Relief history and denudation evolution of the northern Tibet margin: Constraints from $^{40}$Ar/$^{39}$Ar and (U–Th)/He dating and implications for far-field effect of rising plateau

Fei Wang, Huile Feng, Wenbei Shi, Weibin Zhang, Lin Wu, Liekun Yang, Yinzhi Wang, Zhigang Zhang, Rixiang Zhu

A R T I C L E   I N F O

Article history:
Received 18 November 2015
Received in revised form 17 February 2016
Accepted 2 March 2016
Available online 11 March 2016

Keywords:
$^{40}$Ar/$^{39}$Ar dating
(U–Th)/He dating
Age–elevation profile
Denudation evolution
Relief history
Far-field effect

A B S T R A C T

How does the rising Tibetan Plateau affect its peripheral region? The current understanding of the mechanism of orogenic plateau development is incomplete and thus no consensus yet exists in this regard. However, our new $^{40}$Ar/$^{39}$Ar and (U–Th)/He dataset presented in this study may shed some light on this issue. $^{40}$Ar/$^{39}$Ar dating, on two vertical transects from the massif between Nuomuhong and Golmud, indicates that the Eastern Kunlun Range was built-up and exhumated during the later Triassic initially, and a minimum overburden of ~11.7–14.0 km has been eroded since ~220 Ma. (U–Th)/He age–elevation relationships (AERs) indicate a rapid exhumation event at ~40 Ma following a long period of slow exhumation phase from late Mesozoic to early Eocene time. In this study, two scenarios – one assuming a single stage and the other assuming multiple stages of evolution history – are modeled. Modeling of a multiple stage scenario is reasonable and is able to reflect the "actual" situation, which reveals the entire denudation and relief history of the northern Tibetan Plate from late Mesozoic to the present time. After prolonged denudation before 50 Ma, a low topography (~0.17 times the relief of the present) developed by 50 Ma with an erosion rate of 0.013 ± 0.025 mm/yr. The highest relief (~1.82 times the relief of the present) of the Cenozoic time came into being at 40 Ma with an erosion rate of 0.052 ± 0.025 mm/yr, which was possibly a result of the collision between India and Eurasia. Subsequently, the relief steadily decreased to the present level due to continued denudation. This suggests that deformation propagation from the continued convergence boundary between India and Eurasia was insignificant after the construction of the highest relief. This observation is broadly consistent with published accounts on the stratigraphic, cooling, and faulting histories of the northern Tibet margin.

© 2016 Elsevier B.V. All rights reserved.

1. Introduction

The consequences of the far-field effect of continued Eurasia–Indian convergence since ~50 Ma (Rowley, 1996; Wang et al., 2011) on the northern Tibetan margin have been a topic of debate (Tapponnier et al., 2001; Meng and Fang, 2008). This issue is further complicated by a possible linkage between climate change and the uplift of mountain belts. It is believed that alternating glacial and interglacial conditions and increased denudation rates during the Late Cenozoic (Zhang et al., 2001; Molnar, 2004; Valla et al., 2010; van der Beek et al., 2010) can result in isostatic uplift of mountain peaks (Molnar and England, 1990) and thus increase unroofing and cooling of an area (Montgomery, 1994; Small and Anderson, 1998; Champagnac et al., 2007; van der Beek et al., 2010) through perturbation of the underground thermal structure (Braun, 2003). Erosion occurs mainly in the valleys leading to the high relief mountain belts. Therefore, understanding the evolution of topography requires a better comprehension of the linkage between climate, tectonics, and surface processes (Beaumont et al., 1992; Zeitler et al., 2001; Valla et al., 2010).

The terrain along the northern margin of the Tibetan Plateau has been well-studied for its rising-plateau-related tectonics (e.g., Burchfiel et al., 1989; Van der Woerd et al., 1998; Mock et al., 1999; Jolivet et al., 2003; Fu and Awata, 2007; Meng and Fang, 2008; Clark et al., 2010). A few researchers have concentrated on quantitative studies of uplift and denudation of the Eastern Kunlun terrain — the main part of the northern Tibet basin using low-temperature thermochronological techniques, e.g., $^{40}$Ar/$^{39}$Ar (Mock et al., 1999; Wang et al., 2004), fission track (Yuan et al., 2006), and (U–Th)/He (Clark et al., 2010; Dai et al., 2013), from which a cooling history of between 40 and 350°C can be extracted. Based on this cooling history, a rapid cooling event around 30 (Mock et al., 1999; Wang et al., 2004) or 40 Ma (Clark et al., 2010) and therefore the onset time of the initial unroofing of the Eastern Kunlun have been
deduced. This event has been attributed to early uplift (Mock et al., 1999; Wang et al., 2004) or faulting (Clark et al., 2010) induced by Tibet rising. Exhumation rates of between 0.02 and 0.05 mm/yr were reported for the northern part of central segment of the Eastern Kunlun during Late Oligocene–Early Miocene (Dai et al., 2013).

However, direct evidence of couplings between tectonics and surface processes remains elusive, and quantitative data are needed to better constrain denudation evolution and relief history.

A recently developed method for inverse modeling is the one that involves the use of the three-dimensional thermal kinematic model Pecube (Braun, 2002, 2003; Braun et al., 2006), coupled with the Neighbourhood Algorithm (Sambridge, 1999a, 1999b). Pecube is a robust finite-element code to solve the 3D heat transportation equation in a crustal/lithospheric block undergoing uplift and surface erosion, and is characterized by an evolving, finite-amplitude surface topography (Braun, 2003). Following an imposed tectonic scenario, the temperature history of the rocks exhumed at the Earth’s surface is derived from the computed crustal thermal structure. These T–t paths can then be used to calculate apparent isotopic ages for a range of geochronometers. The basic set of the Neighbourhood Algorithm is used to find the optimum values of the given parameters of the model that will minimize the misfit function defined by the difference between the observed ages and calculations. The method has been fully described by Braun (2003), Braun et al. (2006) and Valla et al. (2010), and has been successfully applied to the estimation of denudation and relief history of the Western Alps (van der Beek et al., 2010).

