Mesozoic–Cenozoic Tectonic Evolution and Uplift in Pamir: Application of Fission Track Thermochronology

FAN Baocheng1, 2, *, LIU Mingyi2, HE Zixin3, MENG Guanlu2, WU Huanhuan1 and LI Lu3

1 Xi’an Center of Mineral Resources Survey, China Geological Survey, Xi’an 710054, China
2 Xi’an Center, China Geological Survey, Xi’an 710054, China
3 China Geological Library, Beijing 102249, China

Abstract: The Pamir Plateau can be divided into three secondary tectonic units from north to south: the North, the Middle and the South Pamir Blocks. The North Pamir Block belonged to the southern margin of Tarim-Karakum, thermochronological study of the Pamir structural intersection indicates that accretion of the Middle Pamir Block to the Eurasian Continental Margin and its subduction and collision with the North Pamir Block occurred in the Middle–Late Jurassic. Due to the Neo-Tethys closure in the Early Cretaceous, the South Pamir Block began to collide with the accretion (the Middle Pamir Block) of the Eurasian Continental Margin. Affected by the collision and continuous convergence between the Indian Plate and the Eurasian Plate since the Cenozoic, Pamir is in a multi-stage differential uplift process. During 56.1–48.5 Ma, North Pamir took the lead in uplifting, that is, the first rapid uplift in the Pamir region began there. The continuous compression and contraction of the Indian and Eurasian plates during 22.0–15.1 Ma forced the Pamir tectonic syntaxis to begin its overall uplift, i.e. Pamir began to enter the second rapid uplift stage in the Early Oligocene, which lasted until the Middle Miocene. During 14.6–8.5 Ma, South Pamir was in a rapid uplift stage, while North Pamir was in a relatively stable state, showing asymmetry of tectonic deformation in the Pamir region in space. Since 6.5 Ma, Pamir began to rapidly uplift again.

Key words: fission track, thermal history, tectonic evolution, Pamir


1 Introduction

Pamir Plateau is located to the northwest of the Himalayas-Qinghai-Tibet Plateau, the product of a collision between the Indian and Eurasian plates. The northern and southern margins of the Pamir Plateau are delineated by the Tarim-Karakum Block and the Waziristan-Kohistan-Ladakh suture zone, which is adjacent to the Indian Plate (Li et al., 2013). Taking the Bamiyan-Kangxiwar suture zone and Rushan-Pshart suture zone as boundaries, the Pamir tectonic syntaxis can be further subdivided into the North, Middle and South Pamir (Fig. 1). Chen et al. (2014) proposed that uplift of the Pamir Plateau in the Early Cenozoic was due to collision between the Indian and Eurasian plates, continuous uplift in the late Cenozoic being the widely-accepted model of the time. The results of a thermochronological study in North Pamir by Amidon and Hynek (2010) indicated that the beginning of the Pamir Plateau uplift was in the Eocene (50–40 Ma), other tectonic thermal event activities becoming fixed during the Oligocene–Miocene (25–16 Ma). By conducting oxygen isotopic analysis on sediments sampled from the Oytog profile, which is located at the northwest margin of the Pamir arc structure belt, Bershaw et al. (2015) suggested that the altitude of Pamir was already high enough to block atmospheric circulation during the Eocene to Oligocene. Through detrital zircon and oxygen isotopic analysis, Bershaw et al. (2015) proposed that the Indian Plate and Eurasian Plate collision Deformation Effect affected the Southwest Margin of the Tarim Basin in the Miocene. Arnaud et al. (1993) and Searle et al. (1997) suggested that the tectonically active period of the Pamir Plateau was during the Pliocene–Pleistocene, on the basis of apatite fission track studies at the northeast margin of the Pamir-West Kunlun Mountains. Robinson et al. (2007) suggested that the Tashkarak–Yergang River to the east of the Tashmang-Gongger mountains by Sobel et al. (2011), indicated that thermal events have been widespread in this area since the Miocene. Wang et al. (2011) calculated zircon and apatite fission track ages of intrusive rocks and elastic rocks in the Pamir and West Kunlung regions of China and their peak ages were different, mainly falling into 23–18 Ma, 10–7 Ma and ages less than 5 Ma. In the Piedmont fold transitional zone between the northeastern margin of Pamir and the West Kunlung Mountains, geologists estimated that the

* Corresponding author. E-mail: baochengfan@163.com

© 2021 Geological Society of China
commencement period of Cenozoic tectonic deformation in the area was in the Eocene, through the present strike-slip rate and total strike-slip displacement (Cowgill, 2010; Fu et al., 2010; Sobel et al., 2011).

In summary, the Pamir Plateau is not only different in the process of its internal uplift, but also unclear in the timing of its intracontinental evolution. There are different opinions about when it reached the height affecting atmospheric circulation. Therefore, this research, through the use of zircon and apatite, selected from clastic rocks and intrusive rocks collected in North, Central and South Pamirs, fission track analysis to reconstruct Mesozoic–Cenozoic thermal events in the Pamir tectonic syntaxis, analyzed the thermal evolutionary history of uplift of different tectonic units in Pamir and studied the evolutionary process of the geological structures in this area throughout the Mesozoic–Cenozoic.

2 Regional Geology

The Pamir Plateau is located to the northwest of the Himalayas-Qinghai-Tibet Plateau. In respect of its tectonic position, the Pamir Plateau stretches across the Paleo-Asian and Tethys tectonic domain. Taking the Bamiyan-Kangxiwar suture zone (BKT) as a boundary, the Tarim-Karakum Block of the Paleo-Asian tectonic domain, Central Iran-Gangdis Middle Block (II) and the Indian Plate (III) of the Tethys tectonic domain dominate the North and South of Pamir, while the Middle part, the Hindu Kush-Pamir-West Kunlun cap-shaped tectonic belt, is controlled by long-term interactions between two tectonic domains and three blocks. Regionally, it has experienced a three stage evolution: the closure of the Paleo-Tethys Ocean from Permian to Late Triassic and the expansion of the Neo-Tethys Ocean, subduction and extinction of the Neo-Tethys Ocean from the Jurassic to early Cenozoic, collision and continuous convergence between the Indian Plate and the Eurasian Plate since the Cenozoic (Huang et al., 1987; Pan and Chen, 1997; Xiao et al., 2000; Mo et al., 2006; Xu et al., 2006, 2007, 2011; Li et al., 2011).

