Exhumation History of the Xining Basin Since the Mesozoic and Its Tectonic Significance

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Abstract: The Xining Basin is located in the northeastern Qinghai–Tibetan Plateau, and its continuous Cenozoic strata record the entire uplift and outgrowth history of the Tibetan Plateau during the Cenozoic. The newly obtained apatite fission track data presented here shows that the Xining Basin and two marginal mountain ranges have experienced multiphase rapid cooling since the Jurassic, as follows. In the Middle–Late Jurassic, the rapid exhumation of the former Xining Basin resulted from collision between the Qiangtang Block and the Tarim Block. During the Early–Late Cretaceous, the former Xining Basin underwent a tectonic event due to marginal compression, causing the angular unconformity between the Upper and Lower Cretaceous. In the Late Cretaceous to the Early Cenozoic, collision between the Qiangtang Block and the Lhasa Block may have resulted in the rapid exhumation of the Xining Basin and the Lajishan to the south. In the Early Cenozoic (ca. 50–30 Ma), collision between the Indian and Eurasia plates affected the region that corresponds to the present northeastern Qinghai–Tibetan Plateau. During this period, the central Qilian Block rotated clockwise by approximately 24° to form a wedge-shaped basin (i.e., the Xining Basin) opening to the west. During ca. 17–8 Ma, the entire northeastern Qinghai–Tibetan Plateau underwent dramatic deformation, and the Lajishan uplifted rapidly owing to the northward compression of the Guide Basin from the south. A marked change in subsidence occurred in the Xining Basin during this period, when the basin was tectonically inverted.

Key words: apatite, fission track, Xining Basin, Mesozoic

1 Introduction

The northeastern Qinghai–Tibetan Plateau was deformed strongly during the Cenozoic. The plateau exhibits a typical rhombus-shaped basin and mountain ranges (Song et al., 2003; Liu et al., 2007); and offers an ideal area to study the far-field effects of continental collision and plate extension (Dewey et al., 1988; Molnar et al., 1993; Tapponnier et al., 2001; Clark and Royden, 2000; Lease et al., 2012; Hough et al., 2011; Wang et al., 2012; Ritts et al., 2008). Many previous studies have been conducted over the past two decades to investigate different aspects of the region (Yuan et al., 2006; Jolivet et al., 2001; Lease et al., 2007, 2011, 2012; Horton et al., 2004; Zhang et al., 2004; Clark et al., 2010; Wang et al., 2012; Dai et al., 2006; Dupont-Nivet et al., 2004, 2008; Zheng et al., 2006; Fang et al., 2003, 2005, 2007; Liang et al., 2014; Song et al., 2013). However, the timing of the response of the northeastern Qinghai–Tibetan Plateau to the collision between the Indian and Eurasian plates remains elusive. There are two main schools of thought in this regard. (1) The first suggests that the northeastern part of the plateau is the part that has risen most recently, having grown obliquely with Eocene uplift of the southern plateau and Oligocene–Miocene uplift of the central plateau (Tapponnier et al., 2001; Meyer et al., 1998). (2) Conversely, the second school of thought suggests that deformation occurred in the northeastern plateau soon after the collision of the Indian and Eurasian plates (Yin et al., 2002; Dai et al., 2006; Zhang et al., 2010; Dupont-Nivet et al., 2004, 2007, 2008; Clark et al., 2010; Duvall et al., 2011). Improved

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understanding of the timing of initiation of deformation and the broader evolution of the Qinghai–Tibetan Plateau will be the key to resolving the conflict between these two schools of thought.

The Xining Basin is located in the northeastern part of the Qinghai–Tibetan Plateau. The continuous Cenozoic strata record the tectonic evolution of the Xining Basin and the two adjacent marginal mountain ranges. Currently, the timing of the rapid uplift of the marginal mountains is the subject of much debate. Clack et al. (2010) found that West Qinling, which is connected with the Lajishan, underwent rapid exhumation, ca. 40 Ma, based on low-temperature thermochronology. Horton et al. (2004) suggested that the marginal mountains did not experience an apparent rapid exhumation period until the Tertiary. Fang et al. (2005) and Liu et al. (2007) suggested that the Lajishan started to experience pronounced uplift in the late Miocene, whereas Lease et al. (2007) demonstrated that the pronounced uplift of the Lajishan occurred ca. 8 Ma based on zircon age distributions from igneous clasts in the modern rivers of the Lajishan. Song et al. (2003) also believed that the Lajishan was exhumed rapidly ca. 8 Ma, based on sedimentary facies analysis and palaeomagnetic investigation of the Guide Basin, which is located in the southern part of the Lajishan. Liu et al. (2013) demonstrated that the pronounced uplift of the Lajishan took place later than ca. 16 Ma based on Cenozoic sedimentary facies analysis of the Xunhua and Guide basins. However, recent sedimentary and palaeomagnetic studies of the Xunhua Basin have proven that the initial uplift of the Lajishan occurred ca. 24–22 Ma, with accelerated exhumation ca. 13 Ma (Lease et al., 2012).

Most of these previous studies focus on the Lajishan, which is located along the southern margin of the Xining Basin. Accordingly, little attention has been paid to the Dabanshan, which is located along the northern margin of the basin and the basement of the Xining Basin. Thus, there are no clear constraints on the evolution of the Xining Basin. Based on previous studies and our newly obtained data, the present study utilizes fission track thermochronology to reconstruct the thermal history of the Cenozoic Xining Basin. Furthermore, the response timing, models, and evolution process of the northeastern Qinghai–Tibetan Plateau related to Indian–Eurasian plate collision are discussed based on thermal history analysis.

