

Late Miocene Elevated Horizontal Karst Caves and Landform Evolution as a Response to Tectonic Uplift along with Regional Integration of Fluvial Drainage in Southwestern China

Xiumin Zhai^{1, 2, 3, 4}, Xinggong Kong^{1, 3, 4}, Yuanhai Zhang², Philip John Rowsell²,
Zhijun Zhao^{1, 3, 4}, Baojian Huang², Jing Zhang^{*2}

1. School of Geography, Nanjing Normal University, Nanjing 210023, China

2. Institute of Karst Geology, CAGS/Key Laboratory of Karst Dynamics, MNR & GZAR, Guilin 541004, China

3. Jiangsu Center for Collaborative Innovation in Geographical Information Resource Development and Application, Nanjing 210023, China

4. Key Laboratory of Virtual Geographic Environment (Nanjing Normal University), Ministry of Education, Nanjing 210023, China

ABSTRACT: In Southwestern China, the development of karst landforms and planation surfaces is closely related to local tectonics, fluvial incision, and base level changes, and climate changes. However, researches on when these karst landforms and planation surfaces formed and how they evolved along drainage development are scarce. Fortunately, horizontal caves with numerous fluvial deposits in high karst mountains can be served as time markers in landform evolution. Here we select large horizontal caves to perform studies of geomorphology, sedimentology, and geochronology. Fieldwork revealed that more than 25 km long horizontal cave passages are perched 1 500 m higher than the local base level, but filled with several phases of fluvial sediments and breakdown slabs. The first phase of fluvial gravels and related cave drainage was dated back to 6.4 Ma using cosmogenic nuclide burial dating, and the stalagmite covering the cave collapse was dated by the U-Pb method to be older than 1.56 Ma. These results show that the continuous horizontal cave drainage system and the planation surface were developed before the Late Miocene. The lowering process of the base level as a result of the sharp fluvial incision and water level lowering, along with the regional uplift, led to the abandonment of the horizontal cave and the elevated planation surface at the Late Miocene. After that, the phase of cave collapse, thick fluvial sand, and clay sediments in the recharge of cave areas were deposited at around 1.6 Ma and during the Middle Pleistocene, respectively. Subsequently, speleothems were widely deposited on the collapse and clay sediments during the period from 600 to 90 ka, whereas the deposition of cave fluvial sediments terminated suddenly. The tectonic could control the denudation of surface caprocks and the development of karst conduits before the Late Miocene, whereas the river incision acted as the main driver for the base level lowering and the destruction of the horizontal cave drainage at high altitudes. In addition, the rapid incision and retreat of Silurian gorges finally caused the formation of karst mesas in the Middle Pleistocene.

KEY WORDS: karst, cave sediments, morphology, geochronology, speleogenesis, landform evolution.

0 INTRODUCTION

Horizontal cave passages correspond to periods of

*Corresponding author: zhangj_IKG@outlook.com

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base level stability in the fluvial system (Columbu et al., 2018; Harmand et al., 2017; Wagner et al., 2011). Thus, multiple cave levels of these kinds can be used to interpret the evolution of caves related to surrounding landforms (Calvet et al., 2015). When the karst terrane was uplifted, and surface rivers entrenched, the lowering of the base level induced the abandonment of cave conduits, resulting in the formation of a lower level during another period of stable water level (Columbu et al., 2015;

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Anthony and Granger, 2004). Therefore, it is widely accepted that the altitude of multiple cave levels can be used as a proxy for water table levels (Laureano et al., 2016; Calvet et al., 2015; Strasser et al., 2009). Consequently, cave levels are good markers to link palaeo-fluvial activities with landscape evolution (Ortega et al., 2013; Stock et al., 2005; Audra et al., 2001). Especially, subhorizontal caves acting as terraced landforms on high planation surfaces provide chronological and landform evidence (Calvet et al., 2015). Regionally elevated caves on the planation surface give specific clues to reconstruct the phases of incision and aggradation and indicate their links to regional tectonics, climate, and fluvial incision (Calvet et al., 2015; Columbu et al., 2015).

