Late Cretaceous-Cenozoic Multi-Stage Denudation at the Western Ordos Block: Constraints by the Apatite Fission Track Dating on the Langshan

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Abstract: The apatite fission track dating of samples from the Dabashan (i.e., the Langshan in the northeastern Alxa Block) by the laser ablation method and their thermal history modeling of AFT ages are conducted in this study. The obtained results and lines of geological evidence in the study region indicate that the Langshan has experienced complicated tectonic-thermal events during the the Late Cretaceous-Cenozoic. Firstly, it experienced a tectonic-thermal event in the Late Cretaceous (~90–70 Ma). The event had little relation with the oblique subduction of the Izanagi Plate along the eastern Eurasian Plate, but was related to the Neo-Tethys subduction and compression between the Lhasa Block and Qiangtang Block. Secondly, it underwent the dextral slip faulting in the Eocene (~50–45 Ma). The strike slip fault may develop in the same tectonic setting as sinistral slip faults in southern Mongolia and thrusts in West Qinling to the southwest Ordos Block in the same period, which is the remote far-field response to the India-Eurasia collision. Thirdly, the tectonic thermal event existed in the late Cenozoic (since ~10 Ma), thermal modeling shows that several samples began their denudation from upper region of partial annealing zone (PAZ), and the denudation may have a great relationship with the growth of Qinghai-Tibetan Plateau to the northeast. In addition, the AFT ages of Langshan indicate that the main body of the Langshan may be an upper part of fossil PAZ of the Late Cretaceous (~70 Ma). The fossil PAZ were destroyed and deformed by tectonic events repeatedly in the Cenozoic along with the denudation.

Key words: apatite fission track, cooling history, thermal modeling, Late Cretaceous-Cenozoic, Langshan

1 Introduction

With the India-Eurasia collision, the uplift of the Qinghai-Tibet Plateau is known to be a major geological event occurred in the Cenozoic. This not only has reshaped the landform pattern (De Grave et al., 2007; Vassallo et al., 2007; Jolivet, 2015) of long-term stability in East and Central Asia since the Late Jurassic-Late Cretaceous epoch, but has also impacted the climate change, leading to the formation and enhancement of the Asian monsoon (An et al., 2001; Guo et al., 2002). There are roughly three models about the growth pattern of the Qinghai-Tibetan Plateau. The first one is that the plateau extended and grew gradually from south to north (Meyer et al., 1998; Tapponnier et al., 2001). The second one is that the northern plateau experienced deformation in the same period of collision or shortly later (Yin et al., 2002; Fang Xiaomin et al., 2004; Clark et al., 2010; Duvall et al., 2011, 2013; Zhang Kexin et al., 2010, 2013). The third one is that the plateau extended and grew from the middle part to the north and south sides (Wang et al., 2008, 2014). Moreover, in recent years, there are different opinions on the scope of the far field influence and the epoch of India-Eurasia collision. For example, Yue and Liou (1999) and Darby et al. (2005) thought that the Altyn Tagh fault zone...
extended eastwards into South Mongolia through the Alxa Block of Inner Mongolia during the Oligocene. However, one recent research argued that the Altyn Tagh fault zone in the northeastern Alxa Block. In recent years, many researchers have focused on the growth pattern and influence scope of the Qinghai-Tibetan Plateau (Meyer et al., 1998; Fang et al., 2003, 2005, 2007; Dai et al., 2006; Zheng et al., 2006; Dupont-Nivet et al., 2008; Liu et al., 2013; Zheng et al., 2013a, 2013b; Zhang Kexin et al., 2010, 2013; Duvall et al., 2011; Wang et al., 2013; Yu et al, 2016), and different understandings are obtained. The rift system developed around the Ordos Block during the same time with the India-Eurasia collision and the subsequent compression, most scholars attributed the formation of this graben system to the India-Eurasia collision (Molnar and Tapponnier, 1975; Ordos active fault research group of China Earthquake Administration, 1988). There are a series of high mountains along the eastern Alxa Block distributed from north to south: the Langshan-Bayan-Ul, the Helan Mountain, Large and Little Luoshan Mountains, the Xiangshan-Tianjingshan, the Liupan Mountain, etc. The Langshan-Bayan-Ul and Helan Mountain in the north are controlled by the extension, there are Cenozoic rift basins on the east side of these mountains, with the thickest Cenozoic sediments exceeding 10 km occurring in the Hetao Basin (Ordos active fault research group of China Earthquake Administration, 1988). However, the Large and Little Luoshan Mountains, Xiangshan-Tianjingshan and the Liupan Mountain in the south developed in an oblique compression condition. Although the stress fields are different, some studies have shown that mountains such as the Helan Mountain and the Liupan Mountain began their rapid denudation between 8–12 Ma, and most researchers believed that this rapid denudation relates to the northeastward growth of Qinghai-Tibetan Plateau (Zheng et al., 2006; Liu Jianhui et al, 2010). Previous studies have shown that the Langshan, located to the north of the Helan Mountain and South Mongolia to the north of Langshan, possibly experienced an early deformation event in the Cenozoic (Webb et al., 2006; Zhang et al., 2014). However, this opinion was not based on irrefutable chronological evidence. Therefore, questions, such as whether there is any Cenozoic multi-stage deformation in the Langshan, the ages of deformation and whether the Cenozoic deformation in the Langshan is similar to the Helan Mountain, will be important evidence to answer the far filed effect of India-Eurasia collision and the growth time of the northern plateau. For this purpose, we carried out the apatite fission track (AFT) dating and field work in the Langshan region, to discuss the Cenozoic denudation and deformation of the Langshan.

