Formation of the Huajiang Grand Canyon (southwestern China) driven by the evolution of a Late Pleistocene tiankeng

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Abstract

Collapse is a common geomorphic process in karst areas, especially on the Yunnan-Guizhou Plateau, which has a tectonic background of integral uplift. The frequent occurrence of collapse processes in karst underground caves and canyons indicates that collapses play an important role in the formation of canyons. Through an analysis of the morphology of a semicircular cliff in the Huajiang Grand Canyon and an investigation of sediments at the bottom of the cliff, a large-scale collapse event was found to have occurred. U-series dating of secondary calcium carbonate cement in the collapse breccias indicates that collapse processes occurred approximately 200 ka. According to the geomorphological evolution of the Huajiang Grand Canyon, the following geomorphic evolutionary process is proposed: underground river—cave hall—collapse of a tiankeng—tiankeng degradation—canyon formation. These findings also show that the dating of collapsed breccia cement can be effectively used to determine the development times of karst canyons and the formation ages of tiankengs.

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ORIGINAL ARTICLE

Formation of the Huajiang Grand Canyon (southwestern China) driven by the evolution of a Late Pleistocene tiankeng

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Abstract Collapse is a common geomorphic process in karst areas, especially on the Yunnan-Guizhou Plateau, which has a tectonic background of integral uplift. The frequent occurrence of collapse processes in karst underground caves and canyons indicates that collapses play an important role in the formation of canyons. Through an analysis of the morphology of a semicircular cliff in the Huajiang Grand Canyon and an investigation of sediments at the bottom of the cliff, a large-scale collapse event was found to have occurred. U-series dating of secondary calcium carbonate cement in the collapse breccias indicates that collapse processes occurred approximately 200 ka. According to the geomorphological evolution of the Huajiang Grand Canyon, the following geomorphic evolutionary process is proposed: underground river—cave hall—collapse of a tiankeng—tiankeng degradation—canyon formation. These findings also show that the dating of collapsed breccia cement can be effectively used to determine the development times of karst canyons and the formation ages of tiankengs.

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1 Introduction

Canyons are peculiar landscape morphologies produced by multiple processes (Hill et al. 2008; Karlstrom et al. 2014; Wang et al. 2014). Canyons form in different lithologies, but they are often found in karst terrains (Ford 1973; Abbott et al. 2015; Telbiszet al. 2019). Because karst allows underground drainage, river banks are not significantly eroded, and steep slopes are preserved. Therefore, deep canyons are a common and remarkable feature of karstic landscapes (Sweeting 1995). In uplifting areas, rivers progressively cut across landforms (Nicod 1997); thus, the development of deep canyons is controlled by the base level (Fabre and Nicod 1978). Another key factor in the development of canyons is gradually deepening from the lower to upper reaches of valleys, which is driven by the migration of the knickpoint (Germanoski and Ritter 1988; Hu et al. 2016). However, in karst terrains, cave collapse also plays a significant role (Nicod 1997).

The Yunnan–Guizhou Plateau (Southwest China) has been uplifted since the Cenozoic (Tapponnier 2001; Clark et al. 2006) due to the uplift of the Qinghai–Tibetan Plateau. The rapid uplift of this extensive Chinese karst region has favoured underground drainage and thus the formation of caves. The expansion of underground spaces (lateral and/or vertical expansion) eventually leads to the collapse

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of caves. On the Guizhou Plateau, the collapse of underground river passages is very common (Zhang and Mo 1982; Sweeting 1995; Szczygiel et al. 2018), often causing the opening of the chamber roof to the ground surface. Several morphologies in this area (i.e., large depressions, canyons, valleys, cones, and tower karst) are attributed to cave collapse (Ambert and Nicod 1981; Alexander 2005), including tiankengs. The latter are giant collapse dolines with continuous precipitous walls (Alexander 2005; Zhu and Chen 2005; Waltham 2015; Michelena 2020). In most cases, the accumulation of colluvium can be observed at the bottom of tiankengs. According to the evolution of similar landforms, large underground rivers are prone to collapse, thus forming tiankengs. The Xingwen Tiankeng group in Sichuan (Waltham 2005), Wulong Tiankeng group in Chongqing (Alexander 2005; Szczygiel et al. 2018), and Leye Tiankeng group in Guangxi (Zhu and Waltham 2005) are other examples of tiankengs. Many tiankengs are also distributed on the tributaries of large rivers on the plateau. For example, the Dacaokou and Xiaocaokou Tiankengs on the Yijie River, which is a tributary of the Wujiang River, and the Jiudongtian Tiankeng on the Liuchong River in the upper reaches of the Wujiang River are narrow, long tiankengs formed by collapsed cave passages (An et al. 2019). These tiankengs represent the embryonic form in the evolution from tiankeng to canyon.

The shape of tiankengs evolves because of the lateral expansion of the walls and collapses. If these karst-related features endure through time, the original morphology is obliterated. Thus, understanding the evolution of a karst area where tiankengs have reached a mature stage might be difficult. As for all morphologies related to underground voids (Sasowsky 1998), determining the age of tiankengs is complicated (Shui et al. 2015). There have been several attempts to determine the chronological evolution of these landforms in China using different approaches. According to geological observations, Zhu and Chen (2005) speculated that most tiankengs in China formed since the Late Pleistocene, while Wei et al. (2019) inferred that Fengjie Tiankeng was formed in the late Middle Pleistocene. Meng et al. (2017) also determined that the exposure age of Dashiwei Tiankeng is at least 100–200 ka BP based on bedrock cosmogenic ^{36}Cl exposure dating. Therefore, more exhaustive information about the age and evolution of these morphologies is needed.