Endokarstic galleries in high mountains contain thick alluvial sedimentary sequences, which have the potential to record long-term fluvial entrenchment (Audra and Palmer, 2011). The dating of alluvium-filled sediments in horizontal epiphreatic passages can constrain the minimum age of cave conduits and infer the river incision (and thus mountain uplift) rates (Calvet et al., 2015; Granger et al., 2001). With the improvement of dating methods, evidence from cosmogenic nuclide burial dating of alluvium-filled caves can even date back to the Miocene (Harmand et al., 2017; Wagner et al., 2010). For instance, in the Pyrenees, ages of cave sediments in eight cave levels over a vertical altitude difference of 600 m, were used to reconstruct a more complete valley incision chronology over the last 5 Ma (Sartégou et al., 2018). In the eastern Alps, at least five distinguishable cave levels, which were well correlated with river terraces and planation surfaces, along with dating of cave sediments, provide evidence of bedrock incision processes over the last 4 Ma (Wagner et al., 2010). The U-Th dating of speleothems can yield the minimum age for cave passages or cave flood events (Columbu et al., 2015; Gázquez et al., 2014). In addition, with the development of U-Pb dating technology, stalagmites millions of years old can be accurately dated, providing a reliable minimum age for caves (Woodhead and Pickering, 2012; Woodhead et al., 2012, 2006). On the other hand, speleothem formation usually occurs in warm and humid environments and thus provides climatic information to analyze the role of climate on cave development processes (Columbu et al., 2018, 2017).

Southwest China, as one of the widest areas of karstified terrain, is characterized by underground drainage networks and surface features such as fenglin, fengcong, tiankeng, gorges, stone forest, and karst plateaus (Zhai et al., 2019). Low relief karst plateaus are distributed from the Three Gorges area to the southern margin of the Sichuan Basin and the Yunnan-Guizhou Plateau. They have been regarded as planation surfaces formed at low elevations and uplifted later, the highest one was named the Exi Surface (Li et al., 2001; Tian et al., 1996). Some places were dissected into isolated mesas by deeply incised canyons below the river knickpoints, along with the development of multi-level horizontal caves (Fig-

ure 1). The significant karst plateau surfaces, caves, and canyons are inscribed into the UNESCO World Natural Heritage List (Zhai et al., 2019). We hypothesize that, on one hand, the top surface is the current watershed in this region, and the timing of its formation and disintegration is related to tectonic uplift. On the other hand, its development process is also controlled by the development of large rivers (the Yangtze River) (Li et al., 2001). Dating geomorphological events of these erosional landscapes in karst areas is generally difficult and widely debated (De Waele et al., 2009; Li et al., 2001; Sasowsky, 1998). The timing of this planation has been estimated to range from the Early Cenozoic to the Late Cenozoic, although there is a lack of direct age evidence in the planation area (Yang et al., 2015; Kang et al., 2009). The diverse deposits including gravels, sands, and clays related to cave drainage, stalagmites and talus from the collapse of the cave provide good records to unlock the puzzles of stages and the timing of planation surfaces, the integration of the upstream and downstream of the Three Gorges, as the formation of the modern Yangtze River and thus base level changes (Wang et al., 2021; Zhang et al., 2021; Zheng et al., 2013; Li et al., 2001).

This work has carried out a detailed analysis of the morphology and sedimentary records from the large horizontal continuous caves to study the ages and the evolution of the karst landform, and related base level changes, thus the regional integration of the river system, and tectonic uplift. Especially, a chronological framework by different methods from diverse deposits in caves has been established, and with the related changes in the water table, the fluvial incision process and the abandonment of the karst planation surface are deduced.

1 GEOLOGIC SETTING AND KARST FEATURES

1.1 Geographical and Hydrological Settings

Jinfoshan Mountain is 2 238 m a.s.l. high, and is located near upstream of the Three Gorges, 70 km to the south bank of the Yangtze River (Figure 1). The topography of Jinfoshan Mountain is high in the north and low in the south and consists of the incised karst mesa at the top, two-levels of steep escarpments and deep canyons around. The heights of these platforms range from 1 800 to 2 200 and 1 200 to 1 600 m a.s.l., respectively, covering an area of 66 km². The higher escarpment that encloses this karst platform has an altitude between 1 600 and 2 000 m, 50 km long.

