The Exhumation History of North Qaidam Thrust Belt Constrained by Apatite Fission Track Thermochronology: Implication for the Evolution of the Tibetan Plateau

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Abstract: Determining the spatio-temporal distribution of the deformation tied to the India-Eurasian convergence and the impact of pre-existing weaknesses on the Cenozoic crustal deformation is significant for understanding how the convergence between India and Eurasia contributed to the development of the Tibetan Plateau. The exhumation history of the northeastern Tibetan Plateau was addressed in this research using a new apatite fission track (AFT) study in the North Qaidam thrust belt (NQTB). Three granite samples collected from the Qaidam Shan pluton in the north tied to the Qaidam Shan thrust, with AFT ages clustering in the Eocene to Miocene. The other thirteen samples obtained from the Luliang Shan and Yuka plutons in the south related to the Luliang Shan thrust and they have showed predominantly the Cretaceous AFT ages. Related thermal history modeling based on grain ages and track lengths indicates rapid cooling events during the Eocene-early Oligocene and since late Miocene within the Qaidam Shan, in contrast to those in the Cretaceous and since the Oligocene-Miocene in the Luliang Shan and Yuka region. The results, combined with published the Cretaceous thermochronological ages in the Qaidam Shan region, suggest that the NQTB had undergone rapid exhumation during the accretions along the southern Asian Andean-type margin prior to the India-Eurasian collision. The Cenozoic deformation initially took place in the North Qaidam thrust belt by the Eocene, which is consistent with the recent claim that the deformation of the northeastern Tibetan Plateau initiated in the Eocene as a response to continental collision between India and Eurasia. The immediate deformation responding to the collision is tentatively attributed to the pre-existing weaknesses of the lithosphere, and therefore the deformation of the northeastern Tibetan Plateau should be regarded as a boundary-condition-dependent process.

Key words: apatite fission track, Qaidam Shan, Luliang Shan, North Qaidam thrust belt, Tibetan plateau

1 Introduction

The Tibetan Plateau is the largest highland on Earth, with elevated topography more than 5 km above sea-level and N-S extent more than 2000 km (Fielding et al., 1994). This broad and currently growing plateau is one of the ideal areas to study the interaction between deep geodynamics and topography-building, and significantly influence regional- to global-scale climate, including the Asian monsoon system, Asian intracontinental desertification and the Cenozoic global cooling (e.g. Raymo and Ruddiman, 1992; An et al., 2001; Guo et al., 2002; Liang et al., 2014). The key to understand how the continent-continent convergence created such a broad plateau and its impact on palaeoclimate is to determine the deformation evolution and its spatio-temporal distribution.

It has long been a controversial topic whether the plateau was built through continuous growth from south to north (Meyer et al., 1998; Tapponnier et al., 2001) or whether the deformation could have reached some regions far away from the collision zone soon after the India-Eurasian collision (Yin and Harrison, 2000; Yin et al., 2008b; Wang et al., 2011; Clark, 2012; Yuan et al., 2013). This debate, to some extent, has reflected different viewpoints of the

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lithospheric nature of the plateau. With a homogeneous lithosphere, edge forces would produce deformation that is first concentrated at the collision zone and then propagates northwardly (Clark et al., 2010), exhibiting a south-to-north growth of the plateau. In contrast, an inhomogeneous lithosphere with pre-existing weaknesses would produce deformation along those weak regions immediately after the collision (Kong et al., 1997; Yin and Harrison, 2000; Yin et al., 2008b; Yuan et al., 2013).

To test the above models, two subjects of work have to be done, to determine the collision-age deformation and to separate the pre-Cenozoic deformations from the Cenozoic ones. The former subject has been addressed in central Tibet (Wang et al., 2008; Rohrmann et al., 2012; Ren et al., 2015), the East Kunlun Shan-Qiman Tagh (Clark et al., 2010; Wu et al., 2014) and North Qilian-Haiyuan-Liupan Shan (Lin et al., 2011) based on low-temperature thermochronological study (e.g., Apatite Fission Track, Apatite U-Th/He) and 3-D seismic interpretation. While the later one has been implemented in the Songpan-Ganzi terrane (Tian et al., 2014), the Lhasa block (Murphy et al., 1997; Leier et al., 2007), the Altyn Tagh range (Sobel et al., 2001), and East Kunlun-Tula basin (Robinson et al., 2003).