Besides searching for best-fitting model parameters (Braun and van der Beek, 2004; Braun and Robert, 2005; Herman et al., 2007; Valla et al., 2010; van der Beek et al., 2010), the crustal thermal structure (Braun, 2003) was also calculated and Bayesian probability-density functions derived for the parameters estimated (Valla et al., 2010; van der Beek et al., 2010). In this paper, this method was applied to a new (U-Th)/He dataset collected along two transects in the northern Tibet margin (Eastern Kunlun), with the objective of quantifying the crustal thermal structure, and timing of the denudation and relief development of this terrain. This study also provides constraints on mechanical models of orogenic development in northern Tibet, and the far-field effect of rising plateau.

In the following, a brief geological setting of the study area is first presented, followed by the thermochronological study of 40Ar/39Ar and (U-Th)/He. Age–elevation profiles and their conventional implications regarding cooling and exhumation rates through time are evaluated. The modeling approach used in extracting the denudation and relief histories from the data is summarized, and its implications for understanding the tectonic and climatic controls on these histories are discussed.

2. Geological setting and sample collection

The Eastern Kunlun range, stretching for over 1000 km from east to west, delimits the Tibetan Plateau in the south, and the Qaidam Basin in the north (Fig. 1). Being part of the Paleozioc-Triassic collision belt, the Eastern Kunlun was rejuvenated during the Cenozoic Eurasia–Indian collision (Matte et al., 1996), and confined by the South Qaidam Fault in the north and the Kunlun Fault in the south (Fig. 1b, c). The Eastern Kunlun is dominantly composed of pre-Cenozoic plutonic rocks, Devonian to Early Triassic marine sediments, and Jurassic and Cenozoic non-marine rocks (Fig. 1c; Liu et al., 2005; Dai et al., 2013). The plutonic rocks are characterized by widely spread Early Cambrian to Early Devonian (515–393 Ma; Liu et al., 2005; Xiong et al., 2014; Zhang et al., 2010) and Late Permain to Triassic igneous rocks (261–215 Ma; Harris et al., 1988; Ding et al., 2014; Huang et al., 2014; Dai et al., 2013).

The Eastern Kunlun was built during Late Permain to Middle Triassic as a result of northwards subduction of Tethys ocean plate under the Eastern Kunlun and the following collision between Songpan-Ganzi and Eastern Kunlun blocks (Li et al., 2013; Yang et al., 2005). The Permain to Triassic sediments in the south of the Eastern Kunlun indicate the remnant of foreland basin (Fig. 1), which were reworked intensively by refilling, faulting and folding during Mesozoic and Cenozoic time (Li et al., 2013; Yang et al., 2005).

Two distinct views are advanced for the mechanism of the tectonic regime in northern Tibet: (1) thin viscous sheet model: most of the convergence between India and Asia is expressed in crustal thickening first and then propagated northerly by strike-slip faulting in the shallow crust (England and Houseman, 1986); and (2) synchronous deformation model: initial deformation in the northern Tibet is coeval with the onset of collision between India and Asia under the assumption of a rigid block for the Tibetan Plateau. If the first view is correct, the initiation of the faults, ranges and basins surrounding northern Tibet should be young. Although numerous phenomena do appear along the northern Tibet margin do appear to have been initiated since Miocene, e.g., rapid exhumation around 30 Ma (Mock et al., 1999; Wang et al., 2004), Miocene right-lateral faulting (Wang and Burchfiel, 2004; Fu and Awata, 2007), a mid-Miocene clockwise rotation of the Guide Basin (Yan et al., 2006), U/Pb signatures of mountain building at ~8 Ma (Lease et al., 2007) and Miocene crustal shortening (Bovet et al., 2009), the geological record indicates that the view of initiation and propagation of deformation away from the initial collision boundary may be incorrect (Clark et al., 2010). The depositional and deformation history of sedimentary basins shows that the deformation in numerous localities across northern Tibet could be of Paleocene to Eocene age (Yin et al., 2007; Yin et al., 2008; Meng and Fang, 2008), which roughly coincides with the onset of the continental collision between India and Eurasia (e.g. Rowley, 1996; Wang et al., 2011).

Vertical transects on granite rocks were sampled with minimal horizontal offset where possible. Nine samples in total from two transects were collected for biotite and K-feldspar 40Ar/39Ar dating and apatite (U-Th)/He dating (Fig. 1c). Note that the closure temperatures of biotite and the largest domains in k-feldspar are same (~350 °C, e.g. Lovera et al., 1997, 2002), the ages of biotite and maximum age of k-feldspars from the same sample should be same. These two ages could support one another.

In order to increase representativeness, two transects—50 km from each other, and across the massif between Nuomuhong and Golmud—were sampled (Fig. 1b). Three samples were collected from transect 1, and six from transect 2.

3. Analysis techniques

All samples from the two transects were analyzed by using the modern (U-Th)/He dating technique, while two samples from the top (kl5) and bottom (kl4–2) of transect 1 and three from the top (kl22–2), middle (kl20–2) and bottom (kl18–2) of transect 2 were conducted with the 40Ar/39Ar method. All experiments were carried out in the 40Ar/39Ar and (U-Th)/He Laboratory of the Institute of Geology and Geophysics, Chinese Academy of Sciences (IGGCAS).

The rock samples were first mechanically disintegrated and crushed. Specifically, the coarser shard between 280 and 450 μm and the finer one between 200 and 75 μm in diameter were separated, respectively, from the sample during crushing. K-feldspar and biotite grains free of visible minerals and fluid inclusions were selected by hand under a binocular microscope from the coarser shard, while the apatite crystals were hand-picked from the finer shard.