The studied area is dominated by a subtropical monsoon climate with an annual average precipitation of 1 396 mm (Zhai et al., 2019). Jinfoshan Mountain serves as a regional watershed, causing a small top catchment area and therefore relatively small karst springs discharge at the steep cliffs. In the southern part, due to the low terrain, surface water flow concentrates and larger karst springs and underground rivers are formed (Zhai et al., 2019). A radial drainage is developed around Jinfoshan Mountain, and the base level is near 600 m a.s.l., which relates to the second tributary of the Yangtze River

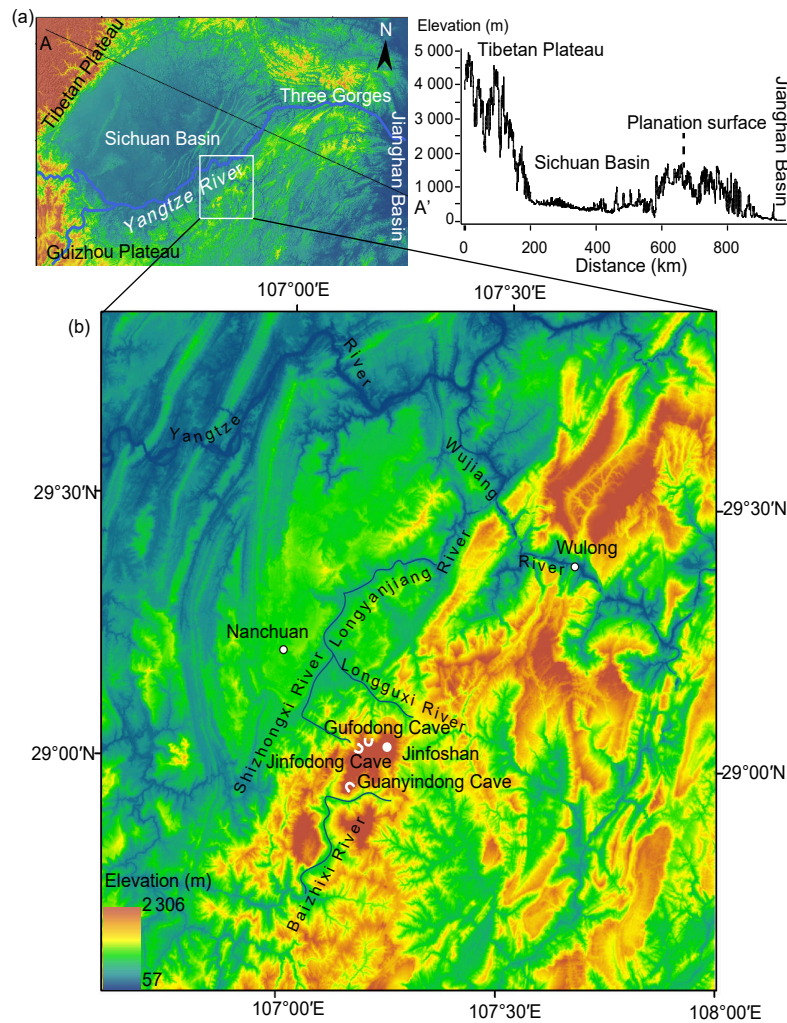


Figure 1. Overview of the study area. (a) Location of typical karst mesas in southwestern China; (b) relief and fluvial network of Jinfoshan and the distribution of the main studied caves.

channel (Figure 1).

1.2 Geologic Setting

The oldest rock of the Jinfoshan Mountain is mainly composed of the Cambrian limestone and dolomite, with a coverage of the Ordovician strata composed of limestone and dolomite (Figure 2) (Zhai et al., 2019; Zhang et al., 1998). Due to the absence of Carboniferous and Devonian strata, the Permian limestone unconformably overlies the Silurian shale and siltstone. Moreover, the most important subsurface karst conduits, more than 20 km long, were developed on the Middle and Lower Permian limestone (Zhang et al., 1998). Instead, the Upper Permian is claystone, with coal and shale interlayers. Thus, rocks of the Silurian and the Upper Permian as the aquitards compartmentalized the middle and lower thick limestone, which formed the sandwiched karst configuration and promoted the subsurface karst development (Figure 2).