2 Geological Backgrounds

The Langshan is located at the northeastern Alxa Block and to the northwest of the Yinshan-Hetao rift basin. This area is considered to have become a part of the North China Block since the Paleoproterozoic (Zhao et al., 2005), and its basement is the high-graded metamorphic Diebusigegroup complex (granulite facies), which is composed of magnetite quartzite, quartzite, marble and TTG of the same era. The study region experienced extension during the Neoproterozoic, the Langshan Group mainly consisting of thicker continental clastics interbedded with marble and thinner layers of volcanic rocks was deposited in rift basins. Recent studies have indicated that, the age of volcanic rocks in the Langshan Group is around 820–800 Ma (Peng Ruimin et al., 2010; Wang et al., 2016). As the Paleo-Asian Ocean had closed in the north side of the study region since the end of the late Paleozoic, the Langshan Group was deformed intensively, forming a series of east-west-trending, isoclinally overturned folds verging south. During the Triassic, the eastern Alxa Block experienced a strong sinistral ductile shearing and the Carboniferous granite in the Dabashan was involved in it (Zhang et al., 2013), almost all of which became gneissic mylonite after deformation. In the Late Jurassic, a series of northeast-southwest trending top-to-the-southeast thrust developed in the northern study region (Darby and Ritts, 2002; 2007). During the Early Cretaceous, a red basin developed and was controlled by a low-angle detachment fault in the study region (Zhang et al., 2014; Tian et al., 2017). In the Early Cenozoic, the early deformation was the top-to-the-northwest thrusting that developed along eastern side of Carboniferous granite of the Dabashan (Zhang et al., 2014), and then a series of NNE-trending high angle normal faults dipping to SSE developed in the east side of Carboniferous granite of the Dabashan, and control the development of the Hetao rift basin (Zhang et al., 1998). The Dabashan was cut by a set of NNE-trending strike-slip faults; however, these brittle faults did not cut through the red Oligocene deposits (i.e., the Wulanbulage Formation) overlapping on the mountain body. Therefore, these strike-slip faults have been inactive since the Oligocene.

3 Samples and Dating Method

3.1 Sample description

The samples of this study were collected from the
Dabashan which is the southern part of the Langshan, in the followings the Dabashan is used instead of the Langshan for conveniently. Most samples were collected from the monzonitic granite in the Langshan (i.e., the Dabashan, Fig. 3), which is the granitic mylonite after the Triassic shear deformation, and two samples were collected from the Oligocene red conglomerates on the top of the Dabashan (Figs. 1 and 2). Granitic samples contain minerals of plagioclase 30%–35%, potash feldspar 30%–40% and quartz 20%–30% with a small amount of biotite. The zircon U-Pb age of the granite is 337±5 Ma (Dan et al., 2016) and 329±1 Ma (Zhang et al., 2014).

Topographically, the Dabashan is steep in the southeast side, and gentle in the northwest side, which forms a northwardly tilted mountain (Fig. 3). The surface of eastern Dabashan is a Cenozoic high angle normal fault (Figs. 2 and 3). The maximum altitude of the Dabashan is about 1700 m, and the altitude of the eastern foot of the Dabashan is around 1100 m. In this study, two profiles (profile A-B and profile I-J) (Figs. 2 and 3) crossing the Dabashan in north and south parts were collected respectively. A majority of granite samples experienced the Mesozoic ductile shearing. Sampling interval is about 100 m; the elevation was measured using a handheld GPS.
Fig. 2. Sample locations and geomorphological sections of the Langshan (see Fig. 1 for location).

Fig. 3. Geomorphological profiles and sample profiles (see Fig. 2 for the profile locations).

Topographic data is based on SRT90m DEM data from the CGIAR consortium for Spatial Information (CGIAR-CSI) (http://srtm.csi.cgiar.org/SELECTION/inputCoord.asp).
receiver and 1: 25000 scale topographical map (Fig. 2). There were totally 18 samples collected, however, no enoughapatite minerais for dating were found in five of them. The geographic locations, lithology, and altitudes of all samples are given in Table 1 and Figure 2, Figure 3.

3.2 Dating

The domestic apatite fission track (AFT) chronology still mainly relies on an external detector in the form of radiation, and while this method is already more mature, it is still restricted by the test process, sample irradiation, and other factors. Currently, analysis based on laser ablation (Laser Ablation-Inductive Coupled Plasma-Mass Spectrometry) (LA-ICP-MS) (Hasebe et al., 2004) has been well developed and widely used internationally. The analysis technology has been becoming mature, and relevant equipment has also been introduced to and similar datings have been carried out in some labs in China.

The method aims at obtaining uranium content from apatite samples by using laser ablation technique accompanied by mass spectrometry. Hasebe et al. (2004) proposed an absolute calibration method to calculate LA-ICP-MS AFT age that is based on $^{238}$U total decay constant and $^{238}$U spontaneous fission decay constant. The detail information about the dating methods can be found in Hasebe et al. (2004, 2013).

To define the chemical composition of apatite affecting the characteristics of annealing and get further effective constraints in the thermal history analysis, we also measured the etch pit diameter (Dpar) of the path length and fission track of apatite grains in this study. Dpar, an important indicator to quantify the solubility of apatite (Donelick et al., 2005), is the maximum diameter of fission track etching parallel with crystallographic axis c and intersecting with polished surface. Its value relates to the content of crystal fluoride and chlorine. In general, the smaller the Dpar is, the higher the fluorine and chlorine content is, and the faster the track annealing rate is. Often, the annealing rate of apatite is relatively faster when Dpar ≤1.75μm, and relatively slower when Dpar ≥1.75μm. The Dpar of the vast majority of samples from the Dabashan is ≥1.75μm, suggesting that the fluorine and chlorine content in the apatite of the samples are normal, the annealing rate is slower, and the temperature for full annealing is about 110°C.