The North Qaidam thrust belt (NQTB) provides an ideal place to evaluate the issues how the pre-existing structure exerted influence on subsequent Cenozoic deformations and when the region deformed in response to the India-Eurasian collision, as this place was once the Paleozoic suture zones (e.g. Wu et al., 2002; Zhang et al., 2008; Song et al., 2009; Shi et al., 2010) that underwent further deformations during the Mesozoic (e.g. Wu et al., 2011; Shen et al., 2009). Preliminary work in the NQTB, located between the Qaidam basin and the Qilian Shan-Nan Shan, was sparse yet indicated the Cenozoic exhumation process (Jolivet et al., 2001; Wang et al., 2004; Wan et al., 2010). However, the detailed exhumation history of this region has not been well understood and may have important implications for the deformation history of the Tibetan Plateau. Observations of tectonic activities during the Mesozoic and again in the early Cenozoic (collision-age) would assort with the inhomogeneous-lithosphere (immediate deformation) model. Otherwise, findings of tectonic activities only in the Plio-Quaternary (e.g. Tappanier et al., 2001) would correspond to homogenous-lithosphere (south-to-north propagation) model.

In this study, systematic investigation was conducted on apatite fission track (AFT) thermochronology in the Qaidam Shan and Luliang Shan in the NQTB. The results, in combination with previously published data, have provided insights to the above two key issues, and through these, enabled better understanding of the evolution of deformation in the Tibetan Plateau.

2 Geological Setting

The study area (NQTB) is located in the joint region between the South Qilian Shan and the North Qaidam basin, northeastern Tibetan Plateau (Fig. 1a). The NQTB can be subdivided into three structural units, the Qaidam Shan, the Dachaidan basin (also referred as Da Qaidam basin) and the Luliang Shan from northeast to southwest (Fig. 1a).

The Qaidam Shan, southern portion of the South Qilian Shan thrust belt, is bounded to the south by the south-vergent Qaidam Shan thrust (Yin et al., 2008a) that expresses significant c. 2 km of topographic relief from c. 5200 m in the hanging wall to c. 3200 m in the footwall (Figs. 1a and 1b). The broad area inside the Qaidam Shan is full of granite plutons (Qinghai Geological Bureau, 1978). The granite, which was once dated to be the Triassic in age (c. 200 Ma) by whole rock Rb/Sr analyses (e.g. Harris et al., 1988), is now believed to be emplaced in early Paleozoic (c. 435–456 Ma) by SHRIMP zircon U-Pb dating, and originated from continental collision (Wu et al., 2002).

The intermontane Dachaidan basin, which constitutes the footwall of the Qaidam Shan thrust, is a minor Jurassic faulted-basin superimposed by thin Cenozoic sediments (<1500 m) (Fig. 1b) (Lou et al., 2009). These Meso-Cenozoic sequences unconformably overlie the Proterozoic-Paleozoic meta-magmatic complex in the Luliang Shan to the south (Qinghai Geological Bureau, 1978; Fig. 1b).

The Luliang Shan, commonly referred as part of the North Qaidam ultra high-pressure (UHP) metamorphic belt, consists of high-grade gneisses intercalating minor eclogites and ultramafic rocks (e.g. Zhang et al., 2008; Song et al., 2009; Shi et al., 2010). These UHP rocks resulted from metamorphism of the Mesoproterozoic to Archaean protoliths during the Neoproterozoic and again early Paleozoic subduction and collision (e.g. Zhang et al., 2008; Song et al., 2009; Shi et al., 2010). These rocks were intruded by granites dated as c. 428–430 Ma in age (Zhang et al., 2008; Meng and Zhang, 2008). The Luliang Shan is bounded by Luliang Shan thrust to the south (Figs. 1a and 1b), a south-vergent thrust fault (Yin et al., 2008a) placing the Luliang Shan meta-magmatic complex over the Cenozoic sediments in the northern Qaidam basin (Fig. 1b).