2 Geological Setting

The Xining Basin is located along the northeastern edge of the Qinghai–Tibetan Plateau, at elevations ranging primarily from ~2300 to ~3000 m. The total area of the Xining Basin is 6000 km² and its deepest basement reaches depths of 3650 m (BGMRQP, 1985, 1991; Zhang et al., 2010). The Lajishan, Dabanshan, and Riyueshan are the marginal mountains of the basin (Fig. 1). The basement of the Xining Basin is composed of Jurassic–Cretaceous terrigenous clastic rocks, Mesoproterozoic–Neoproterozoic schist, and Early Paleozoic granodiorite. These are exposed primarily in the NNE trending anticline core within the basin. Jurassic sediments are exposed fragmentarily in the basin and are composed of coal-bearing clastic rocks with thicknesses of 1122–1557 m; conversely, the Cretaceous sediments are primarily river-shore facies red sandstone and conglomerate with thicknesses of 1213–1376 m. Several angular unconformities have developed among the Mesozoic sediments (BGMRQP, 1985, 1991; Zhang et al., 2009). The Cenozoic sediments are composed of the Xining and Guide groups; the Xining Group can be further divided into the Qiijachang, Honggou, and Mahala formations, from bottom to top. Similarly, the Guide group can be divided into the Xiejia, Chetougou, and Xianshuie formations. A parallel unconformity represents the contact between the Qiijauchuan Formation and the underlying upper Cretaceous Minhe Formation (BGMRQP, 1985).

Generally, the Xining Group consists of a set of brownish red to reddish tan lacustrine deposits fining upward, with thick-beded gypsum occurring in the upper part. The Guide Group is composed primarily of pale brown fluvial deposits coarsening upward with rare gypsum. The average thickness of the Xining Group is 756–984 m and that of the Guide Group is 212–464 m.

The Lajishan is generally an E–W striking mountain range, although its eastern part includes an N–S striking range. Moreover, the Lajishan is composed primarily of Paleozoic basic and intermediate volcanic rocks, volcanioclastic rocks, and clastic rocks. The Dabanshan trends NW and is composed primarily of early Paleozoic marine clastic rocks, volcanic rocks, and volcanioclastic rocks (Fig. 1).

3 Sampling, Experimental Methods, and Results

3.1 Sampling

Eleven samples were collected from the Xining Basin basement along the eastern, central, and western sections in the present study (APE29, APE30, APE31, APE32, APE33, APE34, APE35, APE36, APE37, APE38, and APE39). The eastern section is located in the Laoyaxia basal outcrop area (APE29, APE37, APE38, and APE39), whereas the central section is located in the Daxia area between Ledu and Pingan (APE30, APE31, and APE32). The western section is located in the Xiaoxia area between
Xining and Pingan (APE33, APE34, APE35, and APE36) (Fig. 3). The average elevation interval between the samples is 100 m, measured using a hand-held GPS receiver (Garmin). Detailed information about the samples is presented in Table 1.

To compare the exhumation characteristics between the Xining Basin and the basin marginal mountains, we reanalyzed existing fission track data from the Lajishan and Dabanshan (Zhang et al., 2015a). Samples from the northern slopes of the Lajishan were collected along the Huangzhong–Guide Road (western section) and the Pingan–Guide road (eastern section) (Figs. 2, 3). Five samples were collected from this eastern section, (APE63, APE64, APE65, APE66, and APE68) and three from this western section (APH69, APH70, and APH71). Samples from the southern slopes of the Dabanshan were collected along the Huzhu–Menyuan Road (eastern section) and the Menyuan–Datong Road (western section) (Figs. 2, 3).

Three samples were collected from this eastern section (APD62, APD63, and APD64), and four from this western section (APD65, APD66, APD67, and APD68). Detailed information about the samples from the Lajishan and Dabanshan can be found in Zhang et al. (2015a).

### 3.2 Experimental method

Using the external detector method, the ages and track length distributions of the samples from the Xining Basin were measured in the State Key Laboratory of Earthquake Dynamics, China, in two separate groups. The main test process is as follows: (1) Apatite was separated using standard magnetic and density methods and then mounted on glass slides with araldite epoxy. (2) After grinding and polishing to expose an internal surface, apatite was etched with 5.5 mol/L HNO₃ at 21°C for 20 s. (3) Low-U mica was used as the external detector, and standard glasses CN5 were used for neutron dosimetry. (4) Samples were
Table 1 The fission track age data of Xining basin

<table>
<thead>
<tr>
<th>Sample</th>
<th>lithology</th>
<th>Coordinate (N,E)</th>
<th>Nf</th>
<th>Elevation(m)</th>
<th>p_{0}(Nf)</th>
<th>p(Nf)</th>
<th>P_{Q}</th>
<th>Fission track age (Ma+1σ)</th>
<th>ML (μm+1σ)</th>
<th>SD (μm)</th>
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</thead>
<tbody>
<tr>
<td>APE-29</td>
<td>Granite</td>
<td>36°24'09.88&quot;/102°39'49.05&quot;</td>
<td>17</td>
<td>2040</td>
<td>8.203(1050)</td>
<td>1.451(857)</td>
<td>7.4</td>
<td>91.3±8.5</td>
<td>13.7±0.11</td>
<td>1.15</td>
</tr>
<tr>
<td>APE-30</td>
<td>Sandstone(Pct)</td>
<td>36°28'91.22&quot;/102°14'31.04&quot;</td>
<td>27</td>
<td>2214</td>
<td>9.243(2126)</td>
<td>1.253(2883)</td>
<td>46.9</td>
<td>117.3±10.5</td>
<td>13.9±0.13</td>
<td>1.2</td>
</tr>
<tr>
<td>APE-31</td>
<td>Granite</td>
<td>36°28'88.88&quot;/102°14'53.54&quot;</td>
<td>25</td>
<td>2170</td>
<td>7.212(1666)</td>
<td>1.039(2401)</td>
<td>37.9</td>
<td>109.2±9.9</td>
<td>13.6±0.12</td>
<td>1.18</td>
</tr>
<tr>
<td>APE-32</td>
<td>Granite</td>
<td>36°28'76.92&quot;/102°14'82.88&quot;</td>
<td>19</td>
<td>2060</td>
<td>4.892(2785)</td>
<td>0.991(1466)</td>
<td>5.8</td>
<td>77.2±7.4</td>
<td>13.3±0.14</td>
<td>1.27</td>
</tr>
<tr>
<td>APE-33</td>
<td>Granite</td>
<td>36°33'80.67&quot;/101°54'08.79&quot;</td>
<td>24</td>
<td>2275</td>
<td>8.613(395)</td>
<td>0.859(1391)</td>
<td>21.8</td>
<td>153.8±14.3</td>
<td>13.9±0.12</td>
<td>1.18</td>
</tr>
<tr>
<td>APE-34</td>
<td>Granite</td>
<td>36°33'90.93&quot;/101°54'87.90&quot;</td>
<td>21</td>
<td>2250</td>
<td>10.44(1495)</td>
<td>1.062(1519)</td>
<td>21.2</td>
<td>149.1±13.8</td>
<td>13.2±0.11</td>
<td>1.08</td>
</tr>
<tr>
<td>APE-35</td>
<td>Granite</td>
<td>36°33'80.67&quot;/101°54'87.90&quot;</td>
<td>21</td>
<td>2230</td>
<td>10.00(2150)</td>
<td>0.840(1063)</td>
<td>7.7</td>
<td>176.6±16.7</td>
<td>13.5±0.13</td>
<td>1.26</td>
</tr>
<tr>
<td>APE-36</td>
<td>Granite</td>
<td>36°33'81.30&quot;/101°54'97.77&quot;</td>
<td>25</td>
<td>2223</td>
<td>8.327(1424)</td>
<td>0.897(1533)</td>
<td>13.1</td>
<td>137.8±12.8</td>
<td>13.5±0.12</td>
<td>1.14</td>
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<tr>
<td>APE-37</td>
<td>Granite</td>
<td>36°23'89.92&quot;/102°39.68&quot;</td>
<td>25</td>
<td>2154</td>
<td>11.12(1991)</td>
<td>1.682(354)</td>
<td>6.5</td>
<td>97.3±3.8</td>
<td>14.0±0.14</td>
<td>1.35</td>
</tr>
<tr>
<td>APE-38</td>
<td>Granite</td>
<td>36°23'19.52&quot;/102°39.70&quot;</td>
<td>18</td>
<td>2033</td>
<td>12.83(1495)</td>
<td>1.285(1497)</td>
<td>18.2</td>
<td>142.9±13.2</td>
<td>13.6±0.13</td>
<td>1.25</td>
</tr>
</tbody>
</table>