K-feldspars were carefully checked to match the criteria or requirements for thermochronological study by using the 40Ar/39Ar method (Lovera et al., 1997, 2002; Lee, 1995). For example, the K-feldspar that partially changed to adularia, and/or replaced all earlier microtextures with ultra-porous late feldspar, was eliminated by using electronic microscope probe analyses. To reveal the argon distribution within the K-feldspar grain as finely as possible, the high-resolution (36–40 step) step-heating technique of 40Ar/39Ar analysis was used. Biotite from the same sample was also analyzed for comparison with K-feldspar. Sample
processing and laboratory procedures of $^{40}$Ar/$^{39}$Ar analysis were
depicted in Wang et al. (2007, 2009) and detailed in Appendix A.
Each apatite grain was checked carefully under a high-power micro-
scope in order to exclude those containing impurities and inclusions. Subhedral, fragmentary, needle-like, or rounded apatites were eliminat-
ed, as well as apatites with visible zonations. Then, euhedral apatite
grains longer than 130 $\mu$m and wider than 75 $\mu$m were wrapped in a
1 mm × 1 mm platinum capsule and prepared for He, U and Th analyses. He was measured by using an Alphachron MK II noble gas mass spec-
trometer, and U and Th on a Thermo Fisher X-Series II ICP-MS. Each of
the wrapped apatite grains was moved into a well one after another in
a stainless steel disk for He measurement. Each grain was heated
twice $\approx 1000^\circ$C for 10 min in order to attain complete He extraction.
$^4$He abundance was determined by isotope dilution using a pure $^3$He
spike, calibrated daily against an independent $^4$He standard tank. The
uncertainty in the sample $^4$He measurement averaged $\approx 2\%$. 

The degassed apatite grain was removed from the capsule and
placed in a PFA beaker, to which 25 $\mu$L of 50% HNO$_3$ with $^{235}$U and
$^{230}$Th spikes were added. A set of reagent blank solutions and spiked U
and Th standard solutions were treated similarly. The beaker was gently
ultrasounded until the apatite crystal had dissolved. Samples were
diluted in 5% HNO$_3$, and analyzed by isotope dilution for U and Th. A de-
tailed description of analytical procedures can be found in Evans et al.
(2005a, 2005b). Based on replicate analyses of spiked standard solu-
tions, the analytical precision for $^{235}$U/$^{238}$U and $^{230}$Th/$^{232}$Th was deter-
mained to be 0.8% and 0.5%, respectively. ($U-Te)/He$ methods at
IGGCAS yielded an internal precision (1$\sigma$) of 1.5%, based on multiple
age determinations of Durango apatite that produced an average age of
31.5 ± 1.5 Ma (Appendix C), which is well consistent with the recom-
manded age (McDowell et al., 2005; Reiners and Nicolescu, 2006, Evans
et al., 2005b).

Age calculation was made by using a Java-based program (Helioplot)
(Vermeesch, 2010), and alpha emission correction (Farley et al., 1996)
was done by using measured dimensions of each apatite grain. The
model described by Gautheron and Tassan-Got (2010).

4. Results of $^{40}$Ar/$^{39}$Ar and ($U-Th$)/He geochronology

Detailed $^{40}$Ar/$^{39}$Ar and ($U-Th$)/He analytical results are listed in Ap-
pendices B and C, respectively, and are summarized in Table 1 together
with the sampling locations and elevations.
4.1. Results of $^{40}$Ar/$^{39}$Ar dating and implications for Mesozoic history of the Eastern Kunlun range

$^{40}$Ar/$^{39}$Ar age spectra of K-feldspars and biotites are illustrated in Fig. 2, and the $^{40}$Ar/$^{39}$Ar age–elevation relationship is shown in Fig. 3. All biotite aliquots present flat age spectra with well-defined plateaus accounting for more than 90% of total-release $^{39}$Ar (Fig. 2, Appendix B). Biotite plateau ages of samples from the top (kl5) and bottom (kl4–2) of transect 1 are 224.8 ± 1.2 and 224.4 ± 1.9 Ma, respectively, and do not exhibit differences relative to their elevation (Fig. 3, Table 1). Biotite plateau ages of samples, from the top (kl22–2), middle (kl20–2), and bottom (kl18–2) of transect 2, are 226.6 ± 1.2, 224.3 ± 1.2, and 225.0 ± 1.3 Ma, respectively. Although the sample top is slightly older than the other two, they can be taken as “the same” ages if errors are considered (Fig. 2, Table 1). Diffusion loss and distribution of argon isotopes in mineral, which defines the $^{40}$Ar/$^{39}$Ar age of the mineral, are closely related to temperature in geological regimes. Thus, the nature of these biotite $^{40}$Ar/$^{39}$Ar ages reflects cooling time with a closure temperature of ~350 °C of an exhumation event (e.g., Lovera et al., 1991). The similar ages from the top and bottom of the transects suggest that these vertical transects exhumated and cooled so rapidly that their argon systems were “frozen” at almost the same time (at least they cannot be recognized within errors), giving a cooling time passing the closure temperature of ~350 °C.

K-feldspars usually display complex and variable microstructures usually (Parsons et al., 2013; Cassata and Renne, 2013; Wang et al., 2014) and, as a result, potentially record $^{40}$Ar/$^{39}$Ar ages over a range of closure temperatures spanning 200 °C as they cool (Lovera et al., 2002). These microstructures serve as “domains”, different in size, in which argon resides, which hold a series of closure temperatures below ~75 °C (Wolf et al., 1996); specifically, diffusion removes He as fast as it is produced by decay at higher temperatures. Therefore, apatite $^{40}$Ar/$^{39}$Ar geochronology on biotites and K-feldspars of the two transects imply that rocks now at the surface resided around ~350 °C isotherm during the late Triassic and had cooled to ~150 °C by Middle Cretaceous. Note that although ~350 °C mark approximately the closure of both the biotite and the largest domain in K-feldspar, it is a lower bound of the sample temperature at the initial of exhumation. Therefore, these results pose a minimum bound on total exhumation of ~11.7–14.0 km in the Eastern Kunlun Range, assuming a paleo-geo-thermal gradient of 30 °C/km (Qiu, 2002) or 25 °C/km (Clark et al., 2010).