3 Samples and Methods of the AFT Analyses

Sixteen bedrock AFT samples have been collected from three granite plutons in the NQTB. Among them, three (20-6, 20-8 and 20-9) came from the Qaidam Shan pluton, five (20-1 to 20-5) from the Yuka pluton and eight (21-1,
Fig. 1. Simplified geological map and cross-section of the study area, showing the localities and structural setting of the apatite fission track analysis samples.

(a) Geological map of the study area with sample localities noted. EK, East Kunlun Shan; EKF, East Kunlun fault; QB, Qaidam basin; OL, Qilian Shan; OB, Ondos basin; SB, Sichuan basin; ATF, Ailyn Tagh fault; TB, Tarim basin; WK, West Kunlun Shan; PM, Pamir; TS, Tian Shan; (b) Structural cross-section across the North Qaidam thrust belt and the North Qaidam basin. Portions of AB and CD are from seismic interpretation, while portions of BC and DE are from surface mapping in the geological map.
21-4, 21-5, 20-11 to 20-15) from the Luliang Shan pluton (Fig. 1a and Table 1). All these samples, as noted above, are in early Paleozoic age. Located in the hanging wall of the Qaidam Shan thrust fault, the exhumation history of the Qaidam Shan granite samples should be closely tied to the activity of the Qaidam Shan thrust, while samples from the Luliang Shan and the Yuka plutons are located within the hanging wall of the Luliang Shan thrust fault and thus likely record exhumation along this structure (Fig. 1, e.g., Yin et al., 2008a). For each sample, more than 2-kg materials were collected in the field. Apatite concentrates were prepared by comminution, heavy liquid flotation, and magnetic separation techniques. Individual apatite crystal, euhedral and without inclusions, was selected from these concentrates by handpicking through a binocular microscope. More than 1000 grains, with size of hundreds of micrometer, were selected for AFT analyses.

AFT analyses were conducted at the Institute of High-Energy Physics at the Chinese Academy of Sciences, Beijing, following the methodology described by Lin et al. (2011). Apatite grains were mounted in epoxy resin on glass slides and ground and polished to an optical finish to expose internal grain surfaces. Spontaneous tracks were revealed by etching in 5.5% HNO₃ for 20 seconds at 21°C. The samples were then irradiated with thermal neutrons in the 492 light-water reactor in Beijing, with muscovite used as the external detector. After irradiation, the muscovite detectors were detached and etched in 40% hydrofluoric acid for 20 minutes at 25°C. Densities of both natural and induced fission tracks were measured with a dry objective at ×1500 magnification. Neutron flux was determined using dosimeter glass CN5 with a known uranium content of 11 ppm (Hurford and Green, 1982) included at the ends of the irradiation package. AFT ages were calculated using the IUGS-recommended zeta calibration approach (Hurford and Green, 1982), with a weighted mean zeta value of 386.8 ± 18.1(1σ). Horizontal confined fission tracks were measured to obtain track lengths (Green et al., 1986). Spontaneous track counts from all the samples were adequate for analysis using standard statistical methods for fission track data (Galbraith, 1981) (Table 1).

### 4 Results of the AFT Analyses

AFT analyses were completed for all the sixteen samples, returning AFT ages from 14 ± 1.4 to 125 ± 8.2 Ma with mean track lengths from 11.9 ± 1.9 to 12.8 ± 1.5 μm (Table 1). These ages, significantly younger than the crystallization ages of corresponding samples (Wu et al., 2002; Zhang et al., 2008), are interpreted to primarily represent the post-crystallization cooling events (Fig. 2).
is notable that samples from different structural units yield different age clusters (Fig. 2).