Nf: number of apatite crystals; p_{0}: spontaneous fission track density on the internal surface of apatite crystals analyzed; Nf: total number of fission tracks counted in p_{0}; p(Nf): induced fission track density on the muscovite external detector for crystals analyzed; Nf: total number of fission tracks counted in p_{0}; ML: mean track length; SD: standard error of track length; A chi-squared probability >5% passed the P(Q) test, and the pooled apatite fission track age is used for interpretation; a chi-squared probability ≤5% fail the P(Q) test, and the central apatite fission track age is used for interpretation; Apatite fission track ages were obtained using the external detector method (Gledow and Duddy, 1983) and calculated by the zeta calibration method (Harford et al., 1983). Age calculation standard is Durango apatite (31.4±0.5 Ma); The value of Zeta(0.5) is 352.4±29.

### Results

All of the samples collected from the Xining Basin passed the P(Q) test. The pool ages of samples are present: the P(Q) test, and the pool ages of samples are presented in Table 1. The track length age can be divided into two groups. The first group falls within the range 10-11 Ma, the second group falls within the range 12-13 Ma, and includes the following samples: 13.8 Ma (APE-55), 14.9 Ma (APE-56), and 13.0 Ma (APE-57). The samples from the Xining Basin and the analytical details are shown in Table 1.

3. Results

All of the samples collected from the Xining Basin passed the P(Q) test. The pool ages of samples are presented in Table 1. The track length age can be divided into two groups. The first group falls within the range 10-11 Ma, the second group falls within the range 12-13 Ma, and includes the following samples: 13.8 Ma (APE-55), 14.9 Ma (APE-56), and 13.0 Ma (APE-57). The samples from the Xining Basin and the analytical details are shown in Table 1.
Fig. 2. Locations, ages of the fission track samples from Xining basin, Lajishan, Dabanshan and the low temperature thermochrometry ages which have already reported.

Fig. 3. Fission track sampling geological cross-section map of Xining basin, Lajishan, Dabashan and the sample locations. (a) and (b), the western and eastern section of Lajishan; (c) and (d), the western and eastern section of Dabashan; (e), (f), (g), the eastern, western and middle section of the Xining basin.
and 102.7 Ma (Fig. 4). All of these ages fall within the Early Cenozoic and Late Cretaceous. We will discuss these complex age components with reference to sample locations and properties in the following section.

Samples APD62, APD63, and APD64 were collected from the southeastern part of the Dabanshan, whereas samples APD65, APD66, APD67, and APD68 were collected from the northwestern part of the Dabanshan. Most of the samples met the statistical requirements. All of the samples passed the $P(\chi^2)$ test, except sample APD62. The ages of the samples that passed the $P(\chi^2)$ test can be divided into two groups. One group includes the samples APD63, APD64, APD66, and APD68, whose fission track ages are 47.3 Ma, 52.9 Ma, 49.0 Ma, and 60.0 Ma, respectively; these ages fall within the Early Cenozoic. The other group includes samples APD65 and APD67, whose fission track ages are 32.9 Ma and 36.8 Ma, respectively; these ages fall within the Oligocene. The range of average confined fission track lengths for these samples is 14.24–14.67 μm, and all of the average confined fission track lengths are shorter than the initial fission track length of 16.3 μm (Gleadow et al., 1986). The range of standard errors for these track lengths is 0.95–1.32 μm, which is smaller than that for the samples from the Lajishan. These smaller standard errors and the more concentrated average confined fission track lengths of the samples from the Dabanshan indicate a faster exhumation rate in the Dabanshan. The value of $P(\chi^2)$ for sample APD62 is 0, and the peak ages for this sample were found to be 8.8 Ma and 48.1 Ma (Fig. 4). These values do not agree with those for the other samples, indicating that sample APD62 experienced a complex thermal history.
The implications of these ages will be discussed in the section below, with reference to the sample locations.