AFT ages of samples from the Dabashan (i.e., the Langshan), along with the path length and fission track etch pit diameter (Dpar), were measured at the China State Key Laboratory of Earthquake Dynamics. The main analysis steps are as follows: (1) Apatite was separated using standard magnetic and density methods and then mounted on glass slides with araldite epoxy. (2) After grinding, polishing and exposing to the internal surface, place the apatite in 5.5 mol/L nitric acid with temperature of 21°C to etch for 20s, to show naturally spontaneous fission track. (3) Use the Zeiss polarizing microscope at 10×1000 magnification on the AutoSan platform, carrying out fission track counting and measuring the track length and diameter (Dpar) of fission track etch pit. When possible, at least 1000 tracks distributed between minimum 20 grains were counted per sample, but this target was not always attained. (4) Use an Agilent 7900s mass spectrometer and a Resonetics M-50 with laser system together (see Table 2 for the detailed analysis) for on-site analysis to determine the uranium concentration in each counting grain. In every single measurement, signal strength of $^{238}$U is calibrated according to $^{43}$Ca (internal standard). Both of these two elements appear in standard samples and unknown apatite in the form of matrix elements. By using NIST 610, NIST 612 glass and Durango apatite standard as the main standard to check for every 10 unknown apatite grains in a measure sequence. (5) LA-ICP-MS AFT ages were calculated using the Zeta (ζ) method which was proposed by Hasebe et al. (2013). The sample test results by applying an international standard sample (Durango apatite) to measure ζ value in Table 2, and refer to Figure 4 for radial plots of age distribution of single grain AFT ages and track distribution of samples from the Dabasha.

Table 1 Geographic location, elevation and lithology of the samples from the Langshan

<table>
<thead>
<tr>
<th>Sample no.</th>
<th>Lab no.</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Altitude (m)</th>
<th>Lithology</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSA-01</td>
<td>A01</td>
<td>40°39′20.6″</td>
<td>106°18′40.7″</td>
<td>1295</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSA-02</td>
<td>A02</td>
<td>40°33′26.5″</td>
<td>106°18′32.9″</td>
<td>1398</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSA-03</td>
<td>A03</td>
<td>40°33′29″</td>
<td>106°18′28.4″</td>
<td>1520</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSA-04</td>
<td>A04</td>
<td>40°33′28.8″</td>
<td>106°18′25.7″</td>
<td>1582</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSA-05</td>
<td>A05</td>
<td>40°33′34.4″</td>
<td>106°18′19.9″</td>
<td>1660</td>
<td>Sandstone (Oligocene)</td>
</tr>
<tr>
<td>LSA-07</td>
<td>A06</td>
<td>40°33′40.0″</td>
<td>106°17′35.2″</td>
<td>1462</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSA-08</td>
<td>A07</td>
<td>40°33′31.4″</td>
<td>106°17′16.9″</td>
<td>1338</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSA-09</td>
<td>A08</td>
<td>40°34′14.5″</td>
<td>106°18′41.5″</td>
<td>1208</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSB-01</td>
<td>A09</td>
<td>40°31′56.4″</td>
<td>106°14′25.8″</td>
<td>1517</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSB-06</td>
<td>A10</td>
<td>40°30′38.9″</td>
<td>106°15′27.2″</td>
<td>1410</td>
<td>Sandstone (Oligocene)</td>
</tr>
<tr>
<td>LSB-07</td>
<td>A11</td>
<td>40°30′31.0″</td>
<td>106°15′45.2″</td>
<td>1429</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSB-08</td>
<td>A12</td>
<td>40°30′32.0″</td>
<td>106°15′49.6″</td>
<td>1345</td>
<td>Monzonitic granite</td>
</tr>
<tr>
<td>LSB-09</td>
<td>A13</td>
<td>40°30′33.1″</td>
<td>106°15′52.4″</td>
<td>1286</td>
<td>Monzonitic granite</td>
</tr>
</tbody>
</table>
4 Results

4.1 AFT ages

According to AFT ages from the Dabashan, most of samples underwent a complicated tectono-thermal history. The ages of all single grains in samples were dispersive, the dispersity of most samples exceeded 40%, and 1–3 age peaks appeared (Fig. 4). Therefore, the median ages obtained from these samples were mixed ages, whose geological meaning is ambiguous. In the samples, the median ages are between 112–44 Ma (Table 2), in which the apparent ages of A5 (91±4.6 Ma) and A10 (112±11...
Fig. 4. Radial plots and length distribution of mean confined track lengths for samples from the Dabashan, Langshan.

MTL: mean confined track length; SD: standard deviation; N: number of the fission tracks; Dpar: etch pit diameter of fission track.