Taking the Bamiyan-Kangxiwar suture zone and the Rushan-Pshart suture zone as boundaries, the Pamir tectonic syntaxis can be divided into three secondary tectonic units: the North Pamir Block (I), the Middle Pamir Block (II) and the South Pamir Block (II) (Fan et al., 2017) (Fig. 1).
2.1 The North Pamir Block
The North Pamir Block can be further subdivided into two tertiary tectonic units: the North Pamir late Paleozoic rift (I_{1-2}) and the Northern Pamir Karakuli magmatic arc (I_{1-2}) (Fan et al., 2017). The basement is part of the Karakum-Tarim paleocontinent, where the oldest exposed strata are Proterozoic metamorphic rocks. The Lower–Middle Ordovician is a stable platform sediment. The Middle Devonian is characterized by flysch-like formations. The Upper Devonian is composed of marinecontinental interfacial clastic formations and molasse-like formations. The Lower Carboniferous consists of carbonate rocks, clastic rocks and intermediate-basic volcanic rocks, Middle–Upper Carboniferous are littoral-shallow marine facies clastic rocks and carbonate rocks. The lower Permian is characterized by terrestrial molasse, which are in unconformable contact with the Carboniferous, the lower part of the Triassic is a continental coal-bearing formation, the upper part being continental volcanic rock. The strongest magmatic activity was fixed in the Carboniferous. The oldest strata exposed in the North Pamir Karakuli magmatic arc are the Paleoproterozoic metamorphic rocks, the Middle Proterozoic belonging to the metamorphic rock of medium-pressure and low-temperature amphibolite facies, composed of basement uplifted by folds. The Middle Ordovician and Silurian are continental margin marine metamorphic clastic rocks and carbonate rocks, which have an unconformable contact with the Proterozoic. The Upper Devonian is composed of a red clastic molasse formation of a terrestrial-marine-terrestrial interaction facies. The Carboniferous–Permian is characterized by metamorphic rock formation consisting of phyllites, phyllite shales, quartz sandstones and marble limestones.

2.2 The Middle Pamir Block
The Middle Pamir Block, in terms of its tectonic position, connects with the Bamiyan-Kangxiwa suture zone and the North Pamir Block to the north and with the Rushan-Pshart suture zone and the South Pamir Block to the south. It has a Paleoproterozoic crystalline basement, the oldest exposed strata being Proterozoic schists and high metamorphic rocks of a gneiss facies. The Middle–Upper Paleozoic are composed of schists, quartzites and metamorphic extrusive rocks, the Lower Cambrian being huge thick limestones, clay-carbonaceous shales with a small amount of feldspar quartz sandstones, the thickness of which is more than 2000 m. The thickness of the limestones and shales in the Lower Ordovician is more than 1000 m, which acts as a stable platform sediment. The Silurian and Middle Devonian are characterized by flysch-like formations. The Lower Carboniferous consists of carbonate rocks, clastic rocks, intermediate–mafic volcanic rocks and pillow basalts. The Middle–Upper Carboniferous are littoral-neritic clastic rocks and carbonate beds. The Middle Permian is characterized by terrestrial molasse, which are in unconformable contact with the Carboniferous. The lower part of the Triassic is a continental coal-bearing formation, the upper part being continental volcanic rocks.

2.3 The South Pamir Block
The South Pamir Block is bounded on the north by the Middle Pamir Block with the Rushan-Pshart suture zone, extends southward into Afghanistan and Pakistan to the south, where the boundary is defined by the Waziristan-Kohistan suture zone and connects with the Indian Plate, including two tertiary tectonic units: the Southwestern Pamir Block (II_{1-2}) and the southeastern Pamir foreland basin (II_{2-3}). The Southwestern Pamir Block is mainly composed of Archean crystalline basement, the paleocontinent mainly being composed of regionally deep metamorphic rocks of amphibolite and granulite facies. By the later period, superimposed reformation of intrusive rocks has occurred in the Southwestern Pamir Block, developing marble and plutonic rocks, including gneiss, granite syenite, plagioclase granite, charnockites, gabbro and ultrabasic rocks. The isotopic age data of the various rocks is between 2700–2400 Ma and 1600–1400 Ma (He et al., 2003). The latter group of data reflects the influence of late tectonic transformation. Proterozoic strata, composed of greenish facies series with more quartzite, are distributed on the periphery of the paleocontinent, most of them having tectonic contacts with the Archean. The Carboniferous, Permian, Triassic and Jurassic strata were mainly exposed in the southeastern Pamir foreland basin, while the Lower Carboniferous–Lower Permian strata are flysch-like formations (Bazardarinsky layer C_{1-P_2}), the thickness of which is more than 1.5–2 km, mainly consisting of quartz feldspar sandstones, siltstones, argillaceous slates and interbedding quartz sandstones, siltstones, argillaceous slates. The lenticular conglomerates are in the upper and middle part, only developing limestone beds in the middle part of the depression, which indicates that this period was a basin widely receiving sedimentation settings. The Lower Permian and Upper Triassic are volcanic-siliceous-carbonate formations. The lower part of the series is usually diabase, tuff and other volcanic formations, the upper part transitions to carbonate formations and carbonate-siliceous formations dominated by bioclastic limestones, which generally reflect the deepening process of the water body in the basin. The Cretaceous strata represent a basin sedimentary environment, mainly consisting of argillaceous limestones, marl, bioclastic limestones and so on. In addition, typical terrigenous rocks are occasionally visible. At the end of the Upper Jurassic, southeastern Pamir was slightly uplifted and the sea water retreated. During the Late Jurassic and the Cretaceous, the continents here were formed. During this period, the tectonic movements were intense, accompanied by the intrusion of granitic rocks (Peyve and Kuznetsova, 1968). Mesozoic–Cenozoic plutonic magmatism and thrust nappe structures are well-developed, indicating the northward subduction and thrust of the Indian Plate.

3 Samples and Methodology
3.1 Sample collecting and measuring
In this study, 16 samples of clastic rocks and magmatic rocks were collected from the North, Middle and South
Pamirs (Fig. 1), from which zircons and apatites were selected. Seven samples, including four Carboniferous–Permian clastic rock samples, were collected in North Pamir at an altitude of 4085–4268 m. Four sets of zircon fission track analysis data and two sets of apatite fission track analysis data were obtained. Fission track analysis data of zircon and apatite were obtained from three samples of Carboniferous intrusive rocks, collected at an altitude of 1313–1574 m. Two samples of Early Cenozoic intrusive rocks were collected in Middle Pamir at an altitude of 1973–2034 m, with fission track data of zircon and apatite being obtained. Seven samples were collected in South Pamir, including 2 samples of Permian clastic rocks, 2 samples of Triassic clastic rocks, 3 samples of Cretaceous intrusive rocks, at an altitude of 3927–4650 m. Five zircon fission track ages and five apatite fission track ages were obtained.

Samples were prepared and analyzed at the Fission Track Laboratory of the State Key Laboratory of Geological Processes and Mineral Resources, Chinese University of Geosciences. Apatite and zircon single minerals from each sample were separated by routine methods whenever possible, for adequate testing.