4 Interpretations

4.1 Experimental results

The fission track ages from the Xining Basin and its marginal mountains cannot reflect the thermal evolution history of the study area intuitively. An elevation vs. age plot can indicate the exhumation rate of samples, and a sudden change point (known as an inflection point) in the exhumation rate curve may reflect the occurrence of a thermal event. Moreover, a “boomerang” shape in a confined track length vs. age plot can often reflect the cooling trend of the samples. In the present study, no inflection points are apparent in the figures (Fig. 5(a), (c), (e)), and the confined track length vs. age plots do not exhibit a “boomerang” shape (Fig. 5(b), (d), (f)). Thus, we cannot determine the timing of rapid exhumation of the geological bodies from which the samples were collected based on the current data. Samples APH63, APH64, APH65, and APH66 from the western section of the Lajishan exhibit a linear relationship (Fig. 5(a)). However, the straight line that passes through these four samples does not pass close to sample APH68, suggesting that the inflection point may lie somewhere between samples APH66 and APH68. Thus, the timing of rapid exhumation can be constrained to approximately between 31.9 Ma and 16.3 Ma (Fig. 5(a)). Liu et al. (2013) also suggested that the pronounced uplift of the Lajishan occurred ca. 16 Ma. Samples from the eastern section of the Lajishan do not exhibit any obvious relationship in the elevation vs. age plot (Fig. 5(a)). The fission track ages of samples APH69 and APH70 fall within the Late Cretaceous. Both of these samples have large standard errors (1.26 μm and 1.34 μm, respectively), suggesting that they experienced a more

Fig. 5. The relationships between fission track age and elevation, fission track age and average confined track length of the samples from Xining Basin, Lajishan, Dabanshan. (a) and (b), plots of relationships between fission track age and elevation, fission track age and average confined track length of the samples from Lajishan; (c) and (d), plots of relationships between fission track age and elevation, fission track age and average confined track length of the samples from Dabanshan; (e) and (f), plots of relationships between fission track ages and elevation, fission track age and average confined track lengths of the samples from Xining Basin.
complex annealing process than the other samples. Moreover, these samples did not yield an age similar to that of APH68, although they have similar elevations. This phenomenon may be related to mineral genesis, track statics, and the process of rock exhumation, but is more likely related to fault activity. The northern Lajishan thrust fault passes between sample APH68 and samples APH69 and APH70 (Fig. 3). Strong thrust movement occurred along this fault during the Cenozoic (particularly the Late Cenozoic) (BGMRQP, 1991; Yuan et al., 2005). Therefore, the 16.3 Ma age yielded by the sample may be a record of the thrust movement on the fault. It was not possible to collect additional samples in this area, because APH69 and APH70 were collected from the foothills of the Lajishan. The distribution of fission track lengths for all of the samples from the Lajishan exhibit a narrow shape, and the peak values of the tracks are 14–15 μm. This coincides approximately with the "undisturbed-type" distribution described by Gleadow (1986). This implies that the samples could have passed the 110°C isothermal surface into the partial annealing zone quickly.

Samples from the two sections in the Dabanshan plot as two parallel straight lines in the elevation vs. age plot (Fig. 5(c)). This indicates that these two sections experienced the same exhumation rate and that all of the samples were collected from the Silurian strata. Thus, these results indicate that the geological bodies in which the two sections are located were exhumed as a whole. However, sample APD65, which was collected at the top of the Dabanshan from the western section, does not fall upon the line controlled by samples APD66 and APD67. The scattered ages of these samples (APD65, APD66, APD67) could be attributed to many factors, but a central fault exists between sample APD65 and samples APD66 and APD67 (Fig. 3). We believe that the activity of this central fault resulted in the age scatter of these three samples. The fission track age of sample APD68, which was collected in the foothills of the Dabanshan is gneiss, is 60 Ma. The southern thrust fault of the Dabanshan may have been located between this metamorphic rock and the overlying Paleozoic sedimentary rocks (Fig. 3). The age of APD68 is similar to the ages of samples APH69 and APH70, both of which were collected from the foothills of the Lajishan. Both of the faults mentioned above were active in the Cenozoic; the ages of both of the samples from the foothills of the Lajishan and Dabanshan are similar to those of the samples from the Xining Basin. Accordingly, we posit that it was fault activity that controlled the age distribution of these samples. No inflection point is apparent in the elevation vs. age plot of the Dabanshan (Fig. 5(c)), and no younger ages are available for this area to constrain the timing of rapid exhumation; this suggests that the inflection point has not yet been exhumed to the surface. The standard errors of samples from the Dabanshan are smaller than those of samples from the Lajishan. This suggests that the Dabanshan has experienced faster exhumation than the Lajishan, which is supported by thermal history simulation (see below). Samples from the Dabanshan also conform to the "undisturbed volcanic-type" distribution based on their fission track length distribution (Fig. 6), the average length of confined fission tracks, and the standard errors of the fission tracks.

No inflection point is apparent in the elevation vs. age plot for the Xining Basin (Fig. 5(c)). Samples APE33, APE34, and APE36, which were collected from the western section of the Xining Basin, exhibit a linear relationship, but sample APE35 does not plot on the same linear trend. A fault exists between sample APE35 and samples APE33, APE34, and APE36. Samples from the middle section (APE30, APE31, APE32) exhibit the same linear relationship as the western profile. This suggests that the geological body in which the middle section is located experienced a similar thermal history to that in which the western section is located. Samples from the eastern profile (APE29, APE37, APE38, and APE39) exhibit a scattered distribution in the elevation vs. age plot (Fig. 5(c)). Faults exist in the eastern section, which suggests that all of the samples in this section have experienced complex exhumation histories. This corresponds to the fact that these samples were collected from the basin margin (Fig. 3). All of the samples from the Xining Basin passed the P (χ²) test, suggesting that the ages of all samples are concentrated. Moreover, the narrow shape of the fission track distribution indicates that all of the samples experienced rapid cooling (Fig. 6).

The above analysis indicates that the exact timing of rapid cooling of the three geological bodies considered (the Xining Basin, the Dabanshan, and the Lajishan) cannot be determined accurately or precisely based on the thermochronological data alone. Therefore, it was essential for us to invert the thermal history of the geological bodies through thermal simulation based on the fission track data presented here.

4.2 Thermal history modeling

We simulated the thermal histories using the HeFTy software (Ver. 1.7.5, 2012; Ketcham, 2005, 2007) and a Monte Carlo calculation method. The initial fission track length was 16.3 μm (Gleadow et al., 1986). All samples were simulated using the annealing model of Ketcham (2007). The geological constraints were set as follows: (1) Complete annealing conditions were maintained when the age was older than the single maximum age (Ketcham,
Fig. 6. Thermal history inversion of samples from Xining basin and the track length histograms. The purple area represent good fits; The green area represent accept fits; The black line represent the best fit; A, the fission track age of the sample; ML, mean length; S, standard error of the sample; GOF, the good of fit.