4.2. Results ofapatite (U–Th)/He dating and implications for the Cenozoic history of the Eastern Kunlun range

The advantage of apatite (U–Th)/He dating arises from its ubiquity and moderately high U and Th content, but more importantly form the fact that He accumulation in apatite occurs only at temperatures below ~75 °C (Wolf et al., 1996); specifically, diffusion removes He as fast as it is produced by decay at higher temperatures. Therefore, apatite (U–Th)/He dating results document the latest phase of cooling in the uppermost crust (Ketcham et al., 1999).

Typically, three to four grains from each sample were analyzed separately to calculate the mean age in this study (Table 1 and Appendix C). The analysis results (Appendix C) show that more than two grains at least yielded consistent ages for each sample. The scattered older ages of some grains in a sample (e.g., kl5 and kl18–2) may arise from mineral

---

### Table 1

Sample location and mean apatite (U-Th)/He ages.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Longitude</th>
<th>Latitude</th>
<th>Elevation (m)</th>
<th>40Ar/39Ar Age (Ma)</th>
<th>Biotite plateau age</th>
<th>k-feldspar plateau age</th>
<th>k-feldspar smallest domain age</th>
<th>(U-Th)/He mean age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transect 1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kl5</td>
<td>96.4625</td>
<td>36.0575</td>
<td>3601</td>
<td>223.3 ± 1.6</td>
<td>224.8 ± 1.2</td>
<td>129.9 ± 4.9</td>
<td>54.1 ± 5.5</td>
<td></td>
</tr>
<tr>
<td>kl7</td>
<td>96.4242</td>
<td>36.1046</td>
<td>3446</td>
<td>222.2 ± 1.1</td>
<td>224.4 ± 1.9</td>
<td>138.3 ± 9.2</td>
<td>33.0 ± 3.1</td>
<td></td>
</tr>
<tr>
<td>kl4–2</td>
<td>96.4752</td>
<td>36.2186</td>
<td>3224</td>
<td>224.2 ± 1.2</td>
<td>226.6 ± 1.2</td>
<td>181.8 ± 16.5</td>
<td>82.3 ± 8.6</td>
<td></td>
</tr>
<tr>
<td>Transect 2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>kl22–2</td>
<td>95.7200</td>
<td>36.2160</td>
<td>4010</td>
<td>223.3 ± 1.2</td>
<td>224.3 ± 1.2</td>
<td>110.3 ± 29.2</td>
<td>66.5 ± 6.4</td>
<td></td>
</tr>
<tr>
<td>kl22–3</td>
<td>95.7143</td>
<td>36.2190</td>
<td>3771</td>
<td>222.1 ± 1.2</td>
<td>225.0 ± 1.3</td>
<td>117.1 ± 44.5</td>
<td>40.8 ± 4.1</td>
<td></td>
</tr>
<tr>
<td>kl20–2</td>
<td>95.7123</td>
<td>36.2183</td>
<td>3674</td>
<td>223.3 ± 1.2</td>
<td>224.3 ± 1.2</td>
<td>110.3 ± 29.2</td>
<td>66.5 ± 6.4</td>
<td></td>
</tr>
<tr>
<td>kl21–3</td>
<td>95.7049</td>
<td>36.2161</td>
<td>3481</td>
<td>223.3 ± 1.2</td>
<td>224.3 ± 1.2</td>
<td>110.3 ± 29.2</td>
<td>66.5 ± 6.4</td>
<td></td>
</tr>
<tr>
<td>kl21–1</td>
<td>95.7054</td>
<td>36.2341</td>
<td>3351</td>
<td>223.3 ± 1.2</td>
<td>224.3 ± 1.2</td>
<td>110.3 ± 29.2</td>
<td>66.5 ± 6.4</td>
<td></td>
</tr>
<tr>
<td>kl18–2</td>
<td>95.6902</td>
<td>36.2903</td>
<td>3130</td>
<td>221.1 ± 1.2</td>
<td>225.0 ± 1.3</td>
<td>117.1 ± 44.5</td>
<td>32.0 ± 2.9</td>
<td></td>
</tr>
</tbody>
</table>

* Calculated from replicate Ft corrected (Farley et al., 1996) single-grain ages Appendix B.
inclusions with high U and Th concentrations, especially from zircon and monazite (Ehlers and Farley, 2003) which produce erroneously high He age in some apatites. Although careful microscopic examination of grains to be dated greatly reduces this problem (Farley, 2002), some inclusions may be too small to detect (Ehlers and Farley, 2003). Fortunately, inclusions tend to be heterogeneously distributed from grain to grain, causing poor age reproducibility. Thus, age reproducibility is an indispensable demonstration of the quality of an apatite He age.

Good age reproducibility between grains (Appendix C) indicates that our new (U–Th)/He ages are reliable. Three samples from transect 1 yield ages of 54.1 ± 5.5, 33.0 ± 3.1 and 24.5 ± 2.0 Ma from top to bottom, showing a positive correlation with elevation (Fig. 4). Similarly, six samples from transect 2 give ages of 82.3 ± 8.6, 63.0 ± 6.7, 66.5 ± 6.4, 40.8 ± 4.1, 36.0 ± 3.5, and 32.0 ± 2.0 Ma from top to bottom, consistent with the trend of elevation (Fig. 4).

Considering that there is no fault between the transects 1 and 2 (Fig. 1), which may cause differential movement, it can be assumed that the plutons of transects 1 and 2 were exhumed uniformly, and no different amounts of fault throw along strike of the South Qaidam fault. This is an acceptable assumption based on our new ⁴⁰Ar/³⁹Ar geochronological results above. Moreover, several regional erosion surfaces preserved at an elevation of ~4600 m throughout the study area were recognized from a 60-m-resolution digital elevation model (DEM) (Fig. 1), and they do not show any local tilting. This means that there is no influence from long-wavelength undulations in the geomorphic surface. Therefore, it is reasonable to directly integrate transects 1 and 2 to form

---

Fig. 2. ⁴⁰Ar/³⁹Ar age spectra of K-feldspars (black) and biotites (red) from the transects 1 and 2. Plateau ages are shown for K-feldspars at high temperatures and biotite respectively. Insets indicate the staircase age spectra of K-feldspar at low temperatures with its minimum and maximum ages labeled.
a uniform age–elevation relationship (AER) and discuss them together (Fig. 4).

