Cenozoic Uplift of the Central Yunnan Fragment, Southwestern China, Revealed by Apatite (U-Th)/He Dating

Ke Wu ©, Youpu Dong ©*, Jiaxin Duan, Xin Ru, Dongyue Zhang, Dan Wang
Faculty of Land Resource Engineering, Kunming University of Science and Technology, Kunming 650093, China
©Ke Wu: https://orcid.org/0000-0003-4915-242X, ©Youpu Dong: https://orcid.org/0000-0002-2829-7585

ABSTRACT: The age of central Yunnan fragment uplift has long been debated, with estimates ranging from the Late Eocene to about 1 Ma. To determine the central Yunnan fragment uplift time in the Cenozoic, apatite (U-Th)/He (AHe) was used to analyze the low-temperature thermochronology of samples from the Jiaozi Mountain area of the eastern central Yunnan fragment. The sampling area is located in the Dongchuan District of Kunming, Yunnan Province, near the Xiaojiang fault zone. The results show that AHe ages from the eastern part of central Yunnan fragment were mainly concentrated around 25.7–37.9 Ma, and intensive uplift had happened before 36.5 Ma. Together with previous low-temperature thermochronology research on the western and eastern central Yunnan fragment, we concluded that the Yunnan Plateau uplifted prior to 36.5 Ma, in a west to east sequence. The uplift caused a change in paleo-geographical terrain, which may have altered the ancient river systems of the southwest Tibetan Plateau.

KEY WORDS: central Yunnan fragment, (U-Th)/He dating, uplift, Cenozoic.

0 INTRODUCTION
Since the Early Cenozoic, the collision of Indo-Asian continents has led to the shortening of the Tibetan Plateau crust. The Qiangtang terrane in the middle of the Tibetan Plateau had risen to its current height before 40 Ma (Wang C S et al., 2008), and as the Indian-Asian continental collision continued, the plateau gradually expanded toward the north and the south, respectively. The southern edge of the Qinghai-Tibet Plateau had risen to its present heights in the Mid-Miocene (Zhang et al., 2018; Rowley et al., 2001), while the Hoh Xil Basin reached its present height in the Late Pleistocene (DeCelles et al., 2007). The northeastern part of the Tibetan Plateau gradually uplifted in the Pliocene and Quaternary, forming the present Tibetan Plateau with Qilian Mountains uplift in the Late Cenozoic (Tapponnier et al., 2001).

The southeastern margin of the Tibetan Plateau has distinct geomorphological features with a gradual and slow loss of altitude from northwest to southeast, bearing no significant geomorphological differences (Fig. 1). Two main deformation modes have been proposed to explain the formation of the southeast margin of the Tibetan Plateau: the first is that the IndoChina terrane and the Sichuan-Yunnan fragment extruded to the southeast along a large strike-slip fault with large-scale clockwise rotation (Huangfu et al., 2016; Clift et al., 2006; Leloup et al., 2001; Avouac and Tapponnier, 1993; Peltzer and Tapponnier, 1988; Tapponnier et al., 1986, 1982; Tapponnier and Molnar, 1976). And the second is that the eastern Tibetan Plateau can be explained by the eastward flow of the hot and weak lower crust material (Copley, 2008; Royden et al., 1997, Royden, 1996; Bird, 1991; England and Houseman, 1986).

Yunnan Plateau, named for its average elevation above 2 000 m, is along the southeast margin of Tibetan Plateau and is high in the northwest and low in the southeast. The Yalong River thrust fault represents the Tibetan Plateau boundary and divides the Yunnan Plateau into two parts (Liu et al., 2009). The southeast side of the Yalong River fault is the central Yunnan fragment, and the west side of the Yalong River fault belongs to the Tibetan Plateau. The uplifting age of the central Yunnan fragment uplift has been debated, with estimates ranging from the Late Eocene to about 1 Ma, and Yang et al. (2010) argued that the central Yunnan fragment was formed a million years ago. Wu et al. (2018) considered that Northwest Yunnan began to rise gradually in the Late Eocene by reconstructing the ancient elevation and environment. Hoke et al. (2014) concluded that the central Yunnan fragment reached its current altitude as early as the Late Eocene by calculating the ancient elevation and river profile of the Red River Basin.