2005). (2) The temperature range of the surface was 0°C – 40°C. (3) The geothermal gradient was 35°C/km (Pichon et al., 1997). (4) The temperature range of the partial annealing zone of apatite was 60°C – 110°C (Gleadow et al., 1986). (5) The Dpar parameters were not provided by the laboratory. (6) Because most of the samples from our
study area exhibited linear relationships in the elevation vs. age plots (except for the samples from the eastern margin of the Xining Basin), a single-stage cooling model was used during the simulation. We attempted to adopt a multistage cooling model, but the results were not favorable.

The aim of this thermal simulation of the samples from the Lajishan and Dabanshan was to achieve the best fit. Here, we do not present the thermal simulation results for these samples in detail; these details are provided in Zhang et al. (2015a). The simulation results for the samples from the Xining Basin were the primary focus of this study.

4.2.1 Thermal simulation of the Lajishan

Most of the samples from the Lajishan (except API66) yielded good thermal history simulation results (i.e., their GOF values are larger than 0.5). Samples APH63, APH64, APH65, and APH66 experienced rapid cooling stages at 80–65 Ma, 70–60 Ma, 57–50 Ma, and 50–45 Ma, respectively, such that the rapid cooling stages of these four samples became increasingly younger. This agrees with figure 5a, which illustrates the linear relationship between these four samples. Samples APH69 and APH70, which were collected in the foothills of the Lajishan, experienced their rapid cooling stage during the Late Cretaceous, suggesting that these samples may have been exhumed rapidly to the surface in the Late Cretaceous. The rapid cooling stages of APH68 and APH71 occurred at 20–16 Ma and 17–12 Ma, respectively.

4.2.2 Thermal simulation of the Dabanshan

Most of the samples from the Dabanshan (except APD64) yielded good thermal history simulation results (i.e., GOF values larger than 0.5). The rapid cooling stages for samples APD62 and APD63 from the eastern section were found to occur at 33–27 Ma and 50–40 Ma, respectively (Fig. 7). Conversely, the rapid cooling stages for samples APD66 and APD67 from the western section occurred at 54–43 Ma and 40–35 Ma, respectively (Fig. 7). This corresponds to the results shown in the elevation vs. age plot for the Dabanshan (Fig. 5(c)), where the straight lines controlled by these samples are parallel. The Dabanshan as a whole experienced rapid exhumation in the Early Cenozoic (ca. 50–30 Ma) (Fig. 7). The rapid cooling stages of APD68 and APD65 occurred at 65–57 Ma and 36–33 Ma, respectively, which may represent the activities of the mountain front fault and central fault of the Dabanshan.

4.2.3 Thermal simulation of the Xining Basin

All of the samples yielded good thermal history simulation results (Fig. 6). The rapid cooling stages of the samples from the western section (APE33, APE34, APE35, and APE36) occurred at 180–140 Ma, 170–155 Ma, 200–180 Ma, and 160–140 Ma, respectively. APE35 does not plot on the straight line controlled by samples APE33, APE34, and APE36; and the rapid cooling stage of this sample is older than that of the other three samples. Thus, the fault separating APE35 from APE33, APE34, and APE36 was likely activated rapidly at 200–180 Ma. The rapid cooling stages of the samples from the central section were simulated to have occurred at 130–115 Ma (APE30), 112–102 Ma (APE31), and 90–75 Ma (APE32). Because these cooling ages decrease in turn, this simulation result coincides with the linear relationship represented by the central section in figure 5e. The rapid cooling stages of samples from the eastern section occurred at 105–90 Ma (APE29), 110–80 Ma (APE37),
155–120 Ma (APE38), and 167–150 Ma (APE39). The lack of any clear relationship between these ages suggests that the samples from the eastern section experienced more complex thermal histories than the samples in other sections.

5 Discussions

5.1 Exhumation features of the Xining Basin and the adjacent marginal mountains

To compare the thermal history of the Lajishan, the Dabanshan, and the Xining Basin, we used the best fits of the modeling results from these three areas (Fig. 7). The basin marginal mountains have experienced multiple rapid exhumation phases (Figs. 9, 10). The rapid exhumation periods of the Lajishan occurred in the Late Cretaceous, Early Cenozoic, and Late Miocene, whereas those of the Dabanshan were concentrated in the Early Cenozoic. Moreover, the Dabanshan underwent slow exhumation phases in the Late Cretaceous and Late Miocene. Based on comparison of the exhumation histories of the three areas, the Lajishan has experienced a more complex thermal history (Fig. 7). This is consistent with the shorter fission track length standard errors of the samples from the Dabanshan compared to those from the Lajishan. The samples from the Dabanshan went through the $110^\circ$C isothermal surface more quickly, as demonstrated by the thermal history simulation results (Fig. 7). Interestingly, both the Lajishan and Dabanshan experienced rapid cooling in the Early Cenozoic. Based on U/Th–He dating, Lease et al. (2011) suggested that the rapid cooling occurred in the Lajishan ca. 22 Ma. This age is older than that found by other studies that used different methods, including our study (Liu et al., 2013; Lease et al., 2007). Moreover, no strong thermal events have been found in the Dabanshan from the Late Cenozoic; accordingly, we believe that no obvious tectonic event occurred in the Dabanshan during the Late Cenozoic.