3.2 Experimental method

The principle of fission track analysis relies on a radiometric dating technique based on analyses of the damage trails, or tracks, left by fission fragments in certain 238U-bearing minerals, specifically apatite and zircon. Fission tracks are sensitive to heat and anneal, therefore with increasing temperature, track density increases and track length shortens until it vanishes. Fission track analysis is a cryogenic thermochronology technology, its principle and experimental method have gradually matured, so that it can date the time of rock cooling and the uplift history of geological sections within 10 km. Good application results have been achieved in the field of uplift cooling histories of orogenic belts (Wang Yu., 2004; Yuan et al., 2007). In sample preparation, apatite particles separated by traditional methods were bonded to light sheets with epoxy resin, the light sheets being removed after the epoxy resin consolidated. Grinding and polishing of the largest surface of the minerals occurred, which was observed under a binocular microscope, until a complete plane could be exposed.

A number of apatite and zircon particles were placed on the PTFE board, treated with the prepared epoxy resin, then dried and cured, before etching for 30 seconds in 6.6% HNO3 solution at a constant temperature of 25°C. Using an external detector for dating, apatite samples were attached to a thin sheet of low-uranium muscovite to form a dating module, together with standard uranium glass. Samples were irradiated in the reactor with a neutron flux of 1×1016 cm−2. To reveal the induced fission track, the track density and length were measured using the automatic fission track measuring device imported from Australia. The track length is defined as the complete closed track length in the interior of the mineral. The Zeta constant method was used for age calculation (Hurford and Green, 1983; Wang et al., 1994), the resulting Zeta constants obtained being 410 ± 17.6 (1σ), for apatite with 94.5 ± 3.2 (1σ) for zircon.

4 Results

The age data obtained from the experiment are listed in Table 1, all age grains being detected using the χ2 test. When $P(\chi^2) > 5\%$, it is generally considered that the age of each single particle measured belongs to the same age group. Otherwise, it belongs to a mixed age group, which should be analyzed using special software (Galbraith, 1981). $P(\chi^2)$ for 10 age groups among all age data given in this paper > 5%, indicating that these ages have definite geological significance. $P(\chi^2)$ for other samples < 5% indicated that it resulted from the mixing of multiple thermal events. In this paper, ‘HeFTy’ software was used to do binomial fitting analysis on the ages for which $P(\chi^2) < 5\%$, a series of peak ages being detected. Compared with the single median age or mean age, the peak age has a clear geological significance. The single peak age was analyzed for samples PMR05 (ZFT), PMR06 (ZFT) and NP9 (AFT) by using binomial fitting analysis, in spite of the fact that their $P(\chi^2) < 5\%$. On the single particle age radar (Fig. 2), it can be clearly seen that the age points of the 10 age groups whose $P(\chi^2) > 5\%$ and of PMR05(ZFT), PMR06 (ZFT) and NP9 (AFT) whose $P(\chi^2) > 5\%$ are relatively concentrated, the age distribution of the remaining samples is relatively scattered. The peak ages of the clastic rock samples are less than those of the strata. It can be concluded that the initiation time of the thermal events recorded by the clastic rock samples is not due to the increase of buried geothermal energy, but is the result of late tectonic thermal events. The peak ages of intrusive rock samples were smaller than those of the intrusive rock samples, with the exception of the value of 74.3 Ma of NP9 (ZFT), which retains the age record for time of intrusion, as the result of late tectonic thermal events.

5 Geothermal History and Uplift

The temperature of the apatite fission track annealing zone is generally considered to be 60–120°C. When the temperature is higher than 120°C (the lower part of the annealing zone), the fission track will be annealed completely and the age will be zero. No annealing occurs when the temperature is below 60°C (the upper part of the annealing zone). Fission tracks are formed and accumulated continuously, the age gradually increasing. In the annealing zone, there is both track annealing and new track generation, the age having mixed characteristics. The ideal length of an apatite fission track is 20 μm. However, due to the effect of post-annealing, the standard track length in the actual geological body is 16.3 μm. In contrast, the average track records of apatite obtained from 10 samples in this paper are (12.5 ± 2.2) μm–(14.0 ± 1.8) μm in length, which have similar characteristics. The distribution range is large on the histogram of length distribution (Fig. 3), the length of the ancient track is a single peak and its distribution is asymmetrical. The peak mainly inclines towards large length. The average length is short, the standard deviation is large, the age of track expression being smaller than that of stratum or massif.
Table 1 Fission track age composition of zircon and apatite in Pamir