(U-Th)/He ages record cooling commonly caused by exhumation, i.e., rock motion towards the surface of the Earth. In other words, what processes produced exhumation and when and how fast they operated can be illustrated by (U-Th)/He dating. Usually, these issues are approached by establishing the (U-Th)/He age distribution with increasing elevation or paleo-depth (e.g., Ehlers and Farley, 2003). In most cases crustal temperatures increase and (U-Th)/He ages decrease with depth, but the exact pattern of variability depends on the specific exhumation history (Ehlers and Farley, 2003).

In Fig. 4, the overall pattern of the age–elevation curve of this study shows two distinct segments: from ~80–40 Ma ages decrease approximately linearly with elevation suggesting that rock had experienced a constant exhumation rate at which the He age pattern reached a steady state. A striking increase in the slope during ~40 Ma, which may be related to a rapid uplift event under favorable climatic conditions. The uplift induced increase of erosion and exhumation, and thus samples beneath the closure isotherm moved upwards through the isotherm at almost the same time.

In order to constrain the evolution history of relief and denudation accurately, quantitative analysis by thermal modeling on thermochronological data is needed.

5. Thermal modeling of age–elevation data

5.1. Pécube coupled with Neighbourhood Algorithm (NA)

In nature being a forward model to predict cooling history and age, Pécube, coupled with NA, can be used for back-calculating the parameters concerning the geological past. Pécube devotes to the case of “temporally-changing” surface topographical effect on the thermal structure of the underneath crust by solving the following transient, three-dimensional heat transfer equation (Carslaw and Jaeger, 1959; Braun, 2003):

$$\rho c \left( \frac{\partial T}{\partial t} + v \cdot \nabla T \right) = \nabla \cdot \left( \kappa \nabla T \right) + \frac{\partial}{\partial t} \rho A,$$

where $T(x,y,z)$ is the temperature, $\rho$ is the rock density, $c$ is the heat capacity, $v$ is the vertical rate of rocks relative to the base of the crust, $\kappa$ denotes the conductivity and $A$ is radioactive heat production. This equation must be solved for a set of boundary conditions. For ease of use, some assumptions have been made including that thermal properties such as rock conductivity, heat capacity, density and heat production are spatially uniform and constant through time. A full description of the numerical method is provided in Braun (2003).

The inverse calculation was implemented by using the Neighbourhood Algorithm (NA) (Sambridge, 1997a, 1997b). NA involves an iterative search in the multi-dimensional parameter space in order to find sets of input parameters that minimize the misfit between observed and predicted data normalized by the squares of the errors:

$$\psi = \sqrt{\sum_{i=1}^{N} \sum_{j=1}^{M} \left( \frac{\alpha_{j,\text{mod}} - \alpha_{j,\text{dat}}}{\alpha_{j,\text{dat}}} \right)^2},$$

where $N$ denotes the number of datasets, $M$ is the number of samples in each dataset, $\alpha_{j,\text{mod}}$ and $\alpha_{j,\text{dat}}$ are the predicted and observed value respectively, and $\alpha$ is the error on the data (Valla et al., 2010; van der Beek et al., 2010).

5.2. Modeling: results and evaluations

The input thermo-kinematic parameters used in Pécube are listed in Table 2. The geometry of the surface topography was extracted from 1-km-resolution DEMs (GoodyGIS). Changes in relief were incorporated by only modifying the amplitude of topography but not the shape of the relief as designed by Braun (2003). This assumption requires incision mainly occurred in valley and geometry of the drainage system did not change over the time span modeled. This assumption may not always satisfy the geological situation, but the long standing peak and valley and incision mainly confined in valleys in a region suggest the assumption acceptable (Braun and van der Beek, 2004; Braun and Robert, 2005; Valla et al., 2010 and van der Beek et al., 2010). The Eastern Kunlun...
Kunlun has served as provenance for the Qaidam basin from Late Mesozoic to the present time constantly, as indicated by the sedimentary sequence (Meng and Fang, 2008; Guan and Guan and Jian, 2013), implying the surface runoff system did not change significantly during Mesozoic although the amplitude of topography may keep changing.

He diffusion kinetics from Farley (2000) (Durango apatite) were used in the Pecube calculation of cooling history and theoretical (U-Th)/He ages (Braun, 2003). Modeling calculation was implemented at the MPI Computation Laboratory of IGCCAS.

In order to investigate different possibilities of evolutionary history for the Eastern Kunlun, two scenarios were modeled: Scenario 1, a constant exhumation rate from a high relief over the past 100 Ma, and Scenario 2, variable exhumation rate and relief over the past 100 Ma. In our conceptual model, we assume that relief increases from preferential valley incision, i.e., the shape of the topography is constant spatially over the modeling time span.

Inversion modeling results for Scenarios 1 and 2 are shown in Figs. 5 and 6, respectively, in which each dot represents a forward model. The misfit function $\psi$ allows for a direct comparison of inversion runs with different numbers of data. For this study, the models represented by misfit values $<0.5$ were considered “satisfying”, as shown by the color of each dot (Fig. 5, 6).

