analysis from the KYSB. KY1107 from the Jurassic Qigu Formation located in the hanging wall of the thrust boundary faults, and K1108 from Cretaceous rocks located in the northern limb of the Kanyaken anticline, in the hanging wall of a thrust fault (F2, Fig. 12).

5.3.1. Northern boundary

Four of the five apatite crystals analyzed from KY1107 yielded AHe ages (43 Ma, 32 Ma, 12 Ma, 7 Ma) younger than the depositional age. We excluded the grain yielding an age of 155 Ma because we suspect...
there was an undetected mineral inclusion present. According to the burial and thermal history modeled from VR data, KY1107 was buried to a maximum depth just below the HePRZ, and should have briefly entered the HePRZ. The grain yielding an age of 43 Ma contained a tiny bi-refrangent inclusion, which is likely the cause for its anomalously old AHe age. Compared with the other four grains, the grain yielding an age of 106 Ma has very high Eu and contains approximately 325 ppm U (Table 1). We suspect that the radiation damage plays a significant role in the single-grain age, due to residence below the HePRZ almost immediately prior to the onset of Cenozoic exhumation. Therefore, we consider the two younger ages of 12 Ma and 7 Ma to represent the main exhumation and cooling events in the hanging wall of the thrust fault. HeFTy modeling of the AHe ages shows that sample KY1107 experienced peak burial temperatures higher than 90 °C, corresponding to a fault. HeFTy thermal history models for KY1108 show peak burial temperature ~90 °C and suggest that the timing of the onset of cooling was ~6 Ma during the Cenozoic (Fig. 10 g). Apatite in Cretaceous strata from the Kanyaken anticline partially annealed at temperatures < 110 °C (Du et al., 2007a) and experienced too little exhumation to be dated by AFT. Thus, the AHe data adds critical information indicating that, following their deposition, currently exposed Cretaceous units in this anticline were buried by 3000–3700 m of Cenozoic strata to peak burial temperatures of 90–110 °C at ~6 Ma and that subsequent unroofing exposed the sample at the surface. This means in the last ~6 Ma, 3000–3700 m of overburden was removed during Cenozoic folding and thrusting with a corresponding denudation rate of 0.5–0.62 mm/yr.

5.3.2. Kanyaken anticline

Cretaceous samples from the Kanyaken anticline in the KYSB represent mixed ages and yield central AFT ages (~81 Ma to ~106 Ma; Fig. 12) close to the depositional age (Fig. 7) (Du et al., 2007a; Dumitru et al., 2001), indicating that the sediments have only been weakly to moderately heated after deposition (Du et al., 2007a). Cenozoic samples from this anticline yield central AFT ages from ~50 Ma to ~154 Ma, all of which are older than depositional age (Du et al., 2007a; Luo et al., 2012). Three samples from the Paleogene strata yield central AFT ages older than those from Cretaceous strata, suggesting that all Cretaceous AFT samples were likely buried to a maximum depth within the APAZ and, experienced maximum temperature less than 110 °C, corresponding a depth of 3700 m (assuming geothermal gradient of 26 °C/km, surface temperature of 12 °C (Wang et al., 2003)). However, Cenozoic samples have not experienced any significant post-depositional resetting of the AFT system because limited overburden did not bury the samples deeply enough. AFT samples from Cretaceous strata in this anticline may provide the cooling information of both provenance and post-deposition, while Cenozoic samples only reflect provenance (Du et al., 2007a; Luo et al., 2012). The thermal and burial history yielded by PetroMod software and VR data also implies that KY1108 experienced a maximum temperature between 90 °C and 100 °C and a maximum depth of between 3600 m and 4000 m during the post-depositional period (Fig. 11d).

Fig. 12. Cross-sections of the Kanyaken fold of the KYSB in the KD, modified from Zhang et al. (2007). Locations are indicated in Fig. 5a. (a) Two sets of faults and slickensides developed in the Kumugeliemu conglomerate in the northern limb of the anticline. Cretaceous samples yield central AFT ages close to the depositional age, and Cenozoic samples yield central AFT ages older than the depositional age. (b) The thrust faults cut across Cretaceous strata with faulting occurring before the end of the Pliocene (Zhang et al., 2007).