Table 2 LA-ICP-MS AFT dating results

<table>
<thead>
<tr>
<th>Sample</th>
<th>Sample in Lab</th>
<th>No.</th>
<th>Ns</th>
<th>Area (cm²)</th>
<th>Σ(m)</th>
<th>1σΣ(m)</th>
<th>ζMS</th>
<th>1ζMS</th>
<th>Central age (Ma)</th>
<th>Dispersion (%)</th>
<th>MTL (μm)</th>
<th>N</th>
<th>SD (μm)</th>
<th>Dpar (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LSA-01</td>
<td>A01</td>
<td>20</td>
<td>160</td>
<td>1.64E-03</td>
<td>3.69E-02</td>
<td>6.06E-04</td>
<td>0.9161</td>
<td>0.0121</td>
<td>53.4±6.5</td>
<td>37</td>
<td>13.7±0.12</td>
<td>9</td>
<td>0.64</td>
<td>1.65</td>
</tr>
<tr>
<td>LSA-02</td>
<td>A02</td>
<td>31</td>
<td>722</td>
<td>2.18E-03</td>
<td>1.44E-01</td>
<td>2.94E-03</td>
<td>0.9770</td>
<td>0.0061</td>
<td>72.3±6.6</td>
<td>46</td>
<td>12.6±0.2</td>
<td>33</td>
<td>1.29</td>
<td>2.1</td>
</tr>
<tr>
<td>LSA-03</td>
<td>A03</td>
<td>10</td>
<td>251</td>
<td>7.55E-04</td>
<td>6.54E-02</td>
<td>1.08E-03</td>
<td>0.9280</td>
<td>0.0128</td>
<td>47.2±5.6</td>
<td>30</td>
<td>12.3±0.2</td>
<td>24</td>
<td>1.61</td>
<td>1.2</td>
</tr>
<tr>
<td>LSA-04</td>
<td>A04</td>
<td>16</td>
<td>379</td>
<td>1.18E-03</td>
<td>1.09E-01</td>
<td>2.09E-03</td>
<td>0.9606</td>
<td>0.0074</td>
<td>44.2±5.8</td>
<td>47</td>
<td>12.3±0.2</td>
<td>21</td>
<td>1.17</td>
<td>1.76</td>
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<td>LSA-05</td>
<td>A05</td>
<td>4</td>
<td>403</td>
<td>3.60E-04</td>
<td>4.95E-02</td>
<td>9.33E-03</td>
<td>0.8965</td>
<td>0.0121</td>
<td>91±4.6</td>
<td>0</td>
<td>13.1±0.2</td>
<td>38</td>
<td>1.85</td>
<td>2.39</td>
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<tr>
<td>LSA-06</td>
<td>A06</td>
<td>20</td>
<td>755</td>
<td>1.41E-03</td>
<td>1.66E-01</td>
<td>3.29E-03</td>
<td>0.9024</td>
<td>0.0148</td>
<td>60.7±6.2</td>
<td>41</td>
<td>12.5±0.1</td>
<td>48</td>
<td>1.57</td>
<td>2.1</td>
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<td>LSA-07</td>
<td>A07</td>
<td>12</td>
<td>291</td>
<td>7.05E-04</td>
<td>1.00E-01</td>
<td>2.99E-03</td>
<td>0.9000</td>
<td>0.0208</td>
<td>53.4±9.5</td>
<td>57</td>
<td>12.0±0.3</td>
<td>18</td>
<td>1.46</td>
<td>1.74</td>
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<tr>
<td>LSA-08</td>
<td>A08</td>
<td>18</td>
<td>1012</td>
<td>1.58E-03</td>
<td>1.87E-01</td>
<td>2.68E-03</td>
<td>0.9105</td>
<td>0.0100</td>
<td>53.1±4.4</td>
<td>31</td>
<td>13.6±0.1</td>
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<td>0.64</td>
<td>2.08</td>
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<tr>
<td>LSB-01</td>
<td>A09</td>
<td>13</td>
<td>675</td>
<td>1.30E-03</td>
<td>1.13E-01</td>
<td>2.07E-03</td>
<td>0.9334</td>
<td>0.0124</td>
<td>57.4±7.3</td>
<td>43</td>
<td>13.1±0.1</td>
<td>13</td>
<td>1.17</td>
<td>2.36</td>
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<td>LSB-02</td>
<td>A10</td>
<td>10</td>
<td>688</td>
<td>9.50E-04</td>
<td>6.53E-02</td>
<td>8.42E-03</td>
<td>0.9249</td>
<td>0.0091</td>
<td>112±11</td>
<td>27</td>
<td>12.6±0.2</td>
<td>34</td>
<td>1.88</td>
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<td>LSB-03</td>
<td>A11</td>
<td>12</td>
<td>843</td>
<td>1.63E-03</td>
<td>2.90E-01</td>
<td>5.15E-03</td>
<td>0.9277</td>
<td>0.0049</td>
<td>61.5±6.1</td>
<td>39</td>
<td>13.1±0.2</td>
<td>31</td>
<td>1.41</td>
<td>2.36</td>
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<td>LSB-04</td>
<td>A12</td>
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<td>534</td>
<td>1.08E-03</td>
<td>6.28E-02</td>
<td>6.81E-04</td>
<td>0.9191</td>
<td>0.0091</td>
<td>81.6±5.5</td>
<td>16</td>
<td>12.5±0.1</td>
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<td>12</td>
<td>386</td>
<td>8.60E-04</td>
<td>7.09E-02</td>
<td>3.86E-04</td>
<td>0.8867</td>
<td>0.0144</td>
<td>77.3±4.8</td>
<td>11</td>
<td>12.3±0.2</td>
<td>12</td>
<td>1.19</td>
<td>1.8</td>
</tr>
</tbody>
</table>

Ns, number of counted spontaneous tracks; Area, grain area analyzed; Σ(m), area weighted intensity signal of 238U/43Ca, summed over all the grains per sample; σ, standard error; ζMS, zeta calibration factor; MTL, mean track length; N, number of the fission tracks; SD, standard deviation of fission tracks; Dpar, fission track etch pit diameter.

Ma) are older than the sedimentary age (Oligocene) of the stratum. Hence, the single grain ages in the two samples...
represent the ages of detrital apatite fission track ages in source regions, which also shows that these two samples have not experienced an obvious annealing effect. Furthermore, there were few apatite grains in these two samples for analysis purpose (≤10), and their apparent ages didn’t have statistical significance. The crystallized ages of other samples (monzonitic granite) are 337±5 Ma (Dan et al., 2016) or 329±1 Ma (Zhang et al., 2014), whose AFT ages (81–44 Ma) are far less than their crystallized ages; in addition, the confined track lengths in samples are mostly between 12–14 μm (Table 2), which means all samples stayed in partial annealing zone (PAZ) for a long time. Therefore, their AFT ages represent that these samples have experienced different annealing processes.