Cave deposits can be dated to infer the ages of caves (Polyak et al. 2008; Granger and Fabel 2012; Anthony 2012; Columbu et al. 2021). Chemically precipitated carbonate (i.e., speleothems) is an ideal candidate because U-series dating of calcite is very efficient (Cheng et al. 2016). Importantly, speleothems are deposited after cave formation (Wang et al. 2004; Columbu et al. 2015) in either subaerial or submerged conditions (De Waele et al. 2018). Speleothems found at the surface indicate that the original hosting cave has been disrupted (Columbu et al. 2017).

This paper investigates the evolution of the Huajiang Grand Canyon on the Guizhou Plateau in the middle reaches of the Beipan River. Geomorphological observations suggest the presence of a relict tiankeng, and secondary carbonate dating was applied to deposits previously formed in underground environments. Accordingly, this paper aims to reconstruct the genesis of the current canyon relative to the maturation of the relict tiankeng, placing this karst-related process into a congruent geochronological timeframe.

2 Area of study

The Beipan River originates from the eastern part of Yunnan Province and flows from northwest to southeast across the Yunnan–Guizhou Plateau (Fig. 1A–B). Reaching the slopes of Guangxi, this river is 449 km long with a drop of 1982 m, corresponding to an average drop of 4.42‰, and has a catchment area of 25,830 km^2 (Fan et al. 2018). Wide varieties of rocks are exposed in the basin, including a large number of soluble rocks, such as Devonian, Carboniferous, Permian, Triassic limestone, and dolomite, as well as nonsoluble rocks, such as siltstone and mudstone.

Under the influence of lateral extrusion from the southeastern Qinghai–Tibetan Plateau, the Yunnan–Guizhou Plateau has undergone differential uplift alongside the uplift of the Qinghai–Tibetan Plateau. Low-relief and high-elevation surfaces are broadly distributed, elevation decreases gradually from the northwest to the southeast, and western plateau surfaces with altitudes of 2100–2200 m and eastern plateau surfaces with altitudes of 1300–1400 m are relatively intact (Clark et al. 2006). The valleys of the Beipan River and its tributaries are deep, and the plateau is divided by numerous rivers. The surface has experienced extensive erosion, resulting in a shortage of widespread, continuous Quaternary sediments (Liu et al. 2013).

The Huajiang Canyon is located in the middle reaches of the Beipan River, 5 km upstream from Huajiang village (Fig. 1). Covering a total length of 30 km (Fig. 1C), the canyon coincides with the Zhenfeng Fault. On the western side of the fault, a well-preserved karst plateau surface is maintained, with an average elevation of 1300–1400 m (Fig. 1D). On the eastern side of the fault, the terrain is relatively low with no intact plateau surface, forming a hilly country with an elevation of 500–1000 m. With the fault as the boundary, the lower reaches of the river are open, and the river becomes sluggish, while the upper

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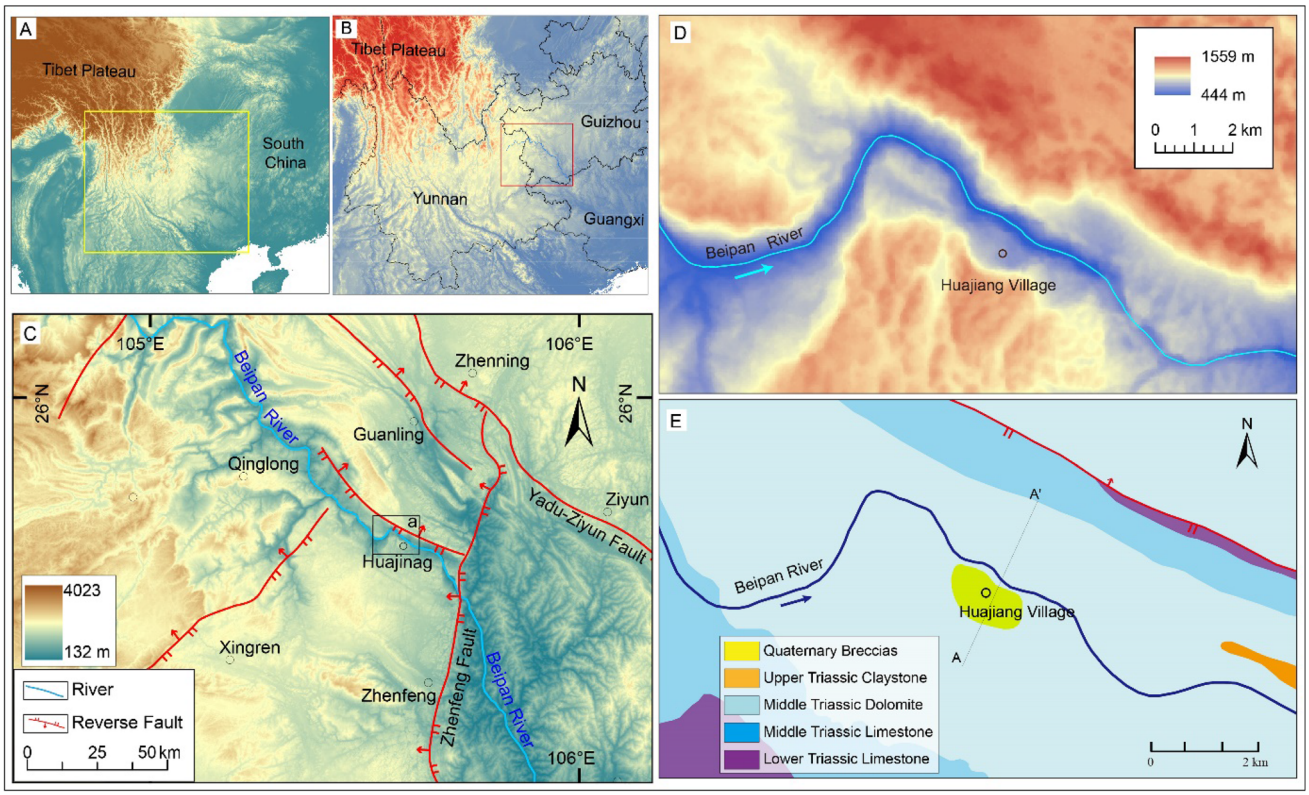