At the end of the Latin Period of the Middle Triassic, the strong Indo-China Movement completely terminated the marine sedimentation and uplifted this area into land,

where it started suffering strong denudation. Thus, a few remnant outcrops of the Lower Triassic and the Upper Permian caprocks are preserved in small areas (Figure 2). The Yanshan Movement between the Early and Late Cretaceous folded the basement into mountains (including the Jinfoshan area), which contributed to the southeast boundary of the Sichuan Basin (He et al., 2011). The folded deformations in the thick Paleozoic marine sediments formed the Jinfoshan syncline, with a broad and generally dipping ca. 4° – 12° , anticlines on both sides and many groups of joint fissures. Later, possibly at the end of the Neogene, the Himalayas' Movement caused the continuous uplift, the denudation, and the formation of karst landforms in this area (Li et al., 2001).

1.3 Karst Landforms and Caves

The epikarst on Jinfoshan is the isolated ancient planation surface—the Exi Surface (around 2 000–2 200 m a. s.l.) with an undulating but broadly flat top that is often bordered by stepped escarpments (Figure S1a) (Li et al., 2001). On the surface, karst dome-depressions with a relative height of about 100 m, stone forests, and sinkholes

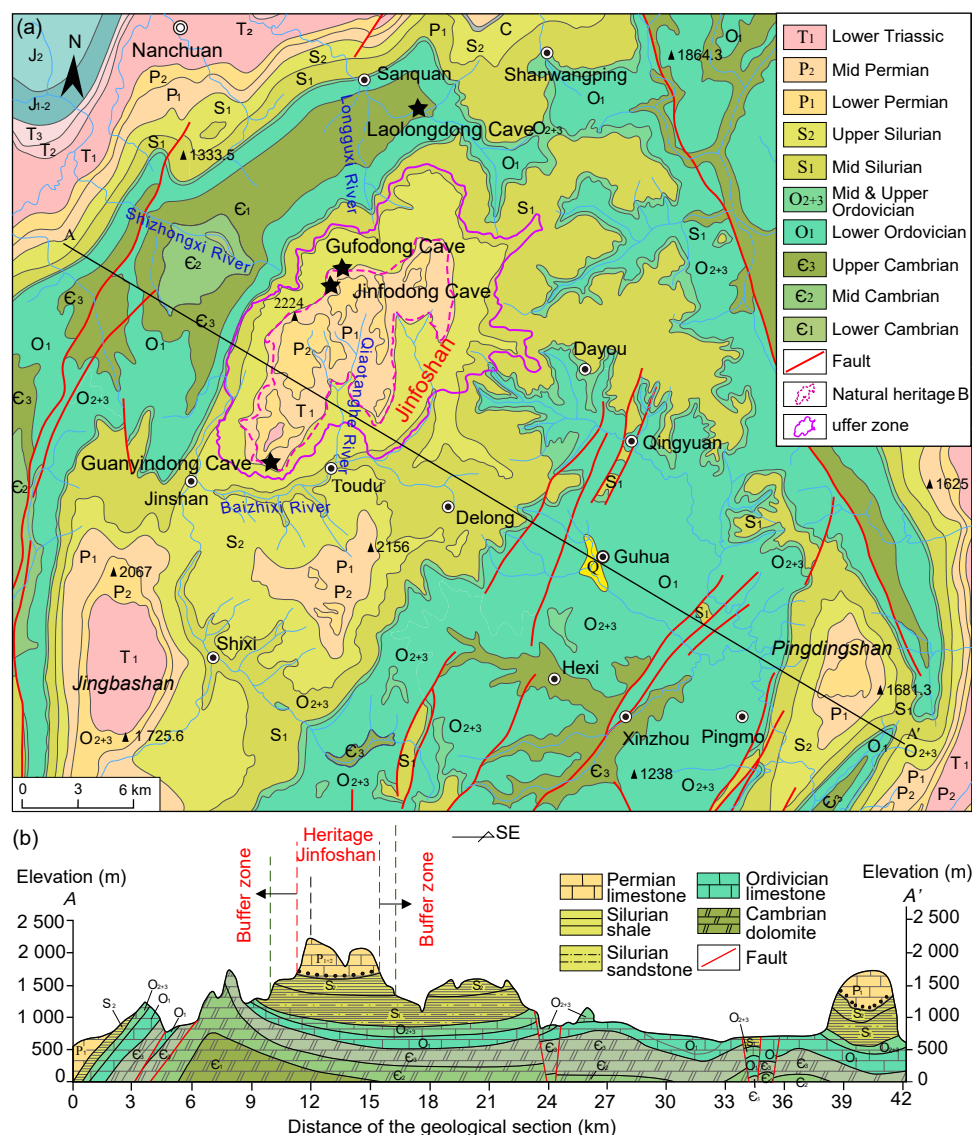


Figure 2. (a) Geological map of Jinfoshan area; (b) cross section showing the geological structure and stratigraphy of Jinfoshan.

are widely developed. Besides that, the endokarst of high altitude is characterized by large horizontal caves. Within an area of only 6 km², six caves about 100 m below the top surface of this mountain were surveyed for more than 20 km in total length (Zhang et al., 1998). All the caves are developed in the Permian limestone, including three large cave systems (Figure S1a): The Jinfodong-Yangzidong, Gufodong-Xiannüdong, and Lingguandong-Yanzidong (Table S1). Spatially, the Gufodong-Xiannüdong cave system is connected with the Lingguandong-Yanzidong cave system by a lower passage, whereas Jinfodong Cave was separated from Yanzidong Cave by one karst depression and the incised escarpment, with a distance of about 300 m. In addition, the Guanyindong Cave and Heidong Cave are two newly surveyed caves located in the southern area of Jinfoshan, and the entrance of Guanyindong Cave is exposed on the southern escarpment, alike the other caves (Figure S1b). The highest cave systems offer a series of geological records for understanding the evolution of the relict cave passages