Scenario 1 assumes a one-stage denudation and relief evolution history, in which the Eastern Kunlun was initially built high and exhumed completely during later Paleozoic and early Mesozoic, and constantly eroded over the past 100 Ma; Moreover, reactivation caused by the Cenozoic collision between India and Eurasia did not affect the relief of Kunlun terrain. Modeling ran over 100 Ma to ensure that all points, which end up at the surface, cool through the AHe closure temperature. Only one phase (100–0 Ma) was modeled. The relief factor ($R$) was set between 0 and 2, denudation rate ($D$) between 0 and 2.0 mm/yr and paleo-thermal gradient ($T$) between 15 and 30 °C/km. The relief factor is defined by Valla et al. (2010) as:

$$ R = \frac{\Delta h_i}{\Delta h_0} $$

where $\Delta h_i$ is the maximum difference of height in the study area at $i$ stage, and $\Delta h_0$ is the present maximum difference of height.

5000 forward models were calculated for Scenarios 1 (Fig. 5). The minimum misfit values of the “best” forward models are around 0.623 (Fig. 5) which is slightly bigger than the “satisfying value” (0.5). The distribution of the forward models are not convergent (Fig. 5), and therefore do not resolve a unique set of parameters for relief evolution ($R = 0–2.0$), denudation rates ($D = 0–2.0$ mm/yr) and paleo-thermal gradient ($T = 15–30$ °C/km). Although the paleo-thermal gradient of change is constrained in a relatively small range of 17–20 °C/km, the denudation rate and relief factor are sinuous in a wide range of $0.06–0.7$ mm/yr and $0.2–1.5$ respectively (Fig. 5). Therefore, the modeling results for Scenario 1 suggest that the assumptions of a one-stage history over the past 100 Ma for the Eastern Kunlun are unreasonable.

Scenario 2 assumes a multiple stage of denudation and relief evolution history, in which. Relief of Kunlun terrain was rebuilt by the effect of the collision. In order to reflect the rejuvenation of the Eastern Kunlun during the Cenozoic Eurasia–Indian collision, the modeling including three phases (100–50, 50–40 and 40–0 Ma) with seven associated parameters: (1) relief factor ($R_1; 0–2.0$) and denudation rate ($D_1; 0–2.0$ mm/yr) during the first stage; (2) relief factor ($R_2; 0–2$) and denudation rate ($D_2; 0–2.0$ mm/yr) during the second stage; (3) relief factor

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crustal thickness (km)</td>
<td>60</td>
</tr>
<tr>
<td>Crustal density (kg/m³)</td>
<td>2700</td>
</tr>
<tr>
<td>Sublithospheric mantle density (kg/m³)</td>
<td>3200</td>
</tr>
<tr>
<td>Equivalent elastic thickness (km)</td>
<td>25</td>
</tr>
<tr>
<td>Young’s modulus (Pa)</td>
<td>1.111</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>0.25</td>
</tr>
<tr>
<td>Thermal diffusivity (km²/Myr)</td>
<td>25</td>
</tr>
<tr>
<td>Sea level temperature (°C)</td>
<td>15</td>
</tr>
<tr>
<td>Atmospheric lapse rate (°C/km)</td>
<td>0</td>
</tr>
<tr>
<td>Crustal heat production (°C/Myr)</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2: Thermo-kinematic and elastic parameters used in Pecube. Poisson ratio, Young’s modulus and equivalent elastic thickness are used for calculating the isostatic rebound in response to relief change. Equivalent elastic thickness is set to a value that simulates moderate isostatic rebound.

Fig. 5. Scatter plots showing results of Pecube + NA inversion for Scenario 1. Each dot denotes a forward model, and its color corresponds to the value of color bar for misfit between modeled and input data. Blue corresponds to misfit value $<0.5$. Each plot is the projection onto a plane by two of the seven parameters (denudation rates $D$; relief factor $R$; and thermal gradient $T$). Horizontal and vertical axes define the parameter space. The results are not convergent and not a unique set of parameters can be determined implying assumptions for Scenario 1 are unreasonable and infeasible. (For interpretation of the references to color in this figure legend, the reader is referred to the online version of this chapter.)
(R3: 0–2) and denudation rate (R2: 0–2.0 mm/yr) during the third stage; geothermal gradient (T: 15.0–30.0 °C/km).

8500 forward models were calculated for Scenarios 2 (Fig. 6). The minimum misfit values of the "best" forward models are around 0.051 (Fig. 6) which is much better than the "satisfying value (0.5). The distribution of the forward modes is converge well as shown in Fig. 6, and a set of parameters for three stages of denudation rates (D1, D2, D3), relief factors (R1, R2, R3) and paleo-thermal gradient (T) are well resolved (Fig. 6). This means that the assumptions of multiple stages of denudation and relief evolution history are feasible for the Eastern Kunlun Belt over the past 100 Ma.

From graphical inspection of Fig. 6, it is further found that the optimum values for these parameters are constrained in small ranges: D1 in 0.3–0.45 mm/yr, D2 in 0–0.05 mm/yr and D3 in 0.04–0.11 mm/yr, R1 in 1.25–1.58, R2 in 0.1–0.3, R3 in 1.7–2.0 and T in 19.4–21.1 °C/km.

By investigating the statistical properties of the model ensemble using probability density function (PDF), the most probable values for the parameters can be obtained (Fig. 7, Table 3) and the uncertainty can be defined by the standard deviation of the marginal PDF. Parameter PDFs confirm three contrasting stages for the exhumation history: (1) high denudation rates (D1 = 0.37 ± 0.27 mm/yr, Fig. 7b) at 100 Ma; (2) low denudation rates (D2 = 0.013 ± 0.025 mm/yr, Fig. 7b) at 50 Ma; and (3) higher denudation rate (D3 = 0.052 ± 0.025 mm/yr, Fig. 7b) at 40 Ma and the present. Relief history is even more precisely constrained: R1 = 1.38 ± 0.21 (Fig. 7a) at 100 Ma; R2 = 0.17 ± 0.14 at 50 Ma (Fig. 7a); and R3 = 1.82 ± 0.21 at 40 Ma (Fig. 7a). Thermal gradient is also well constrained as 20.6 ± 2.1 °C/km (Fig. 7c), not changing for the three stages. AER implies apparent erosion rates <0.2 mm/yr for several tens of millions years, which suggests that the changes in geothermal gradient due to heat advection from erosion were minor (Moore and England, 2001; Ehlers, 2005; Clark et al., 2010). The changes of relief history with time are graphically shown in Fig. 8 as 3D perspective plots.