Five apatite crystals from K1108 yielded AHe ages ranging from 4 Ma to 7 Ma with a mean age of 5.6 Ma, all younger than the depositional age. KY1108 was completely thermally reset and experienced a maximum depth below the HePRZ before the onset of Cenozoic exhumation. Overall, the AHe ages are interpreted to represent recent cooling of the hanging wall of the thrust fault in the Kanyaken anticline. HeFTy thermal history models for KY1108 show peak burial temperature ~90 °C and suggest that the timing of the onset of cooling was ~6 Ma during the Cenozoic (Zhang et al., 2007). Apatite in Cretaceous strata from the Kanyaken anticline partially annealed at temperatures < 110 °C (Du et al., 2007a) and experienced too little exhumation to be dated by AFT. Thus, the AHe data adds critical information indicating that, following their deposition, currently exposed Cretaceous units in this anticline were buried by 3000–3700 m of Cenozoic strata to peak burial temperatures of 90–110 °C at ~6 Ma and that subsequent unroofing exposed the sample at the surface. This means in the last ~6 Ma, 3000–3700 m of overburden was removed during Cenozoic folding and thrusting with a corresponding denudation rate of 0.5–0.62 mm/yr.

6. Discussion

A traditional method for determining the onset of uplift and exhumation is to examine the sediments stored in the adjacent foreland basin (Sobel et al., 2006a). A widespread unconformity and coarse clastic rocks (e.g. conglomerates) above the unconformity marks rejuvenation of source. As observed in the KD and some other foreland basins of Tianshan range, the Kumugeliemu Formation at the base of the Paleogene comprises a laterally extensive unit of conglomerates and sandstones (Lin et al., 2002; Yan et al., 2006; Yin et al., 1998). This succession overlies the Cretaceous strata with a distinct unconformity, which has previously been interpreted as the onset of Cenozoic thrusting within the Tianshan Range following uplift and unconformity formation (Allen et al., 1991; Windley et al., 1990). Cretaceous–Tertiary KD sandstones reveal that the provenance areas have varied distinctly (Li et al., 2006b), reflecting the depositional–tectonic evolution of the Tianshan. STS uplift occurred extensively since the Tertiary, causing detrital materials from the CTS to be blocked and not enter the northern Tarim Basin (Wang et al., 2009a). Therefore, basinal detrital sedimentation in the KD records the timing of uplift and erosion of STS during deposition of Kumugeliemu Formation with a magnetotstratigraphic age of 60.5–38 Ma (Zheng and Meng, 2006).

The collision of India and Asia in the early Tertiary produced widespread thrusting in Tianshan, responsible for the formation of active foreland basins. The STS thrust towards the KD resulting in folding, rapid uplift and denudation of STS and the northern part of the KD during the Cenozoic. Thermochronological data from the STS record a continuous cooling event during the Cenozoic, accelerating from ~42 Ma to 37 Ma.
At the mountain front of the STS, thermochronological data record a continuous cooling event from ~40 Ma, with a period of rapid cooling between 40 Ma and 35 Ma. We assume that this cooling is linked to, and may help constrain the timing and magnitude of, exhumation driven by uplift and thrust during deformation, although cooling may lag behind the onset of deformation. Both the hanging wall and footwall of the KBT fault have experienced a recent episode of exhumation, limiting the initial timing of accelerated Cenozoic uplift and exhumation on the south margins of STS or northern boundary of the KD to ~42 Ma, which represents the first significant contractional deformation in the north of the KD.