Previous assessments of central Yunnan fragment formation were not very consistent, however, so it is still controversial and other means are needed to obtain comprehensive estimates. Low-temperature thermochronology can record when a section of crust cooled through an ororotemperature as it was exhumed towards the surface. Because it has a relatively low closure temperature, apatite (U-Th)/He dating is a useful way to analyze and document the latest stages of topographic evolution and cooling within the uppermost kilometers of the crust (Wu et al., 2017). Previous studies have been conducted in the western

*Corresponding author: dongypsd@126.com
© China University of Geosciences (Wuhan) and Springer-Verlag GmbH Germany, Part of Springer Nature 2020

Manuscript received November 20, 2019.
Manuscript accepted April 06, 2020.

and central parts of the central Yunnan fragment (Jiang et al., 2018; Liu et al., 2018; Chen et al., 2016; Li, 2012; Wang G et al., 2008; Fu, 2005). However, there are not good estimates for the eastern part. Moreover, the eastern part is far from the Tibetan Plateau, which can better reflect and constraint the uplift time. Our sampling locations were in the Jiaozi Mountain, located in the eastern part of the central Yunnan fragment and along the western edge of the Yangtze Craton (Pan, 2009). There have been no prior reports on low-temperature thermal chronological research in this area.

1 GEOLOGICAL SETTING AND METHODS

The basement of the central Yunnan fragment is Proterozoic metamorphic rock, which is overlaid by Late Palaeozoic and Mesozoic continental deposits (Wang and Wang, 2005). The fragment is bounded by the Indo-China Terrane, South China Terrane, the Sichuan-Qinghai fragment, and the Tibetan Plateau to the south, the east, the north, and the west, respectively. The sampling area is Jiaozi Mountain area located in the eastern part of Central Yunnan fragment. The Cenozoic, Mesozoic, Palaeozoic, and Proterozoic strata are well exposed. Samples were collected from the Lower Proterozoic metamorphic sandstone (Yunnan Provincial Bureau of Geology and Mineral Resources, 1990). The Jinsha River runs through the whole region from west to east. The eastern side is the Xianshui River-Xiaojiehe fault zone (Fig. 2). It is an ideal place to limit uplift on the eastern central Yunnan fragment. To better understand the history of denudation in the region, we used low-temperature thermochronology to study four metamorphic sandstone samples collected along vertical profiles (Fig. 3).

We used apatite (U-Th)/He to explore the cooling history of these samples and its relationship to topographic evolution. The low closure temperatures of apatite (U-Th)/He (AHe, 60±20 °C; Farley, 2002) make it possible to measure cooling of the shallow crust that is too small in magnitude to be recorded by higher temperature systems in regions undergoing slow exhumation, and to offer more detailed information for very young cooling events or relief change.

Samples collected by the institute were 400–500 m in height, a vertical sampling interval of 80–100 m, and a weight of about 3–4 kg. The position of each sampling point was recorded with a portable GPS (Fig. 4).

All experiments were conducted at the 40Ar/39Ar and (U-Th)/He Laboratory of the Institute of Geology and Geophysics of the Chinese Academy of Sciences (IGGCAS). The sandstone samples were crushed and sieved to obtain fragments between 280 and 450 μm in diameter. The apatite crystals were manually selected directly from the fragments and carefully inspected under a high-powered microscope to meet (U-Th)/He dating criteria (Reiners and Farley, 2001). Most apatite grains were characterized by different degrees of roundness, which indicates that they experienced erosion and transport for various distances before deposition. To meet the (U-Th)/He dating criteria, less-rounded grains were selected.

Based on the clarity and morphology, hand-picked grains were wrapped in platinum capsules. Length and width measurements for α ejection correction (Farley, 2002) were taken for each grain. The analytical protocol adopted in this study...
followed those described by Foeken et al. (2006). (U-Th)/He dates were calculated using standard procedures developed by Meesters and Dunai (2002). Total analytical uncertainty was calculated as the square root of squares of weighted uncertainties of U, Th, and He measurements, and included the estimated additional variations of ±7% determined after repeating analyses of Durango apatite.

2 RESULTS

Four metamorphosed sandstone samples were selected at different elevations for apatite (U-Th)/He dating (Table 1). Single-grain apatite He ages show no clear relationships with the contents of effective uranium ([eU] = [U] + 0.235 × [Th]), nor a large difference in the retentivity of grains with different amounts of radiation damage (Fig. 5a). No relationship between the length and age of the apatite grains was observed, i.e., there was no correlation between grain size and age, implying that grain size did not affect (U-Th)/He age (Fig. 5b).