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lat (N) Long (E)</th>
<th>Elevation (m)</th>
<th>Lithology (no. of grains)</th>
<th>Age</th>
<th>Standard track density (&lt;10^12 cm^-2)</th>
<th>Fossil track density (&lt;10^12 cm^-2)</th>
<th>Induce track density (&lt;10^12 cm^-2)</th>
<th>Pe (cm2)</th>
<th>Fission track age (Ma±1e)</th>
<th>U (ppm)</th>
<th>Peak age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PMR1 Zircon</td>
<td>38.8325° 73.1235°</td>
<td>4268</td>
<td>Sandstone (31)</td>
<td>C + P</td>
<td>144.814 (3701)</td>
<td>66.024 (1642)</td>
<td>12.129 (6696)</td>
<td>0</td>
<td>124± 8</td>
<td>212.27</td>
<td>106.8 −6.1,-6.5 −12.3,+13.2 64.6% 167.7</td>
</tr>
<tr>
<td>PMR2 Zircon</td>
<td>38.791° 73.1312°</td>
<td>4156</td>
<td>Sandstone (35)</td>
<td>C + P</td>
<td>138.998 (7187)</td>
<td>70.804 (3661)</td>
<td>12.010 (6696)</td>
<td>0</td>
<td>106±5</td>
<td>221.21</td>
<td>110.5 −8.2,+8.8 95%</td>
</tr>
<tr>
<td>PMR2 Apatite</td>
<td>38.791° 73.1312°</td>
<td>4156</td>
<td>Sandstone (35)</td>
<td>C + P</td>
<td>2.317 (856)</td>
<td>12.114 (4475)</td>
<td>7.744 (5864)</td>
<td>44.6</td>
<td>31±2</td>
<td>18.40</td>
<td>30.3 −3.2,+3.6 95%</td>
</tr>
<tr>
<td>PMR3 Zircon</td>
<td>38.741° 73.1523°</td>
<td>4085</td>
<td>Sandstone (31)</td>
<td>C + P</td>
<td>115.207 (4428)</td>
<td>47.612 (1830)</td>
<td>11.811 (6696)</td>
<td>73.2</td>
<td>133±6</td>
<td>160.46</td>
<td>133.6 −10.9,+11.8 95%</td>
</tr>
<tr>
<td>PMR3 Apatite</td>
<td>38.741° 73.1523°</td>
<td>4085</td>
<td>Sandstone (35)</td>
<td>C + P</td>
<td>2.722 (964)</td>
<td>8.371 (2964)</td>
<td>7.511 (5864)</td>
<td>0.1</td>
<td>48±3</td>
<td>14.31</td>
<td>35.2 −3.6,+4.0 30% 55.4 −6.6,+7.4 69.5%</td>
</tr>
<tr>
<td>PMR4 Zircon</td>
<td>38.684° 73.1478°</td>
<td>4132</td>
<td>Sandstone (24)</td>
<td>C + P</td>
<td>112.128 (3483)</td>
<td>43.332 (1246)</td>
<td>11.334 (6696)</td>
<td>2.8</td>
<td>137±8</td>
<td>146.54</td>
<td>115.3 −9.0,+9.8 40% 153.3 −9.7,+10.4 59%</td>
</tr>
<tr>
<td>D23 Zircon</td>
<td>38.425° 71.0440°</td>
<td>1362</td>
<td>Monzogranite (36)</td>
<td>C</td>
<td>37.732 (2511)</td>
<td>101.203 (6735)</td>
<td>10.3745 (6675)</td>
<td>0</td>
<td>18±1</td>
<td>366.35</td>
<td>14.6 −1.3,+1.5 54.3% 22.0 −1.1,+1.2 45%</td>
</tr>
<tr>
<td>D23 Apatite</td>
<td>38.425° 71.0440°</td>
<td>1362</td>
<td>Monzogranite (35)</td>
<td>C</td>
<td>0.336 (51)</td>
<td>5.617 (852)</td>
<td>11.946 (6587)</td>
<td>99.9</td>
<td>15±2</td>
<td>5.78</td>
<td>14.6 −2.0,+2.4 9%</td>
</tr>
<tr>
<td>D28 Zircon</td>
<td>38.471° 70.8740°</td>
<td>1313</td>
<td>Granite (36)</td>
<td>C</td>
<td>108.103 (6089)</td>
<td>138.888 (7823)</td>
<td>12.7215 (6675)</td>
<td>0</td>
<td>44±2</td>
<td>407.74</td>
<td>38.9 −2.6,+2.7 40% 48.5 −4.2,+4.6 59%</td>
</tr>
<tr>
<td>D28 Apatite</td>
<td>38.471° 70.8740°</td>
<td>1313</td>
<td>Granite (35)</td>
<td>C</td>
<td>2.463 (384)</td>
<td>50.756 (7913)</td>
<td>14.498 (6587)</td>
<td>29.6</td>
<td>14±1</td>
<td>42.71</td>
<td>14.4 −1.8,+2.0 9%</td>
</tr>
<tr>
<td>D45 Zircon</td>
<td>38.529° 70.8232°</td>
<td>1574</td>
<td>Granodiorite (36)</td>
<td>C</td>
<td>154.903 (7918)</td>
<td>164.293 (8398)</td>
<td>13.1485 (6675)</td>
<td>0.1</td>
<td>56±2</td>
<td>463.56</td>
<td>56.1 −3.7,+3.9 9%</td>
</tr>
<tr>
<td>D45 Apatite</td>
<td>38.529° 70.8232°</td>
<td>1574</td>
<td>Granodiorite (35)</td>
<td>C</td>
<td>1.605 (430)</td>
<td>25.404 (6805)</td>
<td>11.520 (6587)</td>
<td>67.5</td>
<td>15±1</td>
<td>27.51</td>
<td>14.9 −1.8,+2.0 95%</td>
</tr>
<tr>
<td>D74 Zircon</td>
<td>37.750° 71.5444°</td>
<td>2034</td>
<td>Granodiorite (36)</td>
<td>E</td>
<td>26.899 (2237)</td>
<td>94.527 (7661)</td>
<td>11.868 (6675)</td>
<td>3.1</td>
<td>15±1</td>
<td>296.07</td>
<td>13.7 −1.5,+1.7 56.1% 17.3 −1.0,+1.1 43%</td>
</tr>
<tr>
<td>D74 Apatite</td>
<td>37.750° 71.5444°</td>
<td>2034</td>
<td>Granodiorite (35)</td>
<td>E</td>
<td>1.735 (799)</td>
<td>54.072 (24902)</td>
<td>14.073 (6587)</td>
<td>40.0</td>
<td>9±1</td>
<td>47.7</td>
<td>9.5 −1.0,+1.1 9%</td>
</tr>
<tr>
<td>D80 Zircon</td>
<td>37.906° 71.3722°</td>
<td>1973</td>
<td>Granodiorite (36)</td>
<td>E</td>
<td>47.437 (3432)</td>
<td>162.878 (11784)</td>
<td>12.295 (6675)</td>
<td>0</td>
<td>17±1</td>
<td>483.64</td>
<td>14 −0.6,+0.6 54.6% 20 −1.0,+1.0 45.4%</td>
</tr>
</tbody>
</table>
Continued Table 1