In the Dabashan, Langshan region, more samples in profile A-B provide were dated, while four samples from profile G-H, we couldn’t find enough apatites for further dating, only five samples from profile G-H were dated, four samples of these five samples are located on the east side of the Dabashan (Fig. 3). Except for A5 and A10 samples, there was no significant correlation between the median age of the remaining 11 samples and their altitudes. On the contrary, the higher the altitudes are, the younger the ages (e.g. A03 and A04) are. There wasn’t any inflection point found on the age-elevation map, so it is not possible to determine the timing of the occurrence of rapid denudation crossing the bottom of PAZ (Fig. 5a). The relationship between the distance from the western boundary of Langshan Fault F3 and the ages (Fig. 2) and the age distribution diagram (Fig. 5b) show that except A03 and A04 samples located in the central part of the Dabashan, the ages of samples are gradually older as they are far away from Fault F3. A03 and A04 samples have a high elevation, but the ages are very young, 47.2±5.6 Ma and 44.2±5.8 Ma, respectively (Table 2); these two samples were mainly collected from the regions near a large dextral strike-slip fault and its secondary fault in central part of the Dabashan (Fig. 2), whose age may be affected by the fault activity. Except A03 and A04, all other samples show that ages have a positive correlation with the distance from the F3 transversely, which may indicate that F3 is an important boundary fault to control the deformation of the Dabashan, though the piedmont normal slip fault F1 in the east side of the Dabashan is the most active at present.

The diagrams of the relationship between the ages of AFT of samples from the Dabashan and the horizontal mean confined track length, and the standard deviation of track length indicated a U-shaped (Fig. 6a) and an inverse U-shaped pattern (Fig. 6b), respectively (Fig. 6). Usually, this U-shape pattern between the horizontal mean confined track length and ages is called the “boomerang plot.” In this plot, the timing at which the geologic body experienced an important tectonic thermal evolution history can be determined through comparing among large amount of ages, horizontal mean confined track lengths and the standard deviation of track lengths. However, in principle, there are tracks with a horizontal mean confined track length of more than 14 μm or less than 13 μm (Gallagher and Brown, 1997). The horizontal mean confined track lengths of samples from the Dabashan are
mainly between 12–14 μm, suggesting that they were principally distributed inside the PAZs. Although there is a relatively obvious U-shaped pattern (Fig. 6a), and because the ages are highly dispersed, the timing of tectonic thermal event determined by boomerang plot may be inaccurate (55–50Ma) (Fig. 6).

4.2 Thermal modeling

Because most samples from the Dabashan didn’t obtain ideal AFT ages and the dispersity was larger, we speculated that they had experienced a more complex thermal history. To further study the thermal history process that samples from the Dabashan experienced, the authors performed the thermal modeling of most samples in this study. During thermal modeling, HeFty (Version. 1.7.5, 2012; Ketcham, 2005) was adopted, and the multicomponent annealing model proposed by Ketcham (2007) was applied to all samples. The constraint conditions are: (1) Full annealing state is set as the time limit larger than the maximum age of single grains (Ketcham, 2005); (2) The surface temperature range is 0–20°C; (3) The geothermal gradient was 30–40 °C/km (Research Group of Peripheral Fault System around the Ordos, Institute of Geology, State Bureau of Seismology, 1988); (4) The range of partial annealing zones of AFT is 60–110°C (Gleadow et al., 1986); (5) The Dpar value is given in Table 2; (6) Evaluation functions K-S and GOF are used to check the modeling results. When K-S evaluation values are 0.5 and 0.05, preferable and acceptable results would be obtained respectively, and there are 10000 paths for the statistics of each sample. The deviation of all thermal history modeling in this study was ~5%; (7) The initial track length is 16.3 μm (Gleadow et al., 1986). Because samples A05 and A10 were collected from the Oligocene conglomerate of the Wulanbulag Formation on top of the Dabashan, the apparent ages of its apatite are older than the sedimentary age of the stratum. Furthermore, the dated apatite grains are few, which could not meet the general conditions required for thermal modeling. Therefore, additional thermal modeling is not performed on samples A05 and A10. See Figure7 for the thermal modeling results for other samples.

Good thermal modeling results (GOF>0.5) were obtained for most modeled samples from the Dabashan. It was also revealed that the majority of samples began entering into the partial annealing zone (PAZ) in the Late Cretaceous (~90–70 Ma). However, different samples were inconsistent in their process in the PAZ. Samples A02, A04, A06 and A07 had stayed a long time in the PAZ, and did not leave until the late Cenozoic, while samples A08, A09 and A11 re-entered into the upper region of the PAZ in the late Cenozoic after leaving the PAZ in the early Cenozoic, then left rapidly (Fig. 7). Although above samples have different paths of thermal history, it is still apparent that most samples left the PAZ and rapidly denuded in the late Cenozoic (~10 Ma). Although there are still many different opinions about whether the low-temperature parts have geological meaning, it will be discussed in detail in the following section. The leaving of ~10 Ma from PAZ indicates that these samples may experience important tectonic events in the late Cenozoic. Several samples (A12, A13) left the PAZ rapidly and entered into a steady and slowly rising stage in the late Mesozoic (Fig. 7), which indicates that sample A12, A13 were basically stabilized after experiencing a tectonic thermal event in the Late Cretaceous.