The thermal simulation results for the Xining Basin also indicate that the basin underwent multistage thermal events (Middle Jurassic–Late Jurassic, latest Early Cretaceous–earliest Late Cretaceous, and latest Late Cretaceous–earliest Paleogene) (Figs. 6, 7). Although the early-stage tectonic event and its implications remain poorly understood, it is well known that a strong tectonic event occurred during the Late Jurassic in the Xining Basin and affected a large area to its north (Zhang et al., 2004; Darby and Ritts, 2002; Liu, 1998). Moreover, an angular unconformity is present between the Middle Jurassic and Upper Jurassic in the Xining Basin; the sedimentary facies in the basin changed from coal-bearing strata under humid conditions to red coarse clastic sedimentary strata deposited under dry–warm conditions (BGMRQP, 1985). The collision between the southwestern part of the Qiantang Block and the Tarim Block may have induced this change (Zhang et al., 2004; Darby and Ritts, 2002; Liu et al., 1998). A tectonic event that occurred during the latest Early Cretaceous to the earliest Late Cretaceous is apparent in the strata of the Xining Basin, and this event may have led to the angle unconformity between the Hekou Group (Lower Cretaceous) and the Minhe Group (Upper Cretaceous) (BGMRQP, 1985). Several interpretations of this event have been proposed. First, it may be a result of a transformation of basin properties, during which time the basin changed from a faulted basin to a depression. Conversely, Craddock et al. (2012) argued that the event was a result of inversion of the Xining Basin, which was squeezed by the southwestern part of the Tethys tectonic domain. The thermal history of the Xining Basin from the Late Cretaceous to the Paleocene is similar to that of the Lajishan (Fig. 7). The tectonic implications and background of the thermal history of the Xining Basin are discussed together with those of the Dabanshan and Lajishan below. The Xining Basin remained stable during the Cenozoic. The Lajishan has been exhumed since the Late Cretaceous (Fig. 7), with an exhumation rate of $\sim0.01$ mm/yr from the Late Cretaceous to the Early Cenozoic. Lease et al. (2011) believed that the exhumation rate during this period was 0.02–0.03 mm/yr, based on fission track dating in the Lajishan (Fig. 8). This result is similar to that obtained by our research. The Dabanshan began to be exhumed during the Early Cenozoic, with an exhumation rate of $\sim0.03$ mm/yr; this is similar to the values obtained in our study. Some of the samples from the Xining Basin began to experience rapid cooling from the Late Cretaceous onward, and the rapid cooling period of the Xining Basin occurred earlier than that of the Lajishan. The thermal simulation for the Late Cretaceous–Early Cenozoic in the Lajishan exhibits approximately the same characteristics as that for the Xining Basin (Fig. 7), which suggests that the Lajishan is part of the basement of the Xining Basin.

5.2 Exhumation history and mechanism for the Lajishan and Dabanshan

The fission track data described above demonstrate that the study area underwent three rapid exhumation stages (Fig. 7). During the Late Cretaceous, both of the sections in the Lajishan underwent a rapid cooling stage. It is clear that no inflection point can be observed in the elevation vs. age plot, which presents as two parallel straight lines (Fig. 8). The fission track ages of the samples in the eastern part of the Lajishan (Fig. 2), obtained from Lease
Fig. 8. Relationship of the low temperature thermochronological ages and elevation of samples in Lajishan.

Fig. 9. Evolution model of Xining basin since the late Cretaceous.

et al. (2011), fall within the Late Cretaceous–Oligocene (ca. 70–37.1 Ma). The average exhumation rate for this period was 0.025 mm/yr, which can be considered slow exhumation (Fig. 8). Conversely, no obvious reaction during the Late Cretaceous could be detected in the Dabanshan (Fig. 7). The northern boundary fault of the Lajishan is a thrust fault (Fig. 3, Yuan et al., 2005). Our thermal simulations suggest that the thrust fault may have
been active during the Late Cretaceous, perhaps when the Lajishan was exhumed rapidly as part of the basement of the Xining Basin.

During the Early Cenozoic (ca. 50–30 Ma), both the Dabanshan and Lajishan underwent an exhumation stage (Fig. 7). However, the exhumation rates of these two mountains during the Early Cenozoic were not particularly high (i.e., not >0.1 mm/yr) (Fig. 8). Their low exhumation rates can be attributed to the fact that these two mountain ranges experienced exhumation over a period of 20 Myr, and the normally fast exhumation process may be in short period. This also indicates that their exhumation may not have been caused by thrusting. If the Dabanshan was uplifted by the thrust fault during the Early Cenozoic, there should be corresponding basins present that formed on both sides of the Dabanshan. However, to the northern side of the Dabanshan lies the Menyuan Basin, which formed during the Miocene (Wang et al., 2007). We argue that there would also be an extensional basin formed to the southern side of the Dabanshan because the range existed as a rifted margin uplift; this extensional basin could correspond to the Xining Basin. Similarly, corresponding basins should have formed if the Lajishan were uplifted in the Early Cenozoic. However, the Xunhua Basin, which is located on the southern side of the Lajishan, was formed during the Miocene (Lease et al., 2012) and contains no reliable Paleogene sediments. An extensional basin may have formed on the northern side of the Lajishan and existed as the rifted margin uplift. Thus, we speculate that both the Lajishan and Dabanshan experienced equilibrium uplift processes in an extensional environment.

During the Late Miocene (17–8 Ma), the Lajishan was exhumed rapidly, but the Dabanshan and the Xining Basin do not contain obvious evidence of such a rapid exhumation event. Evidence from our thermal simulations demonstrates that the rapid exhumation of the Lajishan in the Late Cenozoic occurred ca. 16–7 Ma (Fig. 7). Liu et al. (2013) also believed that pronounced uplift of the Lajishan occurred ca. 16 Ma, based on detrital zircon age and provenance analysis. Other studies have shown that rapid exhumation of the Lajishan occurred at ~8 Ma (Fang et al., 2005; Liu et al., 2007) and have indicated that a sudden change in the sedimentary ratio in the Xining Basin also occurred in the Late Miocene (Dai et al., 2006); this may reflect pronounced uplift of the Lajishan at that time.

It is important to note that Lease et al. (2011) achieved different results based on U/Th–He dating and argued that the rapid exhumation of the Lajishan occurred at ca. 24–22 Ma (Fig. 8). One reason for the divergence of this result is that all of the samples analyzed by Lease et al. (2011) were collected from the eastern part of the Lajishan; accordingly, these samples may not be representative of the whole Lajishan. Moreover, the U/Th–He dating method can underestimate the ages of samples (Min et al., 2005). If this were the case here, the tectonic event that occurred ca. 24–22 Ma may correspond to the thermal event assigned to the Early Cenozoic (~30 Ma) in our study. In addition, many studies conducted in the northeastern Qinghai–Tibet Plateau have indicated that records of the ca. 24–22 Ma tectonic event are not particularly widespread. However, the ca. 30–20 Ma and ca. 17–8 Ma tectonic events have been recorded widely (Fang et al., 2003, 2005; Zheng et al., 2006, 2010; Lu et al., 2012; Jolivet et al., 2001; Yan et al., 2006; George et al., 2001).