<table>
<thead>
<tr>
<th>Sample</th>
<th>Lat (N)</th>
<th>Long (E)</th>
<th>Lithology (no. of grains)</th>
<th>Age</th>
<th>Standard track density ($\times 10^2$ cm$^{-2}$)</th>
<th>Fossil track density ($\times 10^2$ cm$^{-2}$)</th>
<th>Induce track Density ($\times 10^2$ cm$^{-2}$)</th>
<th>U (ppm)</th>
<th>Fission track age (Ma ±1σ)</th>
<th>Peak age (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>D80 Apatite</td>
<td>37.9060°</td>
<td>73.1722°</td>
<td>Granodiorite (40)</td>
<td>E</td>
<td>0.193 (66)</td>
<td>9.024 (3080)</td>
<td>14.498 (6587)</td>
<td>5.5</td>
<td>6.5 ± 1</td>
<td>7.72</td>
</tr>
<tr>
<td>PMR05 Zircon</td>
<td>38.2451°</td>
<td>73.7427°</td>
<td>Sandstone (31)</td>
<td>T</td>
<td>166.611 (5634)</td>
<td>68.933 (2331)</td>
<td>11.493 (6696)</td>
<td>2.0</td>
<td>129 ± 6</td>
<td>209.14</td>
</tr>
<tr>
<td>PMR05 Apatite</td>
<td>38.2451°</td>
<td>73.7427°</td>
<td>Sandstone (27)</td>
<td>T</td>
<td>0.702 (146)</td>
<td>11.991 (2493)</td>
<td>7.279 (5864)</td>
<td>72.2</td>
<td>8.9 ± 1</td>
<td>22.21</td>
</tr>
<tr>
<td>PMR06 Zircon</td>
<td>38.2451°</td>
<td>73.7427°</td>
<td>Sandstone (28)</td>
<td>T</td>
<td>146.404 (2720)</td>
<td>62.545 (1162)</td>
<td>11.334 (6696)</td>
<td>0</td>
<td>124 ± 8</td>
<td>226.89</td>
</tr>
<tr>
<td>PMR07 Zircon</td>
<td>37.6957°</td>
<td>74.7160°</td>
<td>Sandstone (5)</td>
<td>P1</td>
<td>144.586 (668)</td>
<td>88.999 (411)</td>
<td>12.805 (6696)</td>
<td>0</td>
<td>85 ± 34</td>
<td>257.11</td>
</tr>
<tr>
<td>PMR08 Zircon</td>
<td>37.7870°</td>
<td>74.9781°</td>
<td>Sandstone (22)</td>
<td>P1</td>
<td>24.073 (549)</td>
<td>104.185 (2376)</td>
<td>12.686 (6587)</td>
<td>0.3</td>
<td>14 ± 1</td>
<td>306.91</td>
</tr>
<tr>
<td>PMR08 Apatite</td>
<td>37.7870°</td>
<td>74.9781°</td>
<td>Sandstone (16)</td>
<td>P1</td>
<td>0.277 (55)</td>
<td>3.490 (693)</td>
<td>7.047 (5804)</td>
<td>100</td>
<td>12 ± 2</td>
<td>4.13</td>
</tr>
<tr>
<td>NP3 Apatite</td>
<td>37.6180°</td>
<td>73.0766°</td>
<td>Granite (35)</td>
<td>C</td>
<td>1.918 (828)</td>
<td>39.341 (16985)</td>
<td>12.5835 (6587)</td>
<td>3.5</td>
<td>12 ± 1</td>
<td>39.18</td>
</tr>
<tr>
<td>NP4 Zircon</td>
<td>37.5341°</td>
<td>73.5174°</td>
<td>Monzogranite (36)</td>
<td>K</td>
<td>57.629 (4382)</td>
<td>216.644 (16398)</td>
<td>10.801 (6675)</td>
<td>0</td>
<td>13 ± 1</td>
<td>749.22</td>
</tr>
<tr>
<td>NP4 Apatite</td>
<td>37.5341°</td>
<td>73.5174°</td>
<td>Monzogranite (35)</td>
<td>K</td>
<td>0.449 (331)</td>
<td>14.370 (10587)</td>
<td>13.222 (6587)</td>
<td>99.9</td>
<td>8.5 ± 1</td>
<td>12.63</td>
</tr>
<tr>
<td>NP9 Zircon</td>
<td>37.9764°</td>
<td>73.2892°</td>
<td>Monzogranite (36)</td>
<td>K</td>
<td>110.975 (7298)</td>
<td>108.755 (7152)</td>
<td>11.228 (6675)</td>
<td>0</td>
<td>49 ± 3</td>
<td>353.36</td>
</tr>
<tr>
<td>NP9 Apatite</td>
<td>37.9764°</td>
<td>73.2892°</td>
<td>Monzogranite (34)</td>
<td>K</td>
<td>0.363 (199)</td>
<td>26.032 (14284)</td>
<td>13.860 (6587)</td>
<td>0.8</td>
<td>3.8 ± 0.4</td>
<td>23.52</td>
</tr>
</tbody>
</table>

Such characteristics indicate that it has experienced paleogeotherms with higher geotemperatures than today. Therefore, the reaction samples entered the annealing zone from a high temperature (usually 60–120°C), then experienced a stable cooling process.

Based on the fission track parameters and geological setting, the Ketcham annealing model and the Monte Carlo method (Leloup et al., 2011) were used to simulate the apatite track length and a track length of two clastic rocks: PMR02AFT and PMR03AFT. As the temperature of both samples reached the annealing temperature of zircon, the simulated temperature of the apatite fission track ranged from ~140°C higher than that of the annealing zone of apatite, relative to the present surface temperature. Considering that the track length is short and the standard deviation of the track length is large, the age characteristics representing a single particle, then the simulation time is from 100 Ma to now. The simulation...
results are shown in Figure 4. Both samples obtained the best thermal history path (black line in Fig. 4), a pink line representing the better fitting path for inversion simulation, the green line range representing the acceptable area for inversion simulation. Sample code, measured track length and simulated track length, measured Pooled age and simulated Pooled age, K-S test and GOF age-fitting parameters are shown in the upper right corner of each graph. It is generally considered that the simulation results are better, when the K-S value and GOF value are greater than 0.5. Considering that two samples have entered the annealing zone completely, there are generally six stages of thermal evolutionary history and three rapid uplift stages: (1) from > 100 Ma to 57 Ma, the temperature is higher and the temperature at the bottom of an apatite fission track annealing zone is higher than 120°C; (2) 57–48 Ma, PMR02AFT and PMR03AFT recorded the first rapid uplift period in the Pamir region. The temperature of PMR02AFT samples decreased from 120°C to 95°C, the temperature difference was 25°C, and the cooling rate was 2.78°C/Ma. The temperature of PMR03AFT samples decreased from 120°C to 80°C, the temperature difference was 40°C, and the cooling rate was 4.44°C/Ma. According to the study of Chen et al. (2013) in the Qinghai-Tibet Plateau, the average geothermal gradient from Late Cretaceous to Paleocene is 25.4°C/km, which is equivalent to the uplift rate of 109.45–174.8 m/ Ma, the uplift rate recorded by the sample records is from 985.05–1573.2 m. (3) From 48 Ma to 26.5 Ma a relatively steady period is indicated. (4) From 26.5 Ma to 15 Ma, during the second rapid uplift period, the temperature of the PMR02AFT samples decreased from 92°C to 40°C, the temperature difference was 52°C, the cooling rate was 4.52°C/Ma, while that of the PMR03AFT samples decreased from 75°C to 35°C, the temperature difference was 40°C, and the cooling rate were 4.0°C/Ma. By this stage, the Pamir Plateau was in the intracratonic subduction stage, the geothermal gradient had increased to 27°C/km (Chen et al., 2013), which corresponded to an uplift rate of 148.19–167.41 m/Ma, the uplift height of sample records reaching 1481.9–1925.22 m. (5) 15–4 Ma, a relatively stable period; (6) For the third rapid uplift period since 4 Ma, the temperature of the PMR02AFT sample has decreased from about 38°C to 20°C, the temperature difference is 18°C, and the cooling rate is 4.5°C/Ma. For the PMR03AFT sample, the temperature has decreased from about 33°C to 20°C, the temperature difference is 13°C, the cooling rate is 3.25°C/Ma and the ground temperature gradient is still 27°C/km (Chen et al., 2013), which is equivalent to 120.37–166.67 m/Ma. The sample records an uplift height of 481.48–666.68 m.