Fig. 6. Relationship between AFT ages and horizontal confined track lengths/deviations of the track length. (a), Relationship between AFT ages and horizontal confined track lengths; (b), relationship between AFT ages and standard deviations of lengths; The gray column represents the rapid cooling time.
5 Discussion

5.1 Denudation stages and characteristics of the Dabashan

The ideal apparent ages of apatite were not obtained from two profiles crossing the Dabashan, because some samples have no enough apatite grains for dating and some even did not contain apatite. Most of the samples that can be dated had age dispersity of single grains >40% (Table 2, Fig. 4), so these ages were mostly mixed ages, whose geological significance needs to be carefully considered and analyzed. However, except for samples A05 and A10 (there were few grains in dated apatite that did not experience the annealing process, so their ages were mostly source area ages), all other samples basically showed similar multi-stage denudation process. Generally, according to the age similarity, the Dabashan can be divided into three regions: the western slope, the central part and the eastern slope (Fig. 5b).

Samples from the central part can be divided into two types, one of which is the sample of Wulanbulag Formation from the top of mountain, and the other were collected from the monzonitic granite. Both APT ages and the median ages of samples (A05 and A10) collected from the sandstone in the red Oligocene Wulanbulag Formation (Fig. 8a) covering the top of the Dabashan were older than the age of stratum, indicating that they may not undergo the annealing process after the deposition of the Wulanbulag Formation. Moreover, the number of single grains with ages in samples A05 and A10 is less than 10, which is also relatively dispersive, and their median age didn’t have reliable geological significance, so we will not discuss these two samples further in this study. The ages of two important samples A03 and A04 which were

![Fig. 7. Thermal history modeling of samples from the Dabashan. The purple area represents good fits (Ketcham et al., 2007), the green area represents acceptable fits, the blue line represents the weighted mean path, and PAZ represents the apatite partial annealing zone (60–110°C).](image-url)
collected near the dextral strike-slip fault in the central part are 47.2±5.6 Ma and 44.2±5.8 Ma, respectively, but the single grain ages of both samples are relatively dispersive, and both of them have an age peak around 31 Ma. A double-peak pattern presented in the track length distribution of sample A03, and the two samples have similar horizontal confined track lengths (Fig. 4), so the ages of both of them are mixed ages. The locations of samples A03 and A04 are close to each other, and both of them have similar track age distributions, implying that they experienced a similar thermal event. The thermal modeling also showed that they passed through the PAZ rapidly in the period of 50–45 Ma (Fig. 7). The sampling locations of A03 and A04 are the highest among all samples (Fig. 5a), but their ages are the youngest (Fig. 5a), which is different from the trend that the ages usually become older with the increase in altitude. Because two samples are located near the dextral strike-slip fault which cut the central part of the Dabashan (Figs. 2, 8c, 8d), the authors speculated that their ages were related to the fault activity. It is necessary to point out that the dextral strike-slip fault is covered by the Oligocene conglomerate of the Wulanbulag Formation (Fig. 8b), which also constrains that the fault was active before the Oligocene.

A06, A07, A08 and A09 are the samples collected from the western slope of the Dabashan (Figs. 2, 5b), whose ages are generally consistent (60–53 Ma); however the ages of single grains of each sample have multiple peaks (Fig. 4). The length distribution is bimodal, the horizontal confined track length of A06 and A07 is shorter (12.5±0.1–12.0±0.3 μm), in addition, the standard deviation of track length is larger (1.46–1.57 μm), and the range of track length distribution is also wider, indicating that the two samples may have stayed longer in the PAZ. The thermal modeling of A06 and A07 also reveals that they entered into the PAZ in ~70 Ma and ~55 Ma separately, while they passed through it at ~10 Ma coevally (Fig. 7).

The horizontal confined track length of A08 and A09 is longer (13.1±0.1–13.6±0.1 μm) (Fig. 4), and they have similar results of thermal modeling, that is, they both rapidly passed through the PAZ at ~70–60 Ma (Fig. 7) and re-entered into the upper PAZ at approximately ~10 Ma and then denuded rapidly (Fig. 7). Because both A08 and A09 are near the boundary fault at the western Dabashan, the fault may experience important activities in the Cenozoic. Therefore, the age of ~10 Ma may be associated
with the fault activity.

On the profile A-B, there are two samples in the eastern slope of Dabashan (A01 and A02), there are few measurable tracks (n=9) from A01. Hence, it is unclear whether the age is significant, which will not be further discussed in this study. The age of A02 is 72.3±6.6 Ma, its single grain ages are largely dispersive, and includes two age peaks, its horizontal confined track length is 12.6±0.2 μm, and the standard deviation of the length is longer (1.29 μm), indicating that the thermal history of the sample is more complex. The thermal modeling shows that the sample entered into the PZA at ~80 Ma approximately. However, it stayed for a longer time in the PAZ and finally passed through it at ~10 Ma (Fig. 7). The fission track characteristics of A02 are exactly similar to those of A06 and A07 from the western slope, that is, they basically entered into and left the PAZ at the same time. Among these samples (A06, A07, A08, A09 and A02), A09 is the highest in the altitude, and its track length distribution and thermal modeling are completely different from A06, A07 and A02 (Fig. 7). In this study, due to the factors that A06, A07 and A02 stayed in the PAZ for a long time and their thermal histories completely different from A09 above them, the authors suggested that A06, A07 and A02 represented the upper part of an ancient PAZ that has been denuded to the earth’s surface, the top of the PAZ should be located between A09 and A06 (Fig. 5a), but the lower-middle part of the PAZ hasn’t been denuded to the earth’s surface. The exposure lower-middle part of Dabashan currently still belongs to an ancient PAZ (Fig. 9), the approximate age of the PAZ is ~80–70 Ma, and the upper PAZ was not denude to the earth’s surface until the Late Cenozoic (~10 Ma). If the geothermal gradient of the area was 36–40°C/km (Ordos active fault research group of China Earthquake Administration, 1988) and the temperature on the top of the PAZ was 60°C, the mean long-term denudation rate of Dabashan is 0.06–0.16 mm/y since ~10 Ma, and the slip rate is similar with the present slip rate (0.1–0.3 mm/y) of piedmont normal fault of Dabashan (Ordos active fault research group of China Earthquake Administration, 1988; Shen Xiaoming et al., 2016)