Fig. 1 Study area. **A** Location of the Yunnan–Guizhou Plateau. **B** Location of the Beipan River. **C** Digital elevation model of Huajiang Canyon and surrounding areas, with the main fault system shown. D Digital elevation model of the Huajiang Canyon area. **E** Simplified geologic map of Huajiang Canyon (section A–A' is shown in Fig. 3a)

reaches exhibit deep canyons. In the section containing Huajiang village, the vertical drop of the canyon is very large, with a depth of approximately 800–1000 m. In this section, the river cuts deeply into the dolomite strata of the Triassic Yangliujing Formation. In the study area, the canyons consist of an ~ 3-km-wide outer canyon and an ~ 150-m-wide inner canyon with a depth of 200 m. The two sides of Huajiang Canyon are surrounded by plateau surfaces, with several 100–200 m-high fengcongs present (Fig. 1D).

Within Huajiang Canyon, a distinct platform is identified (25°41′52″N, 105°35′24″E). The elevation of this platform is higher than that of the modern river channel by approximately 200 m (Fig. 2A). The altitude of the platform is approximately 700 m, and the elevation of the bed of the Beipan River is 500 m. A semicircular vertical cliff is retained on the side of the canyon where the Huajiang platform is located. Furthermore, some residual peaks occur on the opposite bank of the canyon. A large amount of karst breccia has been deposited on the platform of Huajiang village, with a thickness of 5–10 m. The bedrock beneath the breccias is an ancient cave floor. In addition, many remains of ancient stalagmites were observed on the Huajiang platform (Fig. 3).

3 Materials

The breccias on the Huajiang platform are composed of dolomites, have a mixed structure with no obvious bedding, and are densely cemented by secondary calcium carbonate (Fig. 3c–j). According to their sedimentary characteristics, they can be identified as colluvial breccias with a thickness of 5–10 m. Many remains of ancient stalagmites were observed on the Huajiang platform. Some stalagmites remain upright, with dolomite bedrock at the bottom (Fig. 3l). Some of the damaged stalagmites are buried in the soil (Fig. 3k). Although all of the stalagmites were eroded and weathered under the soil in the later stage, laminae and morphological characteristics can be identified in the fracture section.

Four secondary calcium carbonate deposits on the Huajiang platform were investigated (Fig. 3), two of which were breccia samples (BHJT2 and BHJT4): BHJT2 located at the bottom of the tiankeng (695 m a.s.l.) and BHJT4 located on the slope at the edge of the tiankeng (780 m a.s.l.). The remaining samples (BHJT3BS and BHJT3CS) were two ancient stalagmites on the Huajiang platform. Samples for dating were obtained from the top and bottom of each stalagmite. Fortunately, freshly exposed breccias