Three samples (20-6, 20-8 and 20-9) from the Qaidam Shan exhibit the Cenozoic (Eocene to middle Miocene) central ages (14 ± 1.4 to 41 ± 2.8 Ma) (Table 1 and Fig. 2). All the analyses succeed in passing the $\chi^2$ test, with $P(\chi^2)$ values far above 5% (Table 1), suggesting that the dated grains from each sample conform to a common age population (Fig. 3). Such age results are consistent with previously published AFT results, 20.7 ± 2.3 Ma by Jolivet et al. (2001) and 16.7 ± 1.4 Ma by Wang et al. (2004), and the plateau age of 33.5 ± 1.8 Ma defined by low temperature heating steps of K-feldspar $^{39}$Ar/$^{40}$Ar analysis (Wang et al., 2004) in the region. It is notable that these AFT ages are significant younger than zircon fission track (ZFT) age of 143.0 ± 10.9 Ma (Jolivet et al., 2001) and biotite $^{39}$Ar/$^{40}$Ar plateau age of 195.5 ± 0.4 Ma (Wang et al., 2004), suggesting that the AFT ages in the study should represent cooling overprints over the samples during the Cenozoic. However, the fission track lengths of these samples have been significantly annealed (12.1 ± 1.8 to 12.6 ± 2.1 μm, Table 1 and Fig. 4), implying that these samples have experienced potential complex thermal histories.

Five samples from the Yuka region (20-1 to 20-5) present AFT ages of late Cretaceous, ranging from 70 ± 5.4 to 89 ± 6.0 Ma (Table 1 and Fig. 2). The grain ages are commonly dispersed, failing in the $\chi^2$ test with most $P(\chi^2)$ values below 5% (Table 1). Likely attributions of the dispersed grain ages could be: (1) the samples resided in the partial annealing zone (PAZ) for a long time, which significantly shortened their track lengths and therefore brought realistic difficulties in counting track numbers; (2) the samples underwent discrete episodes of cooling events, the temperature ranges of which were cunningly within the PAZ, resulting in multiple grain age clusters of the samples; and/or (3) fission track annealing kinetics varied within individual samples. The fact that all the samples were collected from plutonic sources implies that the annealing kinetics may not be an issue for the attribution of age dispersal. However, it seems that both the first and second attributes are consistent with significantly shortened track lengths and bimodal age peaks or broad age spans of the analyzed results (Table 1, Figs. 3 and 4). The only exception of the grain age dispersion is the Sample 20-4, which passes the $\chi^2$ test with $P(\chi^2)$ value above 5% and returns AFT age of 70 ± 5.4 Ma, suggesting a post-crystallization cooling event during late Cretaceous.

The significantly shortened fission track lengths of these samples (12.6 ± 1.4 to 12.8 ± 1.5 μm, Table 1 and Fig. 4), as noted previously, imply potential complex thermal histories of these samples as well.

The samples from the Luliang Shan region (21-1, 21-4, 21-5 and 20-11 to 20-15) present a wide range of AFT ages spanning from early Cretaceous to Eocene (125 ± 8.2 to 40 ± 6.4 Ma) (Table 1 and Fig. 2). Among them, three samples (21-1, 20-13 and 20-14) failed the $\chi^2$ test, suggesting significant grain age dispersion possibly due to, as mentioned above, either the imprints of discrete episodes of cooling events with the temperature ranges within the PAZ of the AFT or long-term residence within the PAZ. The interpretation is consistent with the bimodal age peaks or broad age spans and shortened tracks in these samples (Table 1 and Fig. 3). The remaining five samples (21-4, 21-5, 20-11, 20-12 and 20-15) succeed in passing the $\chi^2$ test with $P(\chi^2)$ values above 5%, exhibiting AFT ages 112 ± 8.4 to 40 ± 6.4 Ma (Table 1 and Fig. 3). In particular, Sample 21-4 presents an apparent age of 40 ± 6.4 Ma, absolutely different from the Cretaceous ages presented by the adjacent samples in the Luliang Shan region. Whether this sole age represents an actual event or is caused by analytical errors is open for discussion. The other four samples (21-5, 20-11, 20-12 and 20-15) all exhibit the Cretaceous ages, which are consistent with previously published AFT result (105.0 ± 5.5 Ma, Jolivet et al., 2001) but younger than ZFT.
Fig. 3. Grain age distributions of the apatite fission track samples.

age (219.7 ± 19.8 Ma, Jolivet et al., 2001) and crystallization age (zircon U-Pb age of 428–430 Ma, Zhang et al., 2008; Meng and Zhang, 2008) of the pluton, suggesting post-crystallization cooling overprint during the Cretaceous. Again, the significantly shortened fission track lengths of these samples (11.9 ± 1.9 to 12.5 ± 1.7 μm, Table 1 and Fig. 4), imply potential complex thermal histories of these samples.