The modeled denudation rates are similar to those inferred directly from the inspection of AER: 0.013 ± 0.025 (modeled) vs ~0.012 mm/yr at 50 Ma and 0.052 ± 0.025 (modeled) vs 0.05–0.058 mm/yr (AER) at 40 Ma. The modeled geothermal gradient (20.6 ± 2.1 °C/km) is similar to the previous observations for the Eastern Kunlun (25 °C/km) (Clark et al., 2010) and the Qaidam Basin (20–30 °C/km) (Qiu, 2002).

Best-fit Scenario 2 yields the predicted age–elevation relationship reasonably well compared with the observed (Fig. 8). The thermal histories for each sample predicted by the Pecube show similar cooling and exhumation pattern (Fig. 9) to the observations from the AER in Fig. 4: a rapid cooling or exhumation stage between ~40 and ~30 Ma and a relative slow cooling or exhumation from ~100 to ~50 Ma (Fig. 9). The thermal history roughly passes the minimum 40Ar/39Ar ages of k-feldspar (Fig. 9), implying that the cooling or exhumation

![Fig. 6. Scatter diagrams showing results of Pecube + NA inversion for Scenario 2. Same plots as Fig. 5 but seven parameters (denudation rates D1, D2, D3; relief factor R1, R2, R3; and thermal gradient T); horizontal and vertical axes define the parameter space. The results converge and a unique set of parameters can be determined, implying assumptions for Scenario 2 are reasonable and reflect the "real" situation.](image-url)
history extracted from (U–Th)/He ages is consistent with what reflects by 40Ar/39Ar k-feldspar smallest domains (see discussion above).

In summary, our modeling results are reasonable and reflect the "actual" situation. The model results can therefore be used to infer a regional exhumation and relief history from the data set. However, potential improvements to our modeling could be provided by more sophisticated age-prediction models or more realistic evolution scenarios.

Graphically 3D plots of the relief and denudation history of different stages over the past 100 Ma are illustrated in Fig. 10. Modeled thermal structures beneath the Eastern Kunlun terrain at different times are illustrated on the sides of the 3D plots. Contours of the temperature field have been superimposed (Fig. 10). The contours of temperature show the effect of vertical heat advection, where the isotherms are compressed towards the surface and deformed by the high relief surface topography (e.g., Fig. 10c).

6. Implications for evolution of the Northern Tibet margin and the far-field effect of rising plateau

6.1. Denudation evolution and relief history of the Northern Tibet margin

Our new 40Ar/39Ar dating on k-feldspar and biotite from the studied transects suggests that the Eastern Kunlun terrain exhumated and cooled rapidly in the later Triassic (~220 Ma), and implies a total exhumation of ~11.7–14.0 km since then, assuming a paleo-geothermal gradient of 30 °C/km (Qiu, 2002) or 25 °C/km (Clark et al., 2010). New (U–Th)/He dating in this study indicates constant and slow exhumation during ~80–40 Ma, and a rapid cooling event at ~40 Ma.

Inversion modeling results show that the relief decreased from ~100 to ~50 Ma, increased from ~50 to ~40 Ma, and then decreased again from ~40 to the present (Fig. 10). Being a part of the Paleozoic-Triassic collision belt, the Eastern Kunlun was unroofed during ~100–50 Ma, resulting in the decrease of the relief factor from 1.38 ± 0.21 at 100 Ma to 0.17 ± 0.21 at 50 Ma (Fig. 10a,b); meanwhile, the denudation rates decreased sharply from 0.37 ± 0.27 to 0.013 ±0.025 mm/yr (Fig. 10a,b). This possibly suggests that the crust was in a quiet or stable tectonic setting during ~100–50 Ma. Therefore, unroofing constituted the first order tectonic movement at the northern Tibet margin during this period, when high relief areas were denuded and low relief areas filled, resulting in a low topography by ~50 Ma (Fig. 10c). From ~50 to ~40 Ma, the relief increased more than tenfold from a factor of 0.17 ± 0.21 to 1.82 ± 0.21 (Fig. 10b,c), with denudation rates increasing from 0.013 ±0.005 to 0.052 ± 0.025 mm/yr, due to the rapid uplift of the Eastern Kunlun terrain spanning 50–40 Ma. Since 40 Ma, the highest relief decreased by almost half, from a factor of 1.82 ± 0.21 to 1.0 at present (Fig. 10c,d), suggesting that the crust was relatively stable and denudation was the main tectonic setting. Rapid uplift of the mountain ranges at the northern Tibet margin accentuated valley incision that led to the formation of foreland flexural depressions, such as the Qaidam

Table 3

<table>
<thead>
<tr>
<th></th>
<th>R1 (relief)</th>
<th>R2 (relief)</th>
<th>R3 (relief)</th>
<th>T (°C/km)</th>
<th>D1 (mm/yr)</th>
<th>D2 (mm/yr)</th>
<th>D3 (mm/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input</td>
<td>0–2</td>
<td>0–2</td>
<td>0–2</td>
<td>15–30</td>
<td>0–2.0</td>
<td>0–2.0</td>
<td>0–2.0</td>
</tr>
<tr>
<td>Model</td>
<td>1.38 ± 0.21</td>
<td>0.17 ± 0.14</td>
<td>1.82 ± 0.21</td>
<td>20.6 ± 2.1</td>
<td>0.37 ± 0.27</td>
<td>0.013 + 0.025/−0.013</td>
<td>0.052 ± 0.025</td>
</tr>
</tbody>
</table>
and Kumkuli Basins. Consequently, increasing denudation rates could have resulted in increased sedimentation rates in the basins.