and the lowering process of local base levels.

In addition, there are another two levels of cave entrances and passages at the lower elevation (600–800, 1 000–1 200 m a.s.l.), which together with the highest cave level constitute successive tiers over a vertical relief of ~1 500 m, from Laolongdong Cave at 598 m a.s.l. to Gufodong Cave at 2 100 m a.s.l. (Table S1).

2 METHODS

We undertook speleological and geomorphological analyses for each cave in the three levels (Table S1), and took geochronological studies in Jinfodong Cave because of its reasonable length and the presence of various mineral deposits, fluvial sediments, and morphological characteristics. However, cave sediments in the highest Gufodong Cave have been destroyed, only the cave morphology could provide some clues (Figure S1a). Besides, Lingguandong Cave and Yanzidong Cave lack materials for dating (Figure S1a). And Guanyindong Cave is located at the southern escarpment which requires 200

m long rope to enter, and thus prior studies only recorded cave morphologies and cave infill and distribution features (Figure S1b). Samples of cave fluvial sediments were derived with a shovel and a sample sieve, and samples of cave minerals were taken with a geological hammer.

2.1 Cave Geomorphology

The study also performed detailed surveys of four new caves ranging from 598 to 1 800 m a.s.l. and the re-measurement of Jinfodong Cave (Table S1). Caves were surveyed using a paperless technology. Basic data of cave polygons and wall contours are collected by a DistoX device and immediately transferred to a personal digital assistant (PDA: PalmOne T5 and Samsung Mobile Note 3) with the specialized Auriga and Topodroid cave survey software. While the data were displayed in the PDA, cave walls and important details of cave sediments were drawn separately. After the exploration trip in the caves, all data from the DistoX and PDA were downloaded to a PC and processed by the Compass software to draw cave maps. According to the coordinates of cave entrances, sketch maps of these caves were projected in ArcGIS software to study the cave distribution, geometry features, and spatial relationships.