5 Thermal History Interpretation through Modeling

All the AFT data show significant numbers of shortened tracks, implying potential complex thermal histories that these samples have experienced. These complex thermal histories can be accessed, at least to some degree, by thermal history modeling from grain ages and track lengths.

By using the annealing model proposed by Ketcham et al. (1999), we investigated the potentially complex thermal histories of our AFT samples through the HeFTy software (Ketcham et al., 2000; Ketcham, 2005). The AFT grain age and track length data were imposed into the program to assess the relative merit of different thermal histories.

Some T-t (temperature-time) constraints are available to be imposed into the thermal history modeling. Previously reported ZFT ages, 143.0 ± 10.9 Ma in the Qaidam Shan
Fig. 4. The distributions of confined track lengths of the apatite fission track samples.
and 219.7 ± 19.8 Ma in the Luliang Shan (Jolivet et al., 2001), both of which successfully pass the $\chi^2$ test, provide higher T-t constraint for the modeling. Given c. 240°C closure temperature for the ZFT, these ZFT ages, significantly younger than the crystallization ages of corresponding samples (Wu et al., 2002; Zhang et al., 2008), suggest that the samples were cooled to the temperature of c. 240°C during the periods of respective ZFT ages (Fig. 5). A lower T-t constraint was obtained from present temperature of the region. Given the high elevation of the region, the present temperature was assumed to be c. 0–20°C (Fig. 5). The strategy that only two necessary constraints (one higher and the other lower T-t constraints) have been imposed into the modeling guarantees that the models can run freely, rather than being artificially ‘forced’ to. The modeling results are evaluated by the parameters ‘goodness-of-fit’ (GOF) between the model and measured ages and track lengths. Good modeling results are defined by both GOF values of age and track length larger than 0.5, while acceptable results defined by the values ranging from 0.05 to 0.5 (Ketcham, 2005). In the study, ten samples produce good modeling results, i.e. Samples 20-6, 20-8 and 20-9 from the Qaidam Shan, Samples 20-2 and 20-3 from the Yuka region and Samples 20-11, 20-12, 20-14, 20-15 and 21-1 from the Luliang Shan.

Modeling results of the Qaidam Shan samples (20-8 and 20-9) present three episodes of cooling paths, including two episodes of rapid cooling that bracket an episode of slow cooling (Fig. 5). The results show that these two samples passed across the higher limit of the PAZ (c. 125°C) rapidly during early Eocene (c. 45–55 Ma), followed by a slow cooling within the shallow level of the PAZ until late Miocene (c. 5–10 Ma), when another rapid cooling occurred to expose the samples onto the earth’s surface (c. 0–20°C)(Fig. 5). The later rapid cooling episode since late Miocene is mostly outside of the lower limit of the capability of AFT record as the temperatures are generally lower than c. 60°C, suggesting that this less constrained episode should be regarded as indicative. Modeling results of Sample 20-6 show monotonous rapid cooling since late Miocene (c. 15 Ma). While earlier cooling might be possible, the broad range of good result in this sample makes the possibility ambiguous (Fig. 5). Rapid cooling episode since late Miocene has been confidently constrained by the modeling results of Sample 20-6, which is conformable with simultaneous cooling episode observed in samples 20-8 and 20-9 in the Qaidam Shan.

Two samples (20-2 and 20-3) from the Yuka region (part of the Luliang Shan) produce good modeling results of three episodes of cooling paths, showing two rapid ones that bracket a slow one (Fig. 5). The samples entered into higher limit of the PAZ (c. 125°C) during the Cretaceous (c. 100–130 Ma) and underwent rapid cooling to the lower portion of the PAZ until c. 70–80 Ma. This rapid cooling episode was followed by a slow one spanning from late Cretaceous to late Oligocene (Fig. 5), which cooled the samples through lower limit of the PAZ (c. 60°C) until c. 25–30 Ma (Fig. 5). The later rapid cooling episode since late Oligocene with the temperatures lower than the lower limit of the capability of AFT record, again, should be regarded as uncertain. However, given the fact that these samples are on present earth’s surface, the less constrained episode of cooling seems reasonable.