The results of (U–Th)/He AER and inversion modeling have important implications for deciphering the orogenic development of the northern Tibet margin. AER from the two transects suggest that a rapid denudation/exhumation event occurred around 40 Ma (Fig. 4) after the Eurasia–Indian collision at ~50 Ma (Rowley, 1996). This is confirmed by the results of inversion modeling, which show that the denudation rate at 40 Ma and present is 0.052 ± 0.025 mm/yr (Fig. 10c,d). This is much higher than the denudation rate of 0.013 ± 0.025 mm/yr during ~50–40 Ma (Fig. 10b). Our new data of (U–Th)/He ages on the Central Kunlun and the Qimen Tagh Mountains, and Miocene growth strata in the Kumukuli Basin, in the range of 39.5–43.2 Ma (authors’ paper under preparation), suggest that the rapid exhumation event was widespread throughout the Eastern Kunlun Range. Exhumation of the Central Kunlun Range between 41 and 21 Ma is inferred from accelerated cooling determined from feldspar multi-domain diffusion modeling (Mock et al., 1999; Wang et al., 2004). Previous (U–Th)/He data revealed a rapid exhumation event during 30–45 Ma in the Eastern Kunlun and the Western Qinling Mountains (Clark et al., 2010).

Sedimentation rates in the adjacent Qaidam Basin increased rapidly during 40–36.6 Ma (Me’tivier, 1996; Cui et al., 1999; Chen et al., 1998; Wang et al., 2004), implying an increase of denudation rate in the surrounding mountains. Growth strata are extensively preserved from 50 to 40 Ma in the peripheral areas of the Qaidam and Kumkuli Basins (Bally et al., 1986; Meng and Fang, 2008; Yin et al., 2008). In HoXil basin, immediately south of the study area, there was rapid sedimentation around 40 Ma (Wang et al., 2008).

Denudation or exhumation is a result of the combination of climate and tectonic uplift. Moreover, uplifted high land is preferentially subjected to erosion in a moist and hot climate. It is inferred that the denudation rates of the East Kunlun terrain increased from ~50 to 40 Ma implying that the terrain had been uplifted during this period, when...
favorable climatic conditions were prevailed. Recent data of magnetostratigraphy, pollen, and climatic proxies in northern Tibet and neighbouring areas show that the Eocene–Oligocene Boundary (~34 Ma) marks one of the most pronounced climatic changes of the Cenozoic era, implying the dramatic shift of a “greenhouse” to an “icehouse” world (Wang et al., 2003; Graham et al., 2005; Dupont-Nivet et al., 2007; Clark et al., 2010; Sun et al., 2014). The prevalence of a “greenhouse” climate, which is moist, hot and denudation-friendly, is attributed to the existence of the Paratethys Sea in the south, before the early rise of mountain ranges in northern Tibet. The rising land was denuded mainly by incising valleys (Clark et al., 2010), giving rise to the highest relief at the northern Tibet margin during Cenozoic at ~40 Ma.

6.2. Implications for the far-field effect of rising Tibet

How does the rising Tibetan Plateau affect the far-northern peripheral area? Two contrasting models are proposed in this regard: (1) northerly propagating strain from the collision boundary between India and Eurasia (e.g., England and Houseman, 1986); and (2) synchronous deformation with the onset of collision (e.g. Wang et al., 2008; Clark et al., 2010). The data obtained from this study favors the second model and suggest that the northern Tibet margin was built-up in the early phase of India-Eurasia collision history.

Rapid exhumation and the highest relief at ~40 Ma suggest that the Eastern Kunlun Range was rejuvenated during 50–40 Ma, as an immediate response to the Eurasia–Indian collision at ~50 Ma (Rowley, 1996), although the plate boundary was located more than 3000 km away to the south. A growing body of evidence indicates that large-scale deformation began across the eastern and central portions of northern Tibet (Rowley, 1996; Clark et al., 2010) within 10 Ma of the collision between India and Eurasia (41–52 Ma). In other words, the north margin of Tibet was built during the early phase of collision history. A decreasing relief and increasing denudation rate, from ~40 Ma to the present, suggest that unroofing was the first-order activity, implying that uplift was minor and northern Tibet has been rather stable since ~40 Ma. Despite 2000–3000 km of convergence of India and with Eurasia since the collision (Molnar and Stock, 2009; Clark et al., 2010), the northerly propagation of strain was insignificant during the entire period of collision. A stable boundary that was built-up at the time of collision cannot be interpreted by the existing indenter models (e.g. Tappanier et al., 2001) of continental convergence into a uniform lithosphere; instead, it may be better explained by emphasizing the role of strong heterogeneities in the continental lithosphere or basal tractions induced by mantle flow (Clark et al., 2010).

7. Conclusions

A new 40Ar/39Ar Ar and apatite (U–Th)/He dataset from transects of the eastern range indicates a minimum exhumation of ~11.7–14.0 km since ~220 Ma, and a rapid exhumation event along the Eastern Kunlun Range at ~40 Ma, following a long period of slow cooling from late Mesozoic to early Eocene. This process possibly prevailed all along the northern Tibet margin and was marked by sedimentation in basins, rapid cooling of mountains and faulting. Inversion modeling of a multiple stage scenario, which elucidates the entire denudation and relief evolution from ~100 Ma to the present, suggests that the highest relief was built-up at ~40 Ma. Since then, denudation has been the first-order activity leading to decreased relief until the present, implying that the northern Tibet margin was relatively stable over the past 40 Myr. The existing northern Tibet margin was built-up during the early phase of the collision history, and the northward propagation of continued convergence between India and Eurasia is not significant. This may be attributed to the strength of heterogeneities in the continental lithosphere or the basal traction induced by mantle flow.

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.tecto.2016.03.001.

Acknowledgments

This study is supported by the “Strategic Priority Research Program” of the Chinese Academy of Science (XDB03020203), Natural Science Foundations of China (41521062, 410253010). The authors thank Bihong Fu, Pinlong Shi for their kind help in field work. We acknowledge Oscar Lovera and the anonymous reviewer for constructive suggestions and comments.

References