The AHe and AFT ages of detrital grains preserved at the Biyoulebaoguzi anticline in the NMB also provide support for a southward propagation of thrust and deformation as evidenced by a southward younging of uplift and exhumation, from the core of the anticline to the southern limb. However, the results of this work suggest that thrust and deformation initiation in the NMB actually occurred at ~36 Ma. The deformation continued for at least ~18 Ma while the southernmost limb of the anticline started to uplift and become exhumed (e.g., KY1106). This interpretation is supported by the sedimentary record proximal to the NMB. In the thrusting and folding zones, the growth strata, contemporaneous with tectonic deformation, constrain the timing of fold and thrust initiation. Lu et al. (2000) and Liu et al. (2000) considered that deformation in the NMB occurred during the deposition of the Neogene Jidike Formation (26–13.5 Ma) based on syntectonic growth strata in the Jiesidelike anticline, which provided a minimum age of 26 Ma for the onset of folding and deformation. The proposed initiation of deformation, uplift and exhumation in NMB (between 36 and 18 Ma) is compatible with the estimated commencement of thrusting in the STS Range (Dumitru et al., 2001; Hendrix et al., 1994; Huang et al., 2006; Sobel et al., 2006a; Yang et al., 2003), which implies that deformation of the NMB was contemporaneous with Oligocene-Miocene unroofing in the STS Range.

Rapid uplift and exhumation in the hanging wall of the KYT fault occurred at ~10 Ma, as determined by HeFTy thermal modeling of AHe data. This timing accords with an increase in sedimentation rate followed by orogenic uplift at ~11 Ma according to investigations of Miocene deposits in the Yaha section (Charreau et al., 2006), which lay on the south of the KYSB. The suggested uplift and erosion amplified at 11 Ma and it was likely the event leading to initiation of deformation and thrusting in the KYSB. This finding is consistent with the growth of fault-related folds in the Kelasu anticline (Liu et al., 2000), which suggests that the timing of initial deformation was during the deposition of the Neogene Kangcun Formation (13.5–5.9 Ma). This means that significant thrusting of the KYT appears to have occurred at ~10 Ma, a few million years after the initiation of deformation (~13.5 Ma).

A generally similar Cenozoic timing for rapid uplift at ~10–11 Ma has been reported from the Tianshan Range. On the piedmont of the west Tianshan, a rapid exhumation by thrusting yields AFT ages of 13.6 ± 2.2 Ma (Sobel and Dumitru, 1997). Magnetostratigraphic and geochronologic data from the Chu Basin in the western Kyrgyz Tianshan suggest an increase in sedimentation rate by ~11 Ma (Bullen et al., 2001; Sobel et al., 2006b). In addition, a study of the Kuitun section shows that reactivation of the northern Tianshan started before 10 Ma (Charreau et al., 2005). Reactivation ~10 Ma is consistent with extrapolating the current rates of shortening across the range back in time, in order to explain accumulated shortening (Abdrakhmatov et al., 1996; Reiger et al., 2001). Charreau et al. (2006) suggested that by ~11 Ma, the Tianshan Range underwent a rapid transition to a regime with both higher tectonic uplift and erosion rates. These studies suggested that the late Miocene (~11–10 Ma) the Tianshan orogenic belt (including STS, CTS and NTS) uplifted integrally and became more pronounced, which also resulted in deformation of the KYSB.

Available data in drill wells (Kela2, Kela204 and Bashil2, located in the Bashiqikie anticline, to the west of the Kanyaken anticline) in the KYSB indicated that the thickness of Cenozoic strata (including the Kumugeliemu, Suweiyi, Jidike and Kangcun Formations) ranged from 2395 m to 3806 m with a mean thickness of 3248 m, consistent with the thickness of Cenozoic strata (~3021 m) in the Kanyaken anticline, Kuqa River section. This substantiates the thermochronology results from the hanging wall of the Kanyaken anticline suggesting exhumation of 3000–3700 m during Cenozoic thrusting and folding.
In contrast, angular unconformities with underlying deformed strata are usually generated by tectonic events or uplifting (e.g., Coakley et al., 1991; Ghiglione and Ramos, 2005; Paola and Domenico, 1995; Rafini et al., 2002). Some drill wells (e.g., T22, KL204) in the KYSB lack the Kuqa Formation and overlying strata which implies the onset of uplift and exhumation may be ~5.9 Ma. The deformed strata underlying the Kuqa Formation in the KYSB records contraction and uplift, implying tectonic processes in this region that occurred prior to deposition of the Kuqa Formation. The notable increase in sediment accumulation rate in the south of the KYSB (lay on the southeast of KY1108) at ~7 Ma indicated a pulse of rapid uplift in the north (Huang et al., 2006), which may correlate with formation of the thrust fault (F2, Fig. 12) in the Kanyaken anticline. Indeed, the timing of thrust fault activity has been documented using electron spin resonance (ESR) dating in the Kanyaken anticline, suggesting that faulting (F2) had taken place before the end of the Pliocene (~2.1 Ma) (Zhang et al., 2007). These studies all support an important episode of deformation and uplift at ~5–7 Ma, which is consistent with initiation of uplift and exhumation in the Kanyaken anticline at ~6 Ma as derived from AHe data in this work. However, this rapid uplift and exhumation event is not recorded by AFT data (Du et al., 2007a; Dumitru et al., 2001; Hendrix et al., 1994; Jia et al., 2003; Luo et al., 2012; Ma et al., 2006; Sobel and Dumitru, 1997; Yang and Qian, 1995) in the study area. This lack of young AFT ages probably reflects the fact that the total magnitude of erosion has not been enough for AFT dating at this time while it was sufficient for AHe dating.