Among the samples from the Luliang Shan, Sample 21-4 returned an exceptional AFT age, possibly due to analytical errors, and was therefore excluded from the modeling. In Sample 21-5, only 31 fission-track lengths have been measured, which makes the modeling result of the sample uncertain, and therefore it has been excluded from discussions. The remaining samples from the Luliang Shan (samples 21-1, 20-11, 20-12, 20-14 and 20-15) present consistent cooling paths, showing three episodes of cooling with two rapid ones that bracket a slow one (Fig. 5). The earlier rapid cooling event cooled the samples to the higher limit of the PAZ (c. 125°C) during late Jurassic to Cretaceous (c. 170–100 Ma) and subsequently to the lower part of the PAZ in early to late Cretaceous (c. 140–70 Ma)(Fig. 5). This episode of rapid cooling was followed by a discrete slow cooling event, which cooled the sample through the lower limit of the PAZ (c. 60°C) until latest Oligocene to late Miocene (c. 25–10 Ma) (Fig. 5). Again, the later rapid cooling event since latest Oligocene to late Miocene (c. 25–10 Ma), given the present-day surficial constraint, seems reasonable, although the temperatures of this episode of cooling are outside of the capability of AFT record.

6 Discussions

6.1 Differential exhumation histories within the NQTB

Our AFT sample localities are closely tied to major faults within the NQTB, and the results therefore provides insight into the activity of these faults. The AFT ages and related thermal history modeling results, combined with previous ZFT ages, document that the Qaidam Shan thrust activated initially at Eocene and possibly again since late Miocene after its activity during the Cretaceous (Fig. 6), resulting in significant rapid cooling of the hanging wall samples. The Cretaceous activity exhumed the samples from the Qaidam Shan to the temperature of ZFT record, corresponding to depth of c. 8km (given a geothermal gradient of c. 30°C/km) (Figs. 6 and 7), while the Eocene event exhumed them to the temperature of AFT record.
Fig. 5. Thermal histories of representative samples obtained from inverse modeling of track annealing behavior in apatite using the HeFTy program with grain age and horizontal confined track length data (Ketcham et al., 2000; Ketcham, 2005).

T-t constraints imposed into the modeling were described in the text.
that corresponds to depth of c. 4km. In contrast, the Luliang Shan thrust activated dominantly during the Cretaceous and likely again since Oligocene-Miocene (Fig. 6), as indicated by samples from the Yuka and Luliang Shan plutons. The Cretaceous activity exhumed the samples from the Yuka and Luliang Shan regions to the temperature of AFT record, corresponding to depth of c. 4km (Figs. 6 and 7), while the activity since Oligocene-Miocene exhumed the samples to the temperature of the lower limit of the PAZ to surface that corresponds to a depth of less than c. 2km. These results demonstrate differential exhumation histories of different structural units within the NQTB (Figs. 6 and 7).

The Cretaceous cooling event has been identified in the Luliang Shan (including Yuka) and less significantly in the Qaidam Shan as well through published $^{40}$Ar/$^{39}$Ar ages (Wang et al., 2004). Widespread contractional deformation and related coarse-grade sediments within this episode were reported in Qaidam basin (e.g. Ritts and Biffl, 2001; Wu et al., 2011), coinciding with the previous thermochronological findings in the NQTB region (e.g. Jolivet et al., 2001; Wang et al., 2004).

The Eocene cooling event identified in this study coincides with the recent sedimentary investigation in the Dahonggou section which suggests coarse alluvial fan sediments deposited in the Eocene Lulehe Formation, implying an intense weathering in the NQTB at the time (Song et al., 2013). The deposition, sediment thickness distribution and structural analysis results (Yin et al., 2002, 2008a; Zhu et al., 2006; Zhou et al., 2006; Zhuang et al., 2011; Yu et al., 2014) in the Qaidam basin provide independent supportive evidence for this claim. Continuous Oligocene-early Miocene rapid cooling in the Qaidam Shan region has also been documented by published thermochronological results (Jolivet et al., 2001; Wang et al., 2004). The magnetostratigraphical findings in the Dahonggou and Huaizoutala sections, just closely south and east to our study area respectively, indicate an event at c. 14–12 Ma evidenced by variations in lithofacies, sediment accumulation rate and rock magnetic susceptibility (Sun et al., 2005; Fang et al., 2007; Lu and Xiong, 2009), consistent with the later rapid cooling episode since the Miocene in the Luliang Shan region.