The uplift process of the Pamir Plateau has been restored by the thermal history simulation of two clastic rock samples from the North Pamir Late Paleozoic Basin. The uplift of the Pamir Plateau has exceeded 4165.1 m since the Paleocene, which is to say, that the Pamir Plateau...
has experienced at least three rapid uplifts, with a 57–48 Ma uplift rate of 174.8 m/Ma and an uplift height of 1573.2 m reached. The uplift rate of 26.5–15 Ma reached 167.41 m/Ma with the uplift height reaching 1925.22 m. Since 4 Ma, the uplift rate has reached 166.67 m/Ma with the uplift height reaching 666.68 m.

6 Analysis and Interpretation

The Pamir tectonic junction and its adjacent areas have experienced complex tectonic activity, which have been severely remodelled in the later stages. Therefore, only a limited analysis can be made on the origin of zircon and apatite fission track dating. The fission track dating of zircon and apatite mainly reflects the tectonic activity of Pamir tectonic syntaxis and its adjacent areas. In order to better analyze the geological structural evolutionary process of the Pamir tectonic syntaxis, the peak ages of different components in each sample were obtained by Gaussian or binomial fitting method using BinomFit software (Table 1 and Fig. 5). From Table 1 it can be seen that the peak age of all clastic rock samples obtained is less than the stratigraphic age of the sampled material, indicating that all the clastic rock samples have undergone a thermal reset. For all intrusive rock samples except for NP9 samples whose P2 peak age is similar to the intrusive age of the massif, the age peaks obtained by other samples are less than the intrusive age, all intrusive rock samples having undergone a thermal reset. Except for NP9 samples whose P2 peak age represents the intrusive age of the massif, the other peak ages have definite geological significance. According to the characteristics of segment concentration of track age, the track age can be summarized as 7 peak periods (intervals): P1, 6.5–4.0 Ma; P2, 14.6–8.5 Ma; P3, 22.0–15.1 Ma; P4, 38.9–30.3 Ma; P5, 56.1–48.5 Ma; P6, 142.4–106.8 Ma; P7, 167.7–153.3 Ma. The peak track age of a sample usually indicates a tectonic thermal event in the rapid uplift exhumation period or source area. Based on the tectonic evolutionary history of the Pamir tectonic syntaxis and its adjacent areas, the geological implications of the seven peak ages mentioned above will be discussed below.

The peak P7 interval is 167.7–153.3 Ma, which is equivalent to the Middle Jurassic–Late Jurassic. Two samples from North Pamir obtained the peak values for this interval, which mainly reflected the closure of the Paleo-Tethys ocean basin during the Late Triassic (T4)–Early Jurassic (J4). At about the same time, or slightly earlier, the Neo-Tethys Ocean to the south of the Paleo-Tethys opened. Since the Early Jurassic (especially the Middle and Late Jurassic), the northern margin of the Neo-Tethys Ocean began to subduct from SW to NE, resulting in the collision of many Paleo-Tethys banded terranes (Sobel et al., 2011; Cowgill et al., 2000). During this period, a series of collision-related granites developed in Pamir and West Kunlun. In terms of sedimentary strata, the Upper Triassic–Lower Jurassic Jeffho Formation is distributed in the North-Middle Pamir Rushan Mountains: the lower part is dark keratinized shales (100 m) and thick layered carbonate rocks (300 m), middle part is marble limestones (200 m), the upper part is metamorphic alkaline extrusive rocks with interbedded slates and conglomerates (300 m). Middle–Upper Jurassic Dammad Formation outcrops in Middle Pamir: it consists of banded limestone and gradually becomes sandstones upward through the succession. In North Pamir, the strata of this period were not deposited except on the northern margin of the Bamiyan-Kangxiwa suture zone. Reflected on both sides of the Chibamiyan-Kangxiwa suture zone of the Middle–Late Jurassic Pamir structure, the collision of the North and Middle Pamirs was completed during this period, i.e. the Middle Pamirs accreted to the Eurasian continental margin and subducted and collided with the North Pamirs (Fig. 6b).

The peak P6 interval is 142.4–106.8 Ma, which is equivalent to the Late Jurassic–Early Cretaceous. The age of tectonic thermal events recorded in this period reflects that Pamir and its adjacent areas were affected by the closure of the Neo-Tethys Ocean. South Pamir moved towards the Eurasian continental margin in the Late Jurassic (early separation from Gondwana) and began to collide with the proliferated Eurasian margin (Middle Pamir) in the Early Cretaceous. The location of the collision is the Rushan-Pshart suture zone (Fig. 6c). At the end of the Early Cretaceous (K1), to the east, the Northern Tibetan Block in China began to subduct northward, forming the Late Cretaceous (K2) island arc magma belt with bi-directional distribution in the Pamir-Karakoram belt in the same period. During the Late Cretaceous (K3), the Pamir-Karakoram belt collided with the Northern Tibetan Block and the southern Western Kunlun belt, forming a series of collisional orogenic granites and post-collisional granites (Cao et al., 2013). Robinson et al. (2007) conducted 40Ar/39Ar dating of biotite and electron probe dating of monazite around the Gongger Mountains, the results revealing that during 125–110 Ma, a strong crustal thickening and shortening, controlled by thrust faults, became fixed (Robinson et al., 2007). Xu et al. (2011) through 40Ar/39Ar dating also revealed that the Kangxiwa fault exhibited strong left-lateral strike-slip characteristics at 125–101 Ma and that the northern margin fault of West Kunlun was formed at this time (120–110 Ma), which constituted the compression transition region. Arnaud et al. (1993) also obtained strike-slip ages for several faults in West Kunlun during 120–100 Ma, suggesting that West Kunlun and its adjacent areas were controlled by strike-slip faults in this area. In addition, Wang et al. (2011) obtained the tectonic thermal event age of 131–103 Ma as a peak range in the fission track chronology analysis of clastic zircons in the piedmont of the northern West Kunlun Mountains. Therefore, this evidence suggests that a collision occurred between South Pamir and Central Pamir during the peak period (Wang et al., 2011).