There are three samples (A11, A12 and A13) in the eastern slope of Dabashan, whose apparent ages are the oldest and all three samples are collected in the hanging wall of a thrust in the east part of profile G-H (Figs. 2, 3 and 10). Their ages are between 61.7–81.6 Ma (Figs. 4 and 5b). Among them, the age dispersities of single grains of A12 and A13 are less than 40%, which indicates that their age compositions are comparatively simple and their median ages are 81.6±5.5 Ma and 77.3±4.8 Ma, respectively. The thermal modeling showed that samples A12 and A13 had passed through the PAZ rapidly during 90–70 Ma. While the history of A11 is relatively complex, there are two single grain age peaks, the track length distribution is wider (Fig. 4). According to the thermal modeling, sample A11 entered into the PAZ at ~70 Ma and left at approximately 50 Ma, but it returned to the upper PAZ at around ~15 Ma, then left again rapidly (Fig. 7).

The above data and modeling of samples from the Dabashan indicate that the Dabashan experienced three important tectonic-thermal events in the Late Cretaceous (~90–70 Ma), the Eocene (~50–45 Ma) and the Late Cenozoic (since ~10 Ma) respectively.

5.2 The tectonic setting of the Late Mesozoic-Cenozoic denudation events

5.2.1 The Late Cretaceous (~90–70 Ma)

Almost thermal modeling of all samples and the several
samples (A12 and A13) with concentration of single grain ages from the Dabashan show that they experienced a significant thermal event in the Late Cretaceous (~90–70Ma). In the Early Cretaceous, extensional basins and many metamorphic core complexes developed in the vast areas in China (Meng et al., 2003; Wang et al., 2011). The Alxa Block with the Langshan at its eastern margin also experienced significant extension, namely the development of many rift basins and the subsequent basalt eruptions in large areas (Meng et al., 2003). In the Late Cretaceous, most regions in China experienced a significant tectonic event, many early Cretaceous rift basins stopped developing, and regional uplift started, an angular unconformity developed in regions like the Ordos Basin, Songnen Basin, Sichuan Basin, Erlian Basin and the Huabei Basin (Ren et al., 2002). In the same period, South China also experienced an important change of tectonic settings (i.e., from NWW-SEE extension at early stage to NWW-SSE compression) (Li et al., 1997). At this time, a left-strike-slipping occurred on the Tancheng-Lujiang Fault. Therefore, under the high-speed oblique subduction, the principal compressive stress in the eastern part of East Asia was in the NNW-SSE direction, and the stress field may be probably the main factor for the tectonic inversion of many early Cretaceous basins in the eastern China. A recent research also suggested that, in the Late Cretaceous, the eastern shore of Chinese continent might collide with an unknown microcontinental or oceanic plate (Niu Yaoling et al., 2015). We can see that the ancient stress fields in eastern and western China in the Late Cretaceous were different, the western China was affected by the subduction of Neo-Tethys Ocean and the compression between the Lhasa and Qiangtang blocks, while the eastern China was associated with the movement of the Izanagi Plate and/or the collision between Chinese continent with an unknown block.

In the Late Cretaceous, the northeastern China also experienced a strong tectonic thermal event, while the Great Khingan, Changbai mountains began rapid denudation (~100–70Ma) (Li et al., 2010, 2011). But the tectonic thermal event hasn’t been recorded by the low-temperature thermochronology in the Mandula area at the northern margin of North China Block at the same latitude.
The Dabashan at the same latitude is located further west to the Mandula area. Therefore, the effect of Izanagi Plate from the east may be minor. Although the authors didn’t conduct detailed late Cretaceous tectonic analysis, we have found the late Cretaceous event in areas such as the Longshou Mountain at the northern margin of Hexi Corridor recently, which has resulted in the denudation of the Longshou Mountain (Zhang et al., 2017). Furthermore, we have also discovered late Cretaceous deformation in the Cretaceous basins in the eastern part of Hexi Corridor (the Longzhon Basin), namely the NNW-SSE folds, showing that at least the Hexi Corridor suffered from the NNE-SSW compression in the Late Cretaceous, which is consistent with the tectonic stress from the Qinghai-Tibetan Plateau. The fault (F3) at the western margin of Dabashan is currently a normal fault (Figs. 2, 11a), but it was a dextral strike-slip fault at the early stage (Fig. 11b). Also, the sample A08 close to the fault also revealed that it may be affected by the fault (F3). Sample A08 passed through the PAZ rapidly in the Late Cretaceous, while samples A06 and A07 nearby show a long-term stay in the PAZ. The authors speculate that the major cause of the late Cretaceous tectonic event in the Dabashan is the compression from the Qinghai-Tibetan Plateau at that time; however, the far field effect of compression from the southeast due to the collision between the Chinese continent and an unknown block (Niu Yaoqing et al., 2015) can not be excluded.