Previous studies (Zheng et al., 2006, 2010; Jolivet et al., 2001; Liu et al., 2013; Lease et al., 2007, 2011, 2012) and our study suggest that the northeastern Qinghai–Tibetan Plateau experienced rapid exhumation during the Late Miocene. The exhumation rate of the Lajishan changed from slow in the Early Cenozoic to rapid in the Late Cenozoic; this may reflect a clear change in the tectonic regime of the Lajishan. Lease et al. (2011) believed that this change could have been associated with the northeastern extrusion, which could have led to the uplift of the Lajishan in the Late Miocene; however, they did not infer the mechanism by which the associated paleostress field could have developed. Molnar et al. (1993) argued that the tectonic event could correspond to the delamination of the lithospheric mantle of the Tibetan Plateau, which could have resulted in uplift of the mountains around the plateau. Based on evidence from the existing palaeomagnetic study, the Guide Basin experienced approximately 25° clockwise rotation during the Late Miocene (17–11 Ma) (Yan et al., 2006). However, the Xining Basin did not experience such rotational deformation (Dupont-Nivet et al., 2004, 2008). Therefore, the rotation would have inevitably extruded the Xining Basin, which is located in the Central Qilian Block, causing the rapid uplift of the Lajishan in the Late Miocene.

5.3 Tectonic implications of the exhumation history of the Xining Basin and surrounding areas

The multistage rapid exhumation events that occurred in the study area have important tectonic implications regarding the uplift and extension of the Qinghai–Tibetan Plateau. In particular, a rapid exhumation event occurred in the Late Cretaceous in both the Lajishan and the Xining Basin. Other areas in the northeastern Qinghai–Tibetan Plateau also underwent this thermal event. As the main northern structure in the Qinghai–Tibetan Plateau, the Altyrn Tagh Fault experienced rapid exhumation during the Late Cretaceous (Li et al., 2006). Liu et al. (2005)
identified a tectonic event in the eastern Kunlun area in the Late Cretaceous using $^{39}\text{Ar}^{40}\text{Ar}$ dating methods, and George et al. (2001) recognized the late Cretaceous cooling event in the northwestern part of the Qilianshan based on fission track dating. The exact tectonic background of the above thermal event remains unknown; however, this event has been recorded extensively in the Tibetan region. For example, the 50% crustal shortening of the northern Lhasa Block (Murphy et al., 1997; Kapp et al., 2005; Volkmer et al., 2007), the magmatic activity of the Gangdlese arc, and the formation of central Qinghai–Tibetan Plateau compressional basin (Horton et al., 2002) are related to this event. Murphy et al. (1997) suggested that the collision of the Lhasa–Qiangtang blocks may have been the primary cause of the above phenomena. We tend to agree with this opinion and suggest that the angular unconformity between the Cenozoic strata and the underlying Cretaceous strata in the Xining Basin (BGMRQP, 1985) may also reflect this thermal event.

It should be noted that increasingly abundant lines of evidence from recent studies have supported the assertion that the northeastern Qinghai–Tibetan Plateau had already experienced deformation by the Early Cenozoic. For example, the western Qinling fault experienced rapid activity during 55–42 Ma (Clark et al., 2010; Duvall et al., 2011), and the Xining Basin underwent 24° of clockwise rotation during the Early Cenozoic (Dupont-Nivet et al., 2004, 2008). The fission track evidence from our study demonstrate that the most important exhumation period of the Lajishan and Dabanshan occurred at 50–30 Ma. In combination, all of the above information suggests that the deformation in the northeastern Qinghai–Tibetan Plateau was approximately coeval with the collision between the Indian and Eurasian plates. A series of basins formed in the late phase of the Early Cenozoic, including the Xunhua Basin, the Linxia Basin, and the Guide Basin (Liu et al., 2010; Fang et al., 2003, 2005; Lease et al., 2012). The uplift of the Longmenshan (Wang et al., 2012), the fast slip of the Altyn Tagh Fault (Zhuang et al., 2011; Ritts et al., 2004), the rapid exhumation of the eastern Kunlun (Mock et al., 1999; Clark et al., 2010), and the foreland basin formation in the southern part of Ningxia Province (Wang et al., 2012; Zhang et al., 2010) also occurred during this period. Thus, we argue that the late phase of the Early Cenozoic was likely an important period of thickening of the plateau crust and expansion of the plateau.

Evidence from low-temperature chronology and sedimentology also support the assertion that the northeastern Qinghai–Tibetan Plateau experienced NNE–EW extrusion during the Late Miocene (Lease et al., 2011, 2012). In particular, pronounced uplift in the N–S direction is known to have occurred in the Jishishan ca. 13 Ma; this is younger than the rapid exhumation period in the Lajishan (ca. 24–22 Ma) (Lease et al., 2011). Similarly, pronounced uplift with an N–S trend occurred in the Liupanshan ca. 8.2–7.3 Ma (Zheng et al., 2006). In fact, no sudden change in sedimentary facies occurred in the Xining Basin during 25–20 Ma (Xiao et al., 2012; Zhang et al., 2015), although a sudden change in sedimentation rate occurred in the basin after ca. 17 Ma (Dai et al., 2006). The fission track evidence from our study indicates that a period of pronounced uplift occurred in the Lajishan ca. 17–8 Ma. Moreover, the rapid reactivity period of the Alty Tagh Fault has been shown to have occurred at 8 Ma (Chen et al., 2002), and the Gonghanshan and Qinghainanshan experienced rapid exhumation during 10–6 Ma (Lu et al., 2012). The northern Qilianshan was exhumed rapidly at ~10 Ma (Zheng et al., 2010). Thus, we argue that the period spanning ca. 17–8 Ma may have been an important period in the Miocene regional tectonic evolution of the Qinghai–Tibetan Plateau and represents an overall uplift event for the northeastern Qinghai–Tibetan Plateau.