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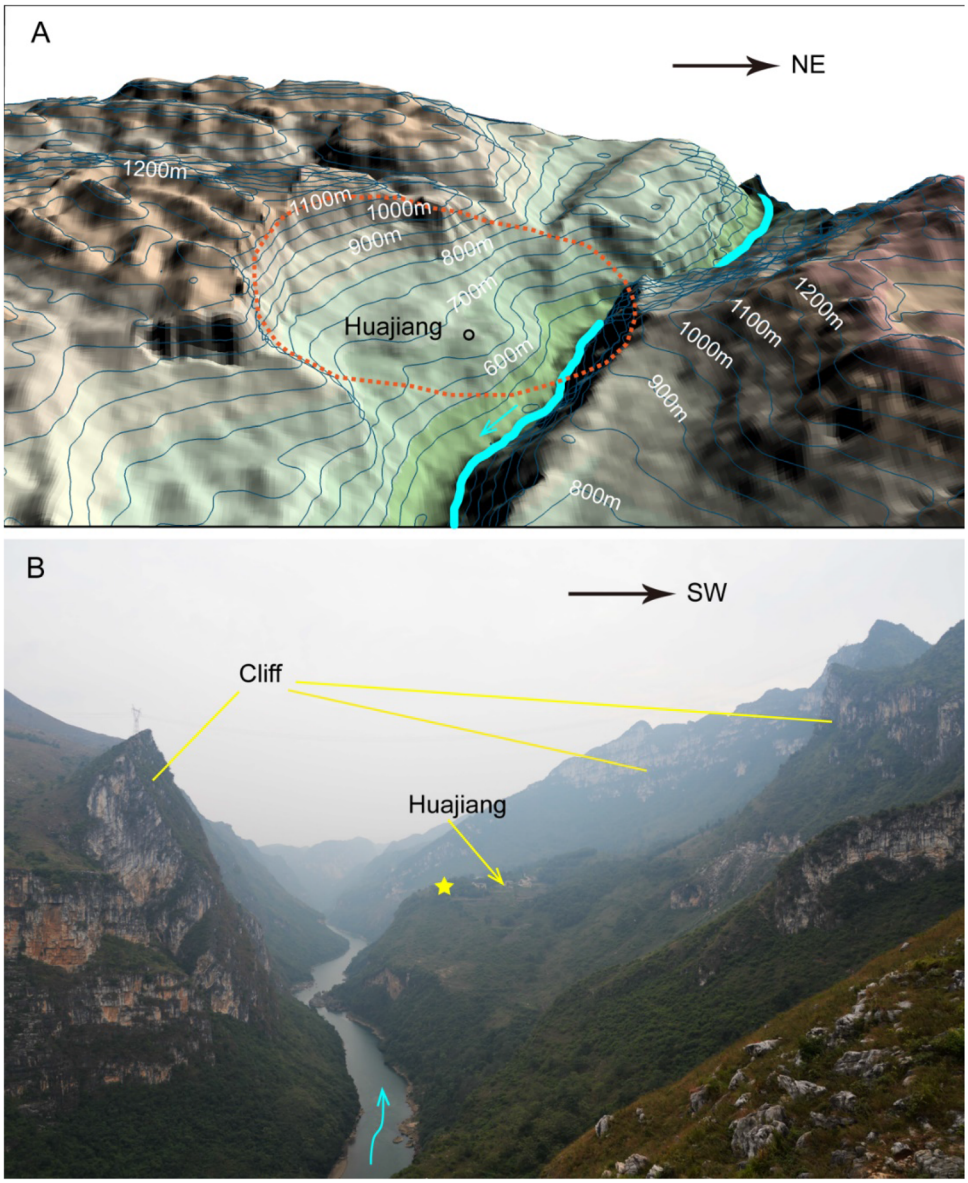

Fig. 2 **A** 3D topographic map of Huajiang Canyon. The orange dotted line indicates the shape of the original tiankeng. **B** Photo of the degraded Huajiang Tiankeng, looking southeast. The yellow lines point to the remaining cliffs from the collapse

could be observed in a slope section excavated during the construction of a road leading to Huajiang village. The breccias were well cemented and compact. Sample BHJT2 was collected beside the road (695 m a.s.l.) from a location 1.8 m below the top surface of the breccias. Sample BHJT4 was collected beside the road (780 m a.s.l.) from a location 3 m below the top of the profile. Sampling targeted locations potentially repaired after post-depositional weathering. Samples were detached from the original surface using a hammer and chisel. Thin sections of all breccia samples were prepared for petrographic investigation (Fig. 3f, g–i, j).

4 Methods

Petrographic thin sections were investigated using a Leica DM4500P polarizing microscope. Subsamples weighing approximately 50–100 mg were collected for U–Th dating by drilling along the growth layers using a dental hand drill. Dating was performed to attempt to establish the ages of the stalagmites and colluvium cementation to constrain the time(s) of the collapse event(s). When the bottom or top of a stalagmite was considered unsuitable for dating due to obvious clastic material in the laminae, samples of the closest clean and unaltered calcite were collected.

The uranium-series dating method is an effective dating method for determining geological age based on the disequilibrium between radionuclide ^{238}U and its decay daughters ^{234}U and ^{230}Th (Edwards et al. 1987). Using