5.2.2 The Eocene (~50–45 Ma)

The thermal modeling of samples from central part of Dabashan displays that a tectonic thermal event occurred in the Eocene (~50–45 Ma) (Fig. 7). It is the time that the main stage of the India-Eurasia collision occurred (Najman et al., 2010), and the thermal event at this stage were found in the vast areas in the Qinghai-Tibet Plateau (Wang Guocan et al., 2010; Rohrmann et al., 2012), such as the Xining Basin (Zhang et al., 2015), the large-scale uplifting in Gangdise and Qiangtang regions (Xu et al., 2013; Ding et al., 2014), crustal thickening in the North Qilian Mountain (Ritts et al., 2004; Zhuang et al., 2011), thrusting in West Qinling (Clark et al., 2010; Duvall et al., 2011), thrusting in the South Qilian Mountain (Yin et al., 2002), and the formation of a large number of basins in the northeastern plateau (Fang et al., 2003, 2005; Zhang Kexin et al., 2010; Wang et al., 2011; Lu et al., 2012), and so on. At present, some researchers believe that deformation at the northeast margin of the Qinghai-Tibet Plateau started from the Late Cenozoic (Zheng et al., 2006, 2010) or later than ~30 Ma (Wang et al., 2011). In the adjoining South Mongolia regions to the north of the study region, researchers found early Cenozoic north-east trending strike-slip faults, which were considered to be controlled by the activity of the Altyn Tagh Fault at the northern margin of the Qinghai-Tibet Plateau (Webb and Johnson, 2006). Unfortunately, such faults lacked precise chronological constraints. Recently, researchers also have discovered deformation caused by nearly south-north compression in West Qinling region to the southwest of the Ordos Block (Clark et al., 2010; Duvall et al., 2011). The activity timing of the north-east trending dextral strike-slip faults in Dabashan constrained by samples (A03 and A04) near the fault (F2) was ~50–45 Ma, which provides a time limit for the formation of the north-east trending dextral strike-slip faults in the study region. At that time, the eastern North China Block experienced strong extension due to the back-arc extension caused by the subduction of Pacific Plate (Ma et al., 1987; Ren et al., 2002). The subduction of Pacific Plate was therefore difficult to provide the driving force of the dextral strike-slip in the research region. The authors tended to argue that the tectonic event which occurred in the study region in the Eocene may be attributed to the India-Eurasia collision, while its remote far field effect could reach at least the northern area at the northeastern Alxa Block at the early stage of collision.

5.2.3 The Late Cenozoic (since ~10 Ma)

In the late Cenozoic (since ~10 Ma), the denudation event has been discovered in all margins and many mountains of the Qinghai-Tibetan Plateau, representing a significant tectonic-thermal event (Molnar et al., 1993; Métivier et al., 1998; Wan Jinglin et al., 2001; Chen et al., 2002; Yuan et al., 2006; Zheng et al., 2010; Craddock et al., 2011; Duvall et al., 2013; Li et al., 2013). Tectonic event occurred in ~10 Ma at the northeastern Qinghai-Tibetan Plateau and the eastern Alxa Block has been also reported recently, such as the Liupan, Lajishan, and Jishishan mountains (13–7 Ma, Zheng et al., 2006; Lease et al., 2007, 2011, 2012; Wang Yannan et al., 2015) and the Helan Mountain (12–10 Ma, Zhao Hongge et al., 2007; Liu Jianhui et al., 2010).

Although there wasn’t apparent age around ~10Ma in samples from Dabashan in this study, the thermal modeling of almost all samples shows that there had been a stage of rapid cooling since ~10 Ma. Many studies have shown that the late Cenozoic rapid cooling in thermal modeling is likely to be caused by the selection of initial track length, but not samples (Gunnell et al., 2003); hence it is necessary to interpret it with caution when encountering cooling events completely occurred outside the PAZ, unless there is independent geological or other evidence. Though all thermal modeling of samples from
the Dabashan shows that many samples (A02, A03, A06, A07, A08, A09 and A11) started cooling from the upper PAZ in around ~10 Ma, and the representative of such cooling history has higher possibility (Vassallo et al., 2007). In addition, active tectonics occurred widely across the study region, as a part of the Cenozoic Peri-Ordos Graben System (Ordos active fault research group of China Earthquake Administration, 1988; Deng Qidong, 1994).

Fig. 11. Fault (F3) at the western margin of Dabashan.
(a), distant view; (b), sinistral strike-slip slickenline (photos were taken on the western front of the Dabashan).

Fig. 12. Piedmont fault of the Dabashan.
(a), Piedmont fault surface; (b), Parallel fault scarps along the piedmont fault; (c) and (d) Piedmont normal slip fault cutting the Late Pleistocene Jilantai Formation (all photos were taken on the eastern front of the Dabashan).
1996), Piedmont fault (F1) is a large active normal fault (Fig. 12) developing at least 4 fault scarps (Fig. 12), which has cut the lacustrine sedimentation of the Jilantai Formation since the Late Pleistocene (Figs. 12c and 12d). A recent study showed that the average earthquake recurrence interval was about 2500 years (Rao et al., 2016). Therefore, thermal event around ~10 Ma displayed in the thermal modeling of samples from the Dabashan is credible.

6 Conclusions

The AFT ages of samples from the Dabashan and their thermal modeling indicate that the northeastern Alxa Block experienced complicated tectonic thermal events in the late Cretaceous-Cenozoic. The Late Cretaceous tectonic thermal event (~90–70 Ma) had no relation to the action of the Izanagi Plate on the eastern Eurasian continent, but related to the Neo-Tethys subduction and the compression between the Lhasa and Qiangtang blocks. The dextral strike-slip fault activity in around the Eocene (~50–45 Ma) shared the same tectonic environment with the contemporary deformation in southern Mongolia and the southwest Ordos Block, which was the remote far-field response to the India-Eurasia collision. Thermal event in the late Cenozoic (since ~10 Ma), coeval to the Cenozoic rapid denudation of mountains near the Langshan may be associated with the northeastward growth of the Qinghai-Tibetan Plateau. At the same time, it has been also found that main body of Dabashan is an incompletely denuded fossil partial annealing zone whose age is the Late Cretaceous (~70 Ma), and this PAZ suffered the destruction of multiple tectonic events with the denudation of Dabashan during the Cenozoic.

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