5.4 Properties and evolution of the Xining Basin

Debate persists regarding the formation of the Xining Basin. One opinion suggests that a large area (including the Xining Basin) formed the foreland basin of the eastern Kunlun or western Qinling and that the Xining subbasin was formed by the uplift of the Lajishan in the Late Cenozoic (Fang et al., 2005; Liu et al., 2007; Zhang et al., 2009; Liu et al., 2013). Horton et al. (2004) argued that the Xining Basin was formed by thermal subsidence from the Early Cretaceous to the Tertiary. However, neither of these explanations can explain all of the observed phenomena, particularly the following examples. (1) Most of the basins (except the Xining Basin) do not contain Paleocene sediments; this is particularly true for the Guide Basin and the Xunhua Basin, which are located in the southern Lajishan (Pares et al., 2003; Lease et al., 2011). In addition, the Xining Basin was formed earlier than other basins (such as the Xunhua Basin, Guide Basin, Gonghe Basin, and Linxia Basin) that were formed at ca. 29 Ma (Dai et al., 2006). Thus, the model invoking a foreland basin of the eastern Kunlunshan and western Qinlingshan requires additional evidence to validate its results. (2) Most of the basin basement in the northeastern Qinghai–Tibetan Plateau is composed of Cretaceous sediments with a tectonic environment similar to that of the Xining Basin. All of these sediments were deposited in an extensional environment. If the Xining Basin was formed by thermal subsidence in the early Cretaceous, basins in the northeastern Qinghai–Tibetan Plateau should
contain early Cenozoic sediments, as in the Xining Basin. However, most of the basins in the northeastern Qinghai–Tibetan Plateau have a sedimentary break spanning ca. 35 Myr between the Cenozoic and the underlying Cretaceous; this is not the case in the Xining Basin. Moreover, the fissure track evidence from the present study indicates that both the Xining Basin and the Lajishan experienced rapid exhumation during the Cretaceous (ca. 124–65 Ma). The unconformity between the Cenozoic and the underlying Cretaceous and the strongly folded Cretaceous strata may reflect this thermal event (Cradock et al., 2012). Together, the above facts do not support the assertion of thermal subsidence.

The evolution of Xining Basin since the Mesozoic can be summarized according to the fissure track data presented in this study and many previous studies involving the surrounding areas, as follows: (1) During the Middle–Late Jurassic, the collision between the Qiangtang Block and the Tarim Block resulted in the rapid exhumation of the former Xining Basin (Zhang et al., 2004; Darby and Ritts, 2002; Liu, 1998), leading to the angular unconformity within the Jurassic strata.

(2) During the Early–Late Cretaceous, an obvious tectonic event occurred in the former Xining Basin, resulting in the angular unconformity between the Lower Cretaceous and the Upper Cretaceous. However, the cause of this event remains unclear. It may have been the result of transformation of the basin’s properties, with the basin switching from a faulted basin to a depression. Conversely, it may have been the result of inversion of the Xining Basin, which was squeezed by the southwestern part of the Tethys tectonic domain (Cradock et al., 2012).

During the Late Cretaceous–Early Cenozoic, both the Xining Basin and the Lajishan experienced rapid exhumation owing to collision between the Lhasa Block and the Qiangtang Block (Murphy et al., 1997; Kapp et al., 2005; Volkmert et al., 2007). The Lajishan was exhumed rapidly as the basement of the Xining Basin and the Cretaceous strata of the basin were deformed strongly during this period. However, the Dabanshan does not appear to have been affected by these events.

During the Early–Late Paleogene (ca. 50–30 Ma), the northeastern edge of the Qinghai–Tibetan Plateau had already been deformed owing to the collision of the Indian and Eurasian plates. Both the Lajishan and the Dabanshan would have experienced exhumation associated with that collision. The Central Qilian Block, including the Xining Basin, has experienced 24° of clockwise rotation (Dupont-Nivet et al., 2004, 2008). However, the Guide Block did not experience that same deformation. Thus, a basin opening to the west would have been formed in association with this rotation. We argue that this basin was the Xining Basin. A series of fining upward fluvial–lake facies (the Qijiaxuan Formation, Honggou Formation, and Mahalagou Formation) was deposited during this period (Zhang et al., 2015b) (Fig. 9). The Xining Basin was an extensional pull-apart basin throughout this period, while the Lajishan and the Dabanshan were exhumed as the edge of the rift valley.

The existing paleomagnetic study of the Xining Basin demonstrated that, during the Late Miocene (ca. 17–8 Ma), the Central Qilian Block (including the Xining Basin) did not experience any rotation (Dupont-Nivet et al., 2004, 2008). However, the Guide Basin experienced 24° of clockwise rotation relative to the Xining Basin (Yan et al., 2006). Thus, the Xining Basin was compressed by the Guide Basin, which would have produced pronounced uplift of the Lajishan (Fig. 9), supplying abundant clasts to the Xining Basin. The sedimentary ratio of the Xining Basin exhibited a sudden change in the Late Miocene, when the sedimentary environment changed from a dry salt lake to fluvial facies, and a series of upward coarsening sediments (the Xiejia Formation and Chetougou Formation) was deposited (Dai et al., 2006). The Dabanshan was not active during this period. These results suggest that the characteristics of the Xining Basin have changed with the transformation from an extensional pull-apart basin in the Early Cenozoic to a compressive foreland basin in the Late Miocene.

6 Conclusions

Multistage exhumation has occurred in the Xining Basin and its marginal mountains. In particular, a tectonic event occurred in the Middle–Late Jurassic, resulting in the rapid exhumation of the former Xining Basin. In the Early–Late Cretaceous, the compression produced an angular unconformity between the Lower Cretaceous and Upper Cretaceous in the former Xining Basin. In the Late Cretaceous–Early Cenozoic, both the Xining Basin and the Lajishan experienced rapid exhumation owing to the collision between the Lhasa Block and the Qiangtang Block. In the Early–Late Paleogene (ca. 50–30 Ma), the Xining Basin was formed when both the Lajishan and Dabanshan were exhumed as the edge of the rift valley; at this time, the Xining Basin was an extensional pull-apart basin. In the Late Miocene (ca. 17–8 Ma), the sedimentary ratio of the Xining Basin increased rapidly owing to the uplift of the Lajishan, which was compressed by the rotation of the Guide Basin. The Xining Basin later transformed from an extensional pull-apart basin to a compressive foreland basin. The evidence presented here demonstrates that the northeastern edge of the Qinghai–Tibetan Plateau had already been deformed prior to the
period considered here, owing to the collision of the Indian and Eurasian plates. This effect is not just represented by the thrusting which resulted in the thickening of the crust. The rotation between different blocks at different scales and times and the resulting extension of the basin are also important indicators of the effects of collision.

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