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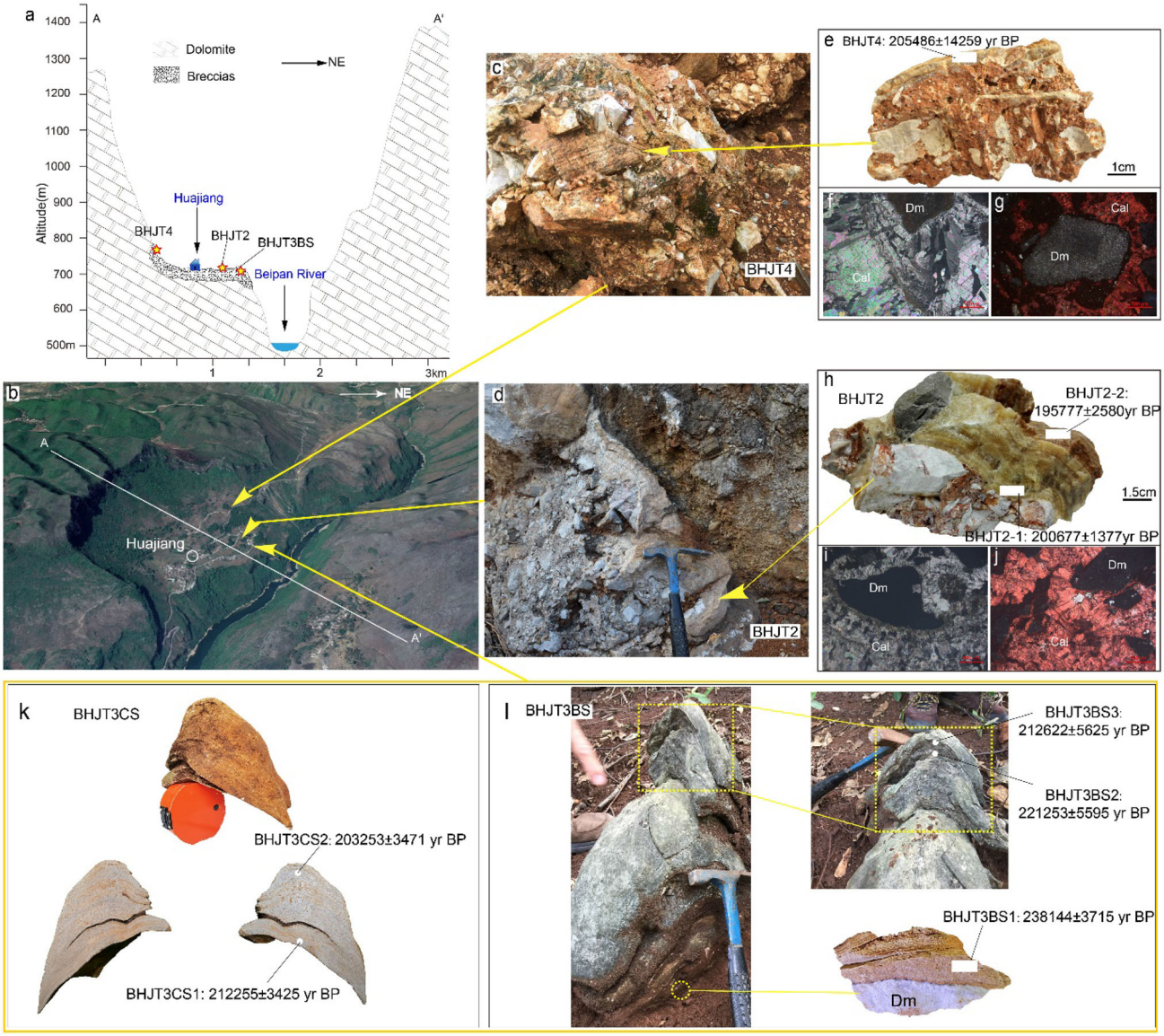

Fig. 3 **a** Huajiang Tiankeng profile. Its position is coincident with the dashed line (A–A') in Fig. 1E. The yellow stars indicate sampling locations. **b** Satellite image (from Google Earth) showing the degraded Huajiang Tiankeng. The yellow arrows indicate the sampling locations. **c** Karst breccias (BHJT4) deposited in the slope area at the edge of the Huajiang Tiankeng. **d** Karst breccias (BHJT2), deposited at the bottom of the Huajiang Tiankeng. **e** Hand specimen, BHJT4. **f–g** Microphotographs of BHJT4. **h** Hand specimen, BHJT2. **i–j** Microphotographs of BHJT2. **k** Stalagmite buried under the soil and its longitudinal section. Crack formation due to dissolution under the soil is visible in the longitudinal section of the stalagmite. **l** Stalagmites exposed on the Earth's surface and their ages (the stalagmites are grown on the dolomite bedrock, and samples for dating were collected from the bottom of the stalagmites). The locations of these residual stalagmites **k–l** are shown by yellow stars in Fig. 2B (Dm represents dolomite, and Cal represents calcite)

multicollector–inductively coupled plasma–mass spectrometry (MC–ICP–MS), the U–Th dating method provides a dating range from decades to 640 ka (Cheng, 2013). U–Th dating was performed at the Uranium Series Chronology Laboratory of the Institute of Geology and Geophysics at the Chinese Academy of Sciences in Beijing. Chemical treatment was performed following the Edwards method (Edwards et al. 1987; Wang et al. 2017). The subsamples were first dissolved in HNO_3, followed by the addition of a few drops of $HClO_4$. All samples were spiked with a ^{229}Th–^{233}U–^{236}U tracer (Chen et al. 1986; Shen et al. 2002; Cheng et al. 2013). The mixed solutions were placed on a 150 °C hot plate for 5–10 h and evaporated to dryness. Then, the samples were dissolved in 2 M HCl and transferred to clean centrifuge tubes. Approximately 10 mg of $FeCl_3$ was added and mixed, followed by a few drops of $NH_3{\cdot}H_2O$ to adjust the pH to 7–8. In this step, a slightly reddish-brown $Fe(OH)_3$ precipitate was formed, with

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simultaneous coprecipitation of U and Th from the mixed liquids. The precipitates were washed twice with ultrapure water, dissolved in 0.5 mL 7 M HNO_3, and dried again at 150 °C. Then, the samples were dissolved in 7 M HNO_3 and loaded onto 7 M HNO_3-conditioned anion-exchange columns. Trace metal elements were eluted with 7 M HNO_3, Th was eluted with 8 M HCl, and U was eluted with 0.1% HNO_3. The U and Th fractions were dried at 150 °C and dissolved in 2% HNO_3 + 0.1% HF. The U and Th recovery in this procedure was higher than 90%. The half-lives of ^{234}U and ^{230}Th were determined based on data proposed by Cheng et al. (2013). MC–ICP–MS was used to determine the ^{230}Th age of the eight samples. The details of the instrumental parameters were described by Wang et al. (2016).