Meanwhile, cave sediments and morphological features were considered within their spatial and stratigraphic relations, to attribute to a relative chronology (Columbu et al., 2018). To construct a robust chronological framework for this study, samples were collected from Jinfodong Cave. Two quartz samples from the cemented gravel section were collected for cosmogenic burial dating (Figure S2). Two sections K2 profile and K3 profile (Figure S2) under the cave floor were excavated to expose the original cave fills, and samples were dated by the electron-spin-resonance method (ESR). Another sample in the natural profile JF45 was also tested with the same method (Figure S2). Speleothems and flowstones were sampled from the surface of cave collapse, loose fluvial sediments, and mudslide sediments (Figure S2). All sampling locations are marked in Figure S2.

2.2 Dating Methods

2.2.1 ESR dating

Four samples from K2 and K3 profiles in the trunk passage were tested by ESR measurement (Figure S2) (Voinchet et al., 2010). The calculation of U, Th, and K contents was measured by the Analytical Laboratory, Beijing Research Institute of Uranium Geology. The artificial irradiation was finished by the Radiochemistry and Radiation Chemistry Key Laboratory of Fundamental Science, College of Chemistry and Molecular Engineering, Peking University. Samples were irradiated with doses of 0, 200, 400, 600, 800, 1 000, 1 200, 1 400, and 1 600 Gy, using a calibrated ^{60}Co source (Yin et al., 2011). Subsequently, the sample test was performed on a Bruker EMX spectrometer in the State Key Laboratory of Earthquake Dynamics, Institute of Geology, China Earthquake Adminis-

tration (Gao et al., 2011; Liu et al., 2011). Test work on the water content and result calculation was conducted by the Marine Geological Testing Center of Qingdao Institute of Marine Geology (Bahain et al., 2007; Ye et al., 2000). The ESR signal intensity was applied with the quartz E' center, with test method and pre-treatment process referred to Gao et al. (2011). Each aliquot was measured three times and averaged.

2.2.2 Cosmogenic burial dating

The gallery of Jinfodong Cave that was sampled for cosmogenic burial dating is overlain by more than 50 m of rocky material in all directions, deep enough to avoid significant post-burial production (Sartégou et al., 2018). The two quartz samples were weighed about 120 and 140 g, respectively. JF-C1 was measured by the AMS facility of Purdue Rare Isotope Measurement Laboratory (PRIME), Indiana (USA), and the JF-C2 sample was tested in the Xi'an Accelerator Mass Spectrometry Center (XAAMS), Shaanxi (China). Normalization was done with ^{10}Be standards documented in Nishiizumi et al. (2007) and ^{26}Al standards documented in Nishiizumi (2004). The burial ages of cave samples were calculated following the method of Granger and Muzikar (2001).

2.2.3 U-Th and U-Pb dating

Seven samples from stalagmites on the collapse and mudslide deposits were retrieved for dating by U/Th disequilibria method on alpha spectrometer (Figure S2) (Wang et al., 2012). These samples were subjected to chemical separation and purification following the procedure described by Tang et al. (2018). Three samples of the flowstones on the loose sediments were also tested using the same method. Based on the inferred antiquity of stalagmites from the weathering surface, three stalagmites on the collapse were taken for U-Th dating using MC-ICP-MS neptune (Figure S3). The $^{230}\text{Th}/\text{U}$ dating method is based on the disequilibrium of radioactive decay series with nuclides of ^{238}U , ^{234}U and ^{230}Th (Shao et al., 2019). Samples were chemically pretreated following the processing method of Shao et al. (2017) at the isotope laboratory of Nanjing Normal University. The stalagmite in Jinfo Chamber was dated using ICP-MS U-Pb analysis by the University of Melbourne (Figure S3) (Woodhead et al., 2012). The raw U/Pb age data have been corrected for the effects of initial disequilibrium in the U-series decay chain (Figure S4) (Woodhead et al., 2006). All samples are characterized by high U content, which provides good conditions for accurate dating.

3 RESULTS

3.1 Cave Morphology