In a regional sense, all AHe ages were interpreted as Cenozoic cooling ages and the initial timing of uplift and exhumation in the north KD systematically became younger from the margin (Eocene) to the interior (late Miocene) by HeFTy modeling of the AHe ages. It is more likely that there has been multistage deformation and uplift since the Cenozoic in the north of the KD and that the deformation migrated from north to south. We assumed a southward propagating deformation and uplift pattern in the north of the KD in a reconstruction of the structural evolution (Fig. 13). The southward propagation of thrust faults and uplift might have caused severe unroofing of the STS reflected as exhumation, beginning in the Tertiary and continuing for at least several million years.

Fission track dating and thermal-simulation results by Ma et al. (2006) indicated rapid uplift from 78 to 58 Ma in the northern part of Tianshan. The thrust propagated southwards to the boundary between the STS and CTS in the Paleocene (~60 Ma), and to the STS in the early Eocene (~50 Ma) (Wang et al., 2009a). These implied that uplift in the Tianshan orogenetic belt first commenced in the north and then gradually moved southwards during the Paleogene. The uplift and exhumation during the Eocene (~42 Ma) started near the boundary between the STS and KD and the KBT fault reactivated. During the Oligocene, the rapid uplift and exhumation extended to the NMB and to the south edge of the Biyoulebaoquzi anticline and during the middle Miocene, and it extended to the north edge of the KYSB and the KYT fault formed. During the late Miocene, the deformation extended to the center of the KYSB, resulting in formation of the Kanyaken anticline. During the deposition of the Pliocene Kuqa Formation (5.9–3.4 Ma), the front extended to the north of the Qiluitage belt (Liu et al., 2000; Lu et al., 2000). Therefore, we speculate that initial thrust and deformation began in the boundary between the STS and KD (near the KBT fault) during the Eocene. Southward-increasing differential thrust and deformation was driven by crustal shortening in response to intracontinental deformation within the convergent India–Asia system.

7. Conclusions

Low-temperature thermochronometry becomes particularly useful when a basin has undergone a period of uplift, during which a section of strata has been removed by erosion. Using new AHe, VR data and existing AFT data, we have better constrained the history of Cenozoic deformation, uplift and exhumation in the north of the KD, verifying that deformation and exhumation in the STS initiated at ~46 Ma. The application of detrital thermochronometry provides insight into spatial and temporal patterns of uplift and exhumation across different thrust–fold belts of the north KD. The timing of uplift and exhumation varied distinctly in space: At ~42 Ma, uplift and exhumation started near the boundary between the STS and KD with removal of at least 4500 m of overburden, representing the first significant contractional deformation in the north of the KD in the Cenozoic; at ~36 Ma, the deformation and uplift extended to the south edge of the Biyoulebaoquzi anticline in the NMB and sampling areas underwent more than about 3400 m of late Cenozoic unroofing; at ~10 Ma, the deformation and uplift extended to the north edge of KYSB and then at ~6 Ma, the Kanyaken anticline formed and uplifted, followed by 3000–3700 m of overburden removal during subsequent folding and thrusting. Initial timing of uplift and exhumation in different thrust–fold belts of the north KD systematically became younger from the margin to the interior, suggesting southward propagation of thrust belts, driven by crustal shortening due to the collision between India and Asia during the Cenozoic.

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