5 Results

Petrographic investigations of two breccia hand specimens facilitated the discrimination of textures and fabrics in each sample (Fig. 3). All thin sections of breccia samples showed no traces of dissolution or redeposition and were thus considered suitable materials for U–Th dating.

The results of $^{230}Th/U$ dating are presented in Table 1. In general, the secondary calcium carbonate ages produced realistic radiometric ages, with samples possessing high ^{238}U contents and mostly high $^{230}Th/^{232}Th$ activity ratios. Although the ^{232}Th content in BHJT4 was high, which may have been caused by detrital contamination, the $^{230}Th/^{232}Th$ ratio was still greater than 20. Accordingly, the obtained ages have moderate to low uncertainties. For the breccia samples, the BHJT2-1 age was 200,677 ± 1377 a, the BHJT2-2 age was 19,577 ± 2580 a, and the BHJT4 age was 205,486 ± 14,259 a (Fig. 3e–h). The age of the bottom of the BHJT3BS stalagmite was 238,144 ± 3715 a, while the ages at the top were 221,253 ± 5595 a (BHJT3BS2) and 212,622 ± 5625 a (BHJT3BS3) (Fig. 3l). The ages of stalagmite BHJT3CS ranged from 212,255 ± 3425 a (BHJT3CS1) to 203,253 ± 3471 a (BHJT3CS2) (Fig. 3k).

6 Discussion

6.1 Age of the colluvium

When the underground river was at the elevation of the platform of Huajiang village, the river eroded the tunnel laterally, continuously expanding the underground cave chamber, which provided storage space for large-scale and possibly multiple collapses. Eventually, a large number of colluvial deposits accumulated at the bottom of the original underground river channel. Due to the loose structure of breccia, cementation can occur if infiltrating water is supersaturated concerning carbonate (Piccini et al. 2003). Thick secondary calcium carbonate deposits were formed in some fractures, and these deposits have laminae similar to cave flowstones (Fig. 3d-h). According to the dates provided, cementation was probably completed within a very short time after the collapse (approximately 200 ka). Because of case hardening, the interblock porosity of the breccia was reduced, significantly lowering the possibility of later dissolution (Ford and Williams 2007). Therefore, the secondary calcium carbonate deposits in the breccia fractures were probably not redeposited. The lack of redissolution/redeposition effects promoted a closed system for uranium, facilitating reliable U-series dating. The cementation time of the breccia represents the time of the collapse event. Stalagmites are products of caves; therefore, the ages of the stalagmites indicate when Huajiang Canyon was still in a cave environment. Karst areas in Southwest China generally lack sufficient surface sediments (Liu et al. 2013). Consequently, the evolutionary history of the Guizhou Plateau is not clear, which greatly restricts our understanding of the formation and evolutionary processes of the Guizhou karst landforms. This study attempted to overcome this limitation by determining the cementation age of karst breccia cement.

6.2 Causes of cave collapse in the Huajiang Grand Canyon

Geomorphological observations and the presence of extensive breccia deposits suggest the occurrence of a large-scale collapse in Huajiang Canyon related to previous subterranean karst drainage. The stability of caves is limited (Ford and Williams 2007), especially in areas characterized by rapid tectonic uplift. When the cavern in the study location was enlarged to a certain volume, it began to gradually collapse, exposing the underground features at the surface. Stalagmite BHJT3BS, which is currently at the surface, clearly supports this scenario. When the tiankeng first formed, it was likely ring-shaped. Its original morphology was eventually obliterated by additional collapses. At present, a residual vertical cliff remains on the western side of Huajiang gorge (Fig. 2).

Cave collapse in the Huajiang Grand Canyon was possibly triggered by a combination of the following tectonic and geological characteristics of the area:

- Rapid uplift of the Yunnan–Guizhou Plateau since the Cenozoic is related to the tectonics of the Qinghai–Tibetan Plateau, which has been in an overall uplift tectonic environment. This has caused ongoing base level deepening, which promotes the formation of

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Table 1 Radiometric (U–Th) ages of karst breccia samples from Huajiang Canyon

Sample	^{238}U (ppb)	^{232}Th (ppt)	$^{230}Th/^{232}Th$ (atomic × 10^{-6})	$\delta^{234}U$* (measured)	$^{230}Th/^{238}U$ (activity)	^{230}Th age (yr) (uncorrected)	^{230}Th age (yr) (corrected)	$\delta^{234}U_{initial}$** (corrected)	^{230}Th age (yr BP)*** (corrected)
BHJT2-1	565.7 ± 0.50	5154 ± 103	1540.3 ± 30.9	7.5 ± 1.5	0.8512 ± 0.0012	201,006 ± 1368	200,744 ± 1377	13 ± 3	200,677 ± 1377
BHJ T2-2	460.7 ± 0.40	51,026 ± 1022	128.2 ± 2.6	21.4 ± 1.5	0.8609 ± 0.0013	198,997 ± 1340	195,844 ± 2580	37 ± 3	195,777 ± 2580
BHJT4	80.7 ± 0.10	52,849 ± 1059	22.9 ± 0.5	34.2 ± 2.3	0.9108 ± 0.0024	225,156 ± 2786	205,554 ± 14,259	61 ± 5	205,486 ± 14,259
BHJT3BS1	347 ± 0.46	44,287 ± 888	118.9 ± 2.4	25.5 ± 1.8	0.9200 ± 0.0021	241,809 ± 2806	238,214 ± 3715	50 ± 4	238,144 ± 3715
BHJT3BS2	605 ± 1.00	147,354 ± 2954	61.0 ± 1.2	22.1 ± 2.1	0.9012 ± 0.0022	228,346 ± 2746	221,324 ± 5595	41 ± 4	221,253 ± 5595
BHJT3BS3	482 ± 1.00	117,894 ± 2362	60.0 ± 1.2	21.8 ± 1.8	0.8904 ± 0.0029	219,759 ± 2745	212,693 ± 5625	40 ± 3	212,622 ± 5625
BHJT3CS1	815 ± 1.00	115,960 ± 2324	102.5 ± 2.1	20.8 ± 1.5	0.8850 ± 0.0019	216,390 ± 1938	212,326 ± 3425	38 ± 3	212,255 ± 3425
BHJT3CS2	570 ± 1.00	83,500 ± 1674	97.9 ± 2.0	17.7 ± 1.7	0.8696 ± 0.0019	207,537 ± 1855	203,324 ± 3471	31 ± 3	203,253 ± 3471