The peak P5 is 56.1–48.5 Ma. The age of this period was obtained in three samples from North Pamir. Based on the thermal simulation results of apatite fission tracks of two clastic rocks in North Pamir, this study holds that the peak is the age when the collision and continuous convergence of the Indian and the Eurasian plates prompted the first uplift of North Pamir, i.e. the first rapid uplift in the Pamir region. Based on the oxygen isotope
analysis of sediments in the Piedmont Oytag section of the northeastern margin of the Pamir tectonic syntaxis (northern margin of West Kunlun), Bershaw et al. (2011) believed that the Pamir region had reached an altitude sufficient to block atmospheric circulation from the Eocene to Oligocene. The apatite and zircon fission track and (U-Th)/He results, obtained by Amidon and Hynek (2010) in the Karakuri area in North Pamir, indicate that the tectonic uplift in this area occurred at the earliest in the Eocene. Searle et al. (1997) have studied the lower crustal xenoliths developed on the Pakistan side of the China-Pamir border in South Pamir, which were formed by Miocene magmatism and late denudation. The results of petrology and U-Pb geochronology of these xenoliths show that they are a magmatic and sedimentary rock association of the Gondwana tectonic domain and are the products of the plunge of the Indian-Eurasian plates into the lower crust (more than 50–80 km beneath the surface).

Fig. 5. Probability density distribution with best-fit for the peak values of the ages. Sample numbers and peak ages are shown at the top left of the figure.
in the early stage of the collision. This indicates that significant crustal thickening took place in South Pamir in the early Cenozoic, which was the early stage of collision. The peak P4 ranges from 38.9 Ma to 30.3 Ma (Oligocene). The ages of 4 samples were detected in this period. The results of two apatite fission track simulations from two clastic rocks show that North Pamir was in a stable phase. Therefore, the age of the four samples should be attributed to local tectonic activity. Wang et al. (2002), Zhu et al. (2005), Yang et al. (2007) and Zubovich et al. (2010) conducted studies on the local ductile shear activities in Oytag and Bulunkou, the front area of the Pamir tectonic syntaxis, obtaining (36.6–37.3) ± 1.2 Ma. Negredo et al. (2007) obtained an age of 36 Ma by studying the tectonic shear zone.

The peak P3 interval is 22.0–15.1 Ma (Miocene), with the North, Middle and South Pamirs all having the age of this stage. Combined with the results of two apatite fission track thermal simulations of clastic rocks in this paper, the rapid uplift and cooling of 26.5–15 Ma are shown, which indicates that the continuous compression and contraction of the Indian and Eurasian plates caused the Pamir tectonic syntaxis to uplift from the end of the Oligocene to the beginning of the Miocene, indicating that Pamir began to enter the second rapid uplift stage in the late Oligocene, which lasted until the middle Miocene. Amidon and Hynek (2010) studied fission track and (U-Th)/He of apatite and zircon in the Karakuri area, North Pamir, the results showing that the area was uplifted again from the late Oligocene to early Miocene (25–16 Ma). Coutand et al. (2002) and Leith et al. (1985) studied sedimentation rates in the Alai Valley and Tajik Basin in the northern margin of Pamir, indicating that basin deflection and acceleration occurred in the Early Miocene. Hubbard et al. (1996) conducted a 40Ar/39Ar chronological study in the Kuhi-Ial, Darai Stazh and Mulvoj regions of southwestern Pamir, that showed that a cooling event was experienced during 22–17 Ma, which is considered to be a reflection of exhumation events associated with tectonic uplift. In addition, this period is also the most intense period of structural tectonic activity in the Pamir Mountains. The ductile shearing time in Oytag and Bulunkou, the front area of the Pamir tectonic syntaxis, is 22.7 ± 1.1 Ma and 36 Ma, respectively (Wang et al., 2002; Zhu et al., 2005; Negredo et al., 2007; Yang et al., 2007; Zubovich et al., 2010). Therefore, it is believed that the Pamir tectonic syntaxis had initially formed by this stage.

The range of peak P2 is 14.6–8.5 Ma, which belongs to the differential uplift stage of the Pamir region in the middle and late Miocene. Although there are samples in the North, Middle and South Pamirs that obtained this peak, the apatite fission track thermal simulation results of two samples from the North Pamir clastic rocks on the north side of the Bamiyan-Kangxiwa fault show that 164 Ma is a relatively static period, so the P2 peak range of 14.6–8.5 Ma reflects that the local rapid uplift period of Pamir is also the differential uplift period of the Pamir region. Differential uplift of the Pamir region was caused by collision deformation between the Indian Plate and the Asian Plate. Among them, there are tectonic thermal events at 15.6 Ma and 8.3 Ma in PMR08 (ZFT) zircon samples, suggesting that there were multi-stage tectonic thermal events in the middle and late Miocene of the Rushan-Pshart suture zone. But the PMR08 (AFT) apatite samples exhibited tectonic thermal event activity at 11.5 Ma, i.e. a rapid uplift event in South Pamir during 15.6–11.5 Ma. Considering that the annealing temperature of zircon and apatite is 210°C and 120°C, the temperature decreases by 90°C and the cooling rate is 21.9°C/Ma during the period of 4.1 Ma. If the temperature gradient of 27°C/km is considered, the uplift rate is 811 m/Ma, with the uplift height being 3325.1 m. The results of differential uplift show an asymmetry in tectonic deformation in the Pamir area in space. Chen et al. (2011) believed that by the middle Miocene (12–10 Ma), the front (north) of the northward thrust margin of the Pamirs (near Urukchati) began to collide with the southern Tianshan Mountains. Its
northward movement was hindered, the thicker and lighter Tianshan crust beginning downward subduction. Burtman et al. (2000) considered that the Late Cenozoic Pamir tectonic syntaxis wedged northward about 300 km, accompanied by a block rotation of tens of degrees. Through the strike-slip displacement of the southern segment of the Karakoram, Murphy et al. (2000) suggested that the initial active age of the Karakoram fault is about 13 Ma. According to zircon SHRIMP and $^{40}\text{Ar}/^{39}\text{Ar}$ dating of mylonite in the Karakoram fault, Wang et al. (2016) believed that the earliest active time of the Karakoram fault was 13–12 Ma. Matt et al. (1996) suggested that the Karakoram fault had undergone dextral shear since 11 Ma. Zhou et al. (2001), through detailed study of fault displacement and chronology, suggested that the Karakoram fault experienced strong strike-slip deformation during 9–7 Ma. Robinson et al. (2007) proposed that the Tahan fault experienced thermal events at 14 Ma and 8 Ma, but in the Gongger normal fault extensive thermal events were fixed from 9–7.5 Ma, according to biotite and muscovite $^{40}\text{Ar}/^{39}\text{Ar}$ thermochronology study. Another thermochronology study in the upstream area of the Tashkurkan-Yerang River to the east of the Tahan-Gongger mountains by Sobel et al. (2013), indicated that thermal events had been widespread in this area since the Miocene. Wang et al. (2010) calculated zircon and apatite fission track ages for intrusive rocks and clastic rocks in the Pamir and West Kunlun regions of China and their peak ages were different, the peak age mainly falling into 10–7 Ma. Through detrital zircon and oxygen isotopic analysis, Bershaw et al. (2011) concluded that the Indian Plate and Eurasian Plate collision deformation effect affected the Southwest Margin of the Tarim Basin in the Miocene. Therefore, the peak response of this period is the differential uplift stage of the Pamir tectonic syntaxis.