### 6.2 Implication for the evolution of the Tibetan Plateau

Our results suggest that the NQTB, northern boundary of the Qaidam basin/block, was deformed during the Eocene immediately during the India-Eurasia collision (e.g. Rowley, 1996) after an older activity in the Cretaceous. This is likely due to the pre-existing lithospheric weakness caused by a fossil suture (Fig. 7).

It has been a consensus that the Cenozoic Tibetan Plateau was built upon a wide Andean-type margin prior to the collision between the India and Eurasia (e.g. Yin and Harrison, 2000), although whether this accretion-related margin created a proto-plateau remains an issue under debate (e.g. Wang et al., 2008; Clark, 2011). Successive accretions of the Qiangtang block during the late Triassic-early Jurassic, the Lhasa block during the late Jurassic-early Cretaceous and the Kohistan Arc during the...
late Cretaceous, respectively (e.g. Burrett, 1974; Allegre et al., 1984; Dewey et al., 1988; Yin and Harrison, 2000), resulting in significant contraction in block margins and basins in NW China (e.g. Hendrix et al., 1992; Murphy et al., 1997; Sobel, 1999; Hendrix, 2000; Yin and Harrison, 2000; Ritts and Biffo, 2001; Wu et al., 2011). Within this tectonic regime, it can be expected that the NQTB underwent significant contraction in the Cretaceous, and the cooling event observed in the belt at the time can therefore be attributed to the accretions along the southern margin of the Asian continent (Fig. 7a).

Moreover, the episodes of the Mesozoic contraction and related thrusting provide a condition of weak lithosphere prior to the India-Eurasian collision (e.g. Kong et al., 1997; Yin and Harrison, 2000; Clark et al., 2010; Lin et al., 2011). When the collision between India and Eurasia took place during the Eocene (e.g. Rowley, 1996), the weak lithosphere immediately underwent significant deformation. It has been documented that the strain can reach as far as West Qinling and Haiyuan-Liupan Shan regions at the present northeast plateau margin immediately after the collision (e.g. Clark et al., 2010; Lin et al., 2011; Clark, 2012), and the impact of the collision during the Eocene can therefore be expected along the NQTB (Fig. 7b). Our results support that the initial condition of weak lithospheric zones plays a significant role during the continuous convergence (e.g. Kong et al., 1997), possibly with more complex mantle flow interaction (e.g. Conrad and Lithgow-Bertelloni, 2004; Clark et al., 2010), allowing the strain forced by the collision to efficiently immigrate into the weak zones immediately after the onset of the collision. The complex preconditions imply that the plateau establishment should be regarded as a boundary-condition-dependent process, and the important parameters relevant to the plateau creation should be established by site-specific geological investigations (Kong et al., 1997).

7 Conclusions

The AFT investigation has been conducted in the Qaidam Shan and Luliang Shan along the North Qaidam thrust belt (NQTB) to determine the fault deformation history.

(1) The AFT ages and related thermal history modeling results suggest that the Qaidam Shan thrust is dominated
by the Cenozoic thrusting events, documented by the rapid cooling episodes initiating at the Eocene and possibly again since late Miocene identified in the Qaidam Shan samples. The Mesozoic events may also registered in the Qaidam Shan, as indicated by published thermochronological data.

(2) In contrast, the Luliang Shan thrust mainly activated during the Cretaceous, documented by widespread the Cretaceous AFT ages and the rapid cooling events initiating in this episode and subordinately since the Oligocene-Miocene.

(3) These results together provide new evidence to separate the events tied to India-Eurasian collision from those prior to the collision. Moreover, the initial activity of the NQTB at the Eocene suggests that the deformation forced by the India-Eurasian convergence could reach the northeastern plateau immediately after the onset of the collision. We tentatively attribute the immediate deformation in the NQTB to the pre-existing lithospheric weakness prior to the India-Eurasian collision.

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