*$\delta^{234}U = ([^{234}U/^{238}U]_{activity} - 1) \times 1000$. **$\delta^{234}U_{initial}$ was calculated based on the ^{230}Th age (T), i.e., $\delta^{234}U_{initial} = \delta^{234}U_{measured} \times e^{234 \times T}$. Corrected ^{230}Th ages assume an initial $^{230}Th/^{232}Th$ atomic ratio of $(4.4 \pm 2.2) \times 10^{-6}$. This value is for material at secular equilibrium, with a bulk earth $^{232}Th/^{238}U$ value of 3.8. The errors are arbitrarily assumed to be 50%. ***B.P. denotes "before present", where "present" is defined as the year 1950 A.D

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underground rivers (Sweeting 1995). The Huajiang Grand Canyon is located west of the Zhenfeng thrust fault. The western side is the hanging wall of the thrust fault, and its tectonic uplift significantly increases the river drop on both sides of the fault, resulting in accelerated river downcutting.

- From a geological perspective, the Huajiang Grand Canyon is carved into dolomite. In the past, the dissolution rate of dolomite was believed to be lower than that of limestone. However, a recent study on the chemical denudation rate of dolomite in the Shibing area of Guizhou Province showed that the dolomite chemical denudation rate is similar to or even higher than that of limestone under a similar climate (He et al. 2018). Importantly, dolomite is prone to collapse if a static equilibrium is compromised (Luo et al. 2019). Therefore, physical collapse is particularly important for the formation of dolomite caves. The platform around Huajiang village is characterized by abundant collapse breccia deposits, which suggest the occurrence of a large-scale collapse event. U-series dating analysis of breccia cement samples from different parts and altitudes in the tiankeng showed that the samples experienced approximately synchronous cementation. This implies that the collapse leading to the formation of the tiankeng was completed in one main event or at least within a short period. There are no younger large-scale colluvial deposits above the breccia, except for recent small-scale colluvial deposits found under the cliff at the Huajiang Tiankeng. Minor collapse processes may continue, but the collapse event that played a decisive role in the landscape of Huajiang gorge occurred ~ 200 ka. In addition, many ancient stalagmites were observed on the Huajiang platform (Fig. 3). As stalagmites do not occur at the surface, the development of the gorge can certainly be attributed to cave collapse.

6.3 Evolutionary processes of Huajiang Canyon

According to field observations during the geomorphological survey and based on chronological data, the development and evolutionary process of Huajiang Canyon can be divided into four stages as follows:

- During the Early Pleistocene, surface rivers flowed through wide valleys in the Huajiang gorge (Stage 1 in Fig. 4), and the karst system had not yet formed. Previous studies have also indicated the formation of wide valleys in the upper reaches during the early Pleistocene (Li 2001).
- Subsequently, due to the tectonic uplift of the western side of the Zhenfeng Fault, the Beipan River base level dropped, promoting underground excavation. The underground river channel likely continued to erode laterally, continuously expanding the tunnel and forming large caverns, which favoured the occurrence of collapse and provided storage space for the accumulation of colluvium (Stage 2 in Fig. 4). At this stage, stalagmites formed at the bottom of the newly formed caves (Fig. 4). These stalagmites stopped growing approximately 203 ka.
- The space in the underground cave continuously expanded, leading to one or more collapse events. According to the U-series dating of the cement, some collapses occurred ~ 200 ka BP. Subsequently, the underground rivers were exposed as surface rivers, and colluvium accumulated at the bottom of the tiankeng (Stage 3 in Fig. 4).
- After colluvial deposition, with continuous tectonic uplift, the river underwent rapid incision. From the bottom of the colluvium, at altitudes of 685 to 500 m (current height of the river), the incision depth reached 185 m, forming a deep canyon (Stage 4 in Fig. 4). Since 200 ka, the river incision rate has reached 0.92 m/ka. This result is close to the research result of the incision rate of the Nizhu River canyon in the upper reaches of the Beipan River (Fan et al. 2021). Crustal uplift is a necessary condition for the formation of deep canyons (Hu et al. 2016). Rapid downcutting of the Huajiang gorge by the Beipan River was mainly controlled by the activity of the Zhenfeng Fault, which was attributable to the acceleration of tectonic uplift on the western side of the Zhenfeng Fault.