The peak P1 ranges from 6.5 Ma to 4.0 Ma. Two South Pamir samples obtained this peak value. At the same time, the thermal simulation results of two clastic apatite samples from North Pamir show that rapid uplift has occurred since 6 Ma up to now. Since 4 Ma, the thermochronological age has been widespread throughout the Qinghai-Tibet Plateau. Wan and Wang (2002) considered that the molasse in front of the West Kunlun Mountains developed around 5 Ma, the West Kunlun Mountains beginning to rise rapidly. Wang (1998) suggested that pulsating uplift has occurred in Tashkurkan since 5 Ma. The studies of Arnaud et al. (1993) suggested that there has been a cooling period in the Gongger Mountains since 5 Ma. A study by Wang et al. (2011) found that from 5.0–4.8 Ma, the northwest basin of the Pulu area in the Qinghai-Tibet Plateau experienced a rapid cooling event. Pan et al. (2007) suggested that the lowest uplift rate of the West Kunlun Mountains since the Late Pliocene to the Early Pleistocene was 1.5 mm/a. According to Fang et al. (2017), the Qinghai-Tibet Plateau entered the late uplift stage at about 8 Ma. Through the study of the western region conglomerate widely-developed in the southwestern margin of Tarim, Chen et al. (2001) considered that the region west conglomerate has diachronism, deposition beginning at 4.6–3.5 Ma.

Through palaeomagnetic measurements of the Yecheng section on the southern margin of the Tarim Plateau and analysis of sandstone and gravel components, Liu et al. (2002) and Zheng et al. (2002) concluded that the northern margin of the Qinghai-Tibet Plateau began to uplift at 4.6 Ma, accelerated at 3.5 Ma, with large-scale uplift occurring before 2.4 Ma. Zhang et al. (2013) believed that, according to the evolution of Paleogene–Neogene sedimentary basins in the whole Qinghai-Tibet Plateau basin, that the West Kunlun experienced a great uplift in the Middle-Pliocene. Studies by Sun et al. (2008) suggest that, at about 5.3 Ma, the Taklimakan Desert drought intensified. The occurrence of the above events coincide with the peak value of P1 in this study, which indicates that the third rapid uplift event occurred in Pamir from 6.5 Ma.

7 Discussion

In this paper, the fission track chronology of zircon and apatite in Pamir clastic rocks and intrusive rocks is analyzed. According to the characteristics of segment concentration of track age, the track age can be summarized as 7 peak periods (intervals): P1, 6.5–4.0 Ma; P2, 14.6–8.5 Ma; P3, 22.0–15.1 Ma; P4, 38.9–30.3 Ma; P5, 56.1–48.5 Ma; P6, 142.4–106.8 Ma; P7, 167.7–153.3 Ma. This periodic fission track chronological record is directly controlled by the thermal events of Pamir's tectonic evolution.

Since the Mesozoic, Pamir and its adjacent areas have experienced the closure of the Paleo-Tethys Ocean Basin during the Late Triassic (T1)–Early Jurassic (J1). At about the same time, or slightly earlier, the Neo-Tethys Ocean to the south of the Paleo-Tethys opened. Since the Early Jurassic (especially the Middle and Late Jurassic), the northern margin of the Neo-Tethys Ocean began to subduct from SW to NE, resulting in the collision of many Paleo-Tethys banded terranes. During the Late Jurassic–Early Cretaceous, the Pamir and its adjacent areas were influenced by the closure of the Neo-Tethys Ocean and the collision and combination of the Lhasa and Qiangtang massif, forming the Late Cretaceous (K2) island arc magma belt with bi-directional distribution in the Pamir-Karakoram belt in the same period. The collision and continuous convergence of the Indian and Eurasian plates in the Paleoecene prompted Pamir to rise, i.e. a rapid uplift took place in the Pamir area; the rapid uplift began again in the early Oligocene, with the uplift rate reaching 109.45–174.8 m/Ma, the Pamir-West Kunlun Mountains continuing to thrust northward in the late Oligocene and continued to uplift in the middle Miocene. In the middle and late Miocene, Pamir uplifted rapidly with regional differences. There were at least two tectonic thermal events at 15.6 Ma and 8.3 Ma in the Rushan-Pshart suture zone.

8 Conclusions

According to the analysis of zircon and apatite fission track chronology of Pamir clastic rocks and intrusive rocks, there are seven peaks in the thermal age of the
Pamir tectonic syntaxis, the seven peaks reflecting well the tectonic evolutionary process since the Middle Jurassic.

(1) Peak analysis and thermal history simulation indicate that the collision collage of the North and Middle Pamir of the Middle–Late Jurassic was completed on both sides of the Bamiyan-Kangxiwa suture zone. In this period, Middle Pamir collided with the Eurasian continental margin and subducted and collided with North Pamir.

(2) Affected by the closure of the Neo-Tethys Ocean in the Early Cretaceous, South Pamir began to collide with the Eurasian marginal accretion (Middle Pamir). The location of the collision was the Rushan-Pshart suture zone.

(3) The collision and persistent convergence of the Indian Plate and the Eurasian Plate during the Eocene led to the first rapid uplift in the Pamir region. The continuous compression and contraction of the Indian and Eurasian plates during the end Oligocene–Middle Miocene forced the Pamir tectonic syntaxis to begin to uplift as an integral unit. That is to say, Pamir began to enter the second rapid uplift stage at the end of the Oligocene, which lasted until the middle Miocene, with the uplift rate reaching 148.19–167.41 m/Ma. In the middle and late Miocene, the Pamir region was at the stage of differential uplift, the results of the differential uplift demonstrating the asymmetry of tectonic deformation in the Pamir region in space. Pamir is engaged in its third rapid uplift process since 6.5 Ma.

Acknowledgements

This work was supported by the Projects of the China Geological Survey (grant nos 12120114018601, 121201011000150010). The Pamir Project Group of the Xi'an Center, China Geological Survey, is thanked for sample collection. Prof. Yuan Wanning is thanked for sample analysis, while Dr. Pan Feng is thanked for data processing. Prof. Li Jianxing is thanked for providing a constructive review for this paper. Other reviewers are thanked for their valuable opinions and elaborate guidance.

Manuscript received Feb. 18, 2019 accepted Nov. 11, 2020 associate EIC: XIAO Wenjiao edited by Jeff LISTON and GUO Xianqiang

References