The apatite He ages of the samples range from 50.1 to 25.7 Ma and are much younger than the depositional ages.
Table 1 Test results for apatite (U-Th)/He age in the Jiaozi Mountain region

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Latitude (N)</th>
<th>Longitude (E)</th>
<th>Elevation (m)</th>
<th>Lithology</th>
<th>Mean AHe (Ma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDS03</td>
<td>26°13′16.87″</td>
<td>102°57′10.48″</td>
<td>3 606</td>
<td>Metamorphic sandstone</td>
<td>37.9</td>
</tr>
<tr>
<td>JDS04</td>
<td>26°14′07.05″</td>
<td>102°57′17.73″</td>
<td>3 332</td>
<td>Metamorphic sandstone</td>
<td>50.1</td>
</tr>
<tr>
<td>PDS05</td>
<td>26°13′50.16″</td>
<td>102°57′12.23″</td>
<td>3 290</td>
<td>Metamorphic sandstone</td>
<td>36.5</td>
</tr>
<tr>
<td>PDS06</td>
<td>26°14′09.76″</td>
<td>102°57′04.64″</td>
<td>3 220</td>
<td>Metamorphic sandstone</td>
<td>25.7</td>
</tr>
</tbody>
</table>

Figure 5. (a) (U-Th)/He ages versus effective uranium content eU; (b) (U-Th)/He ages versus length.

This indicates that the apatites were exposed to higher temperatures than the apatite He closure temperature after deposition, at which point all samples had undergone complete or partial annealing. He ages are cooling ages that are usually related to a tectonic uplifting event (Ehlers and Farley, 2003; Dodson, 1973). There was an obvious turning point in the altitude-He age plot, and the cooling rate from 37.9 to 36.5 Ma was much higher than 36.5–25.7 Ma (Fig. 6 and Table 1), implying that intensive uplift occurred prior to 36.5 Ma.

One much older age (50.1 Ma from sample S04) was difficult to explain. It may be because, in some cases, the unaccounted-for effects of specific types of U and Th zonation within apatite can lead to older ages when the Ft correction is applied under a homogeneous distribution assumption, resulting in a >30% difference in age (Farley et al., 1996).

3 DISCUSSION

3.1 Xiaojiang Fault Zone and Central Yunnan Fragment Uplift

The sampling locations were very close to Xiaojiang fault, which may have affected tectonic activity in the region. Xiaojiang fault is the southern part of the Xianshui River-Xiaojiang fault belt that is made up of several faults: Ganzi-Yushu and Xianshui River faults in the northwest, Anning River fault in the north-south direction after extending to Shimian County, and Zemu River fault in the northwest direction (Zhang, 2008). The Xianshui River-Xiaojiang fault zone sequence is north to south (Schoenbohm et al., 2006). Ganzi-Yushu and Xianshui River faults were initiated at 12.6 and 9 Ma, respectively (Zhang et al., 2017; Wang et al., 2009), which implied that Xiaojiang fault activity should have occurred after 9 Ma. The AHe ages from our study area were older than 23 Ma, on the other hand. Thus, in the eastern part of the central Yunnan fragment, tectonic activity did not appear to account for the uplift prior to the Neogene.

3.2 Central Yunnan Fragment Uplift

Sample data from the Jiaozi Mountain area in the eastern part of the central Yunnan fragment allowed us to plot an elevation-age map. As age increased, elevation also increased in a positive linear relationship. The cooling rate from 37.9 to 36.5 Ma was much higher than 36.5–25.7 Ma, implying that intensive uplift occurred prior to 36.5 Ma.

Other research conducted in the central part of the central Yunnan fragment (Xiangyun, Sazhi, Ximping, and Dali) observed that a rapid uplift occurred during 20–43 Ma (Jiang et al., 2018; Wu et al., 2018; Hoke et al., 2014; Fu, 2005). The western part of the central Yunnan fragment, west of the Yalong River, uplifted prior to 40 Ma according to studies of stratigraphy and sedimentation, and low temperature and thermal chronological data were concentrated within 33–56 Ma (Liu et al., 2018; Li, 2012; Wang CS et al., 2008) (Fig. 7).