7 Conclusion

In this study, the formation and evolutionary processes of Huajiang Grand Canyon were explored. Field surveys were conducted, and analyses of samples collected from Huajiang Canyon in the middle reaches of the Beipan River were performed. The main findings can be summarized as follows:

- A large number of collapsed breccias were preserved on the platform in the residual tiankeng of the Huajiang Grand Canyon on the Beipan River. U-series dating of two stalagmites found at the surface attested to the presence of an underground environment between 238 and 203 ka. In contrast, the ages of breccia cements revealed that a large-scale collapse event occurred in Huajiang Grand Canyon at least ~ 200 ka.
- Collapse is a very common geomorphic process in karst areas, especially under a tectonic background of integral uplift, such as that of the Yunnan–Guizhou

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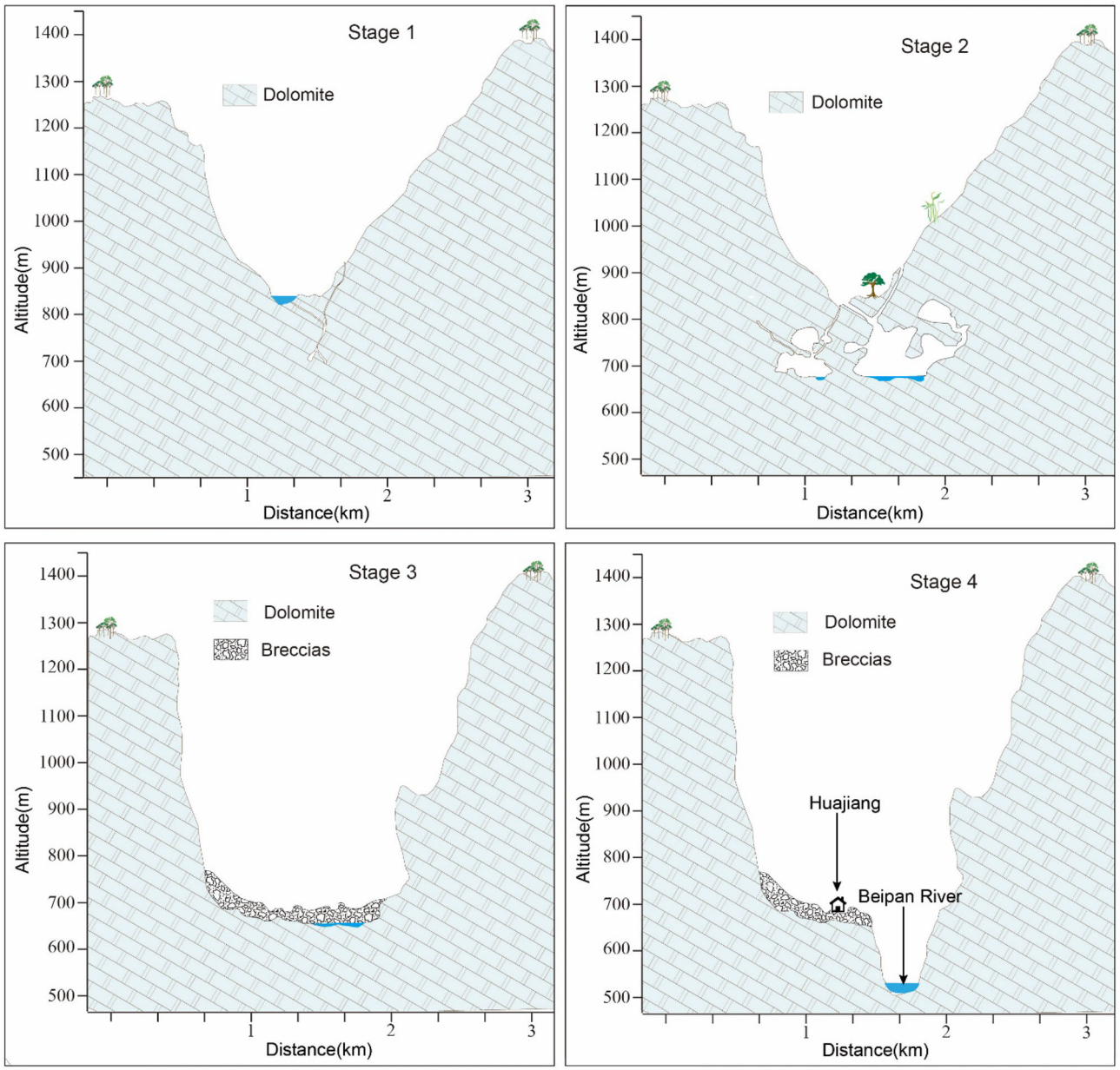

Fig. 4 Evolutionary model of Huajiang Canyon and the Beipan River

Plateau. Collapses frequently occur in karst underground caves and canyons. Many cave collapses lead to the formation of skylights and tiankengs, and continuous collapse leads to the formation of canyons. Therefore, the collapse process is a common and very important formation mechanism in the evolution of karst gorges.

- Collapse phenomena and associated colluvium are very common in karst areas, but their ages of occurrence are difficult to determine. By U-series chronology testing of collapse breccia cement, the time of collapse can be accurately determined. This approach, combined with analyses of cave-specific deposits such as stalagmites, may provide an effective means for studying canyon development and determining the ages of tiankeng formations in karst areas.

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Declaration

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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