In conclusion, it can be inferred that central Yunnan fragment uplift occurred from west to east, and that eastern uplift may have occurred prior to 36.5 Ma. It can be explained by the India-IndoChina oblique convergence in the Cenozoic. The
Indian Block indented against the Asian Plate during its northeastward drifting (Molnar and Stock, 2009; Bertrand and Rangin, 2003), and the eastern Himalaya syntaxis has wedged into Eurasia Block before 60 Ma (Zhong and Ding, 1996), and the India Block showed a counterclockwise rotation compared with the Eurasian Block before 37 Ma (Lee and Lawver, 1995). So the west part of the central Yunnan fragment would be affected earlier than the east part. The extrusion model inferred that the extrusion of Indo-China Block initiated at about 35 Ma (Socquet and Pubellier, 2005), and its main extrusion period was from 27 to 17 Ma (Gilley et al., 2003; Leloup et al., 1995). The channel flow model concluded that the southeast of Tibetan Plateau deformed before 13 Ma (Clark et al., 2005). Therefore, together with all the deformation ages described above, it could be inferred that there had been an obvious uplift in the southeast of the Tibetan Plateau before the extrusion or the material flow happened.

Multiphase uplifts are considered as an important form in Tibetan Plateau (Zhong and Ding, 1996), and in this paper, the uplift before 36.5 Ma could represent the initiative uplift in the southeastern margin of the Qinghai-Tibet Plateau in Cenozoic. There are two strong cooling events around 13–10 and 5 Ma in this area (Jing et al., 2018; Wang and Lu, 2014; Wang et al., 2013; Wang and Wang, 2005).

Central Yunnan fragment uplift may have also altered the geographical framework, impacting the southeast Tibetan Plateau river systems. Prior to 35 Ma, there was no connection between the ancient Jinsha and Yangtze rivers, but the ancient Chuan River might meet with Jinsha River in the Shigu area, and flowed into the ancient the Red River (Zheng, 2016). The ancient Sichuan River changed flow direction from westward to eastward around 36–23 Ma (Fig. 8) (Zheng et al., 2013). The ancient Red River, which connected the Tibetan Plateau with the South China Sea prior to 35 Ma, was cut off and lost its northern source after 35 Ma (Chen et al., 2017; Clark et al., 2006, 2004; Clift et al., 2006; Brookfield, 1998). Although many works had been done (Wu et al., 2018; Gourbet et al., 2017; Xu et al., 2016), there is no convinced evidence to describe the paleoaltitude of the southeast of Tibetan Plateau due to the enormous error of modern research methods. Study results that ancient rivers system changed their incipient course were consistent with our research. It is likely that the central Yunnan fragment uplift altered the ancient river systems of the southeastern Tibetan Plateau.

4 CONCLUSIONS

In this study, we used low-temperature thermochronology to determine the timing of the eastern central Yunnan fragment uplift. AHe ages were mainly concentrated from 25.7–37.9 Ma and intensive uplift occurred prior to 36.5 Ma, implying that the
Figure 8. Simplified tectonic map of paleo-Red River and paleo-Chuanjiang River during the Early Cenozoic. Tectonic reconstructions and the positions of the terranes are based on Zheng et al. (2013) and Chen et al. (2017).

sampling area was less likely to be affected by Xiaojiang fault movement. Together with previous studies conducted in the central and western parts of the central Yunnan fragment, we concluded that the uplift sequence occurred from west to east. The central Yunnan fragment uplift altered the geographical framework, which may have changed river system courses. Other researches on the ancient Sichuan and Red rivers were consistent with our study.

ACKNOWLEDGMENTS
This study was supported by the National Natural Science Foundation of China (Nos. 41802215, 41762017). We are also grateful for the helpful comments from the anonymous reviewers. The final publication is available at Springer via https://doi.org/10.1007/s12583-020-1328-4.

REFERENCES CITED
Farley, K. A., 2002. (U-Th)/He Dating: Techniques, Calibrations, and Ap-

Wang, G., Wang, E., 2005. Extensional Tructures within the Compressio-

naior Ogenic Belt and Its Mechanism: A Case Study for the Late Ce-


Wu, J., Zhang, K. X., Xu, Y. D., et al., 2018. Paleoelevations in the Jian-


Xu, H., Su, T., Zhang, S. T., et al., 2016. The First Fossil Record of Ring-Cupped Oak (Quercus L. Subgenus Cyclobalanopsis (Oersted) Schneider) in Tibet and Its Paleoenvironmental Implications. *Palaeo-


Zhang, Y. Z., Replumaz, A., Leloup, P. H., et al., 2017. Cooling History of the Gongga Batholith: Implications for the Xianshuihe Fault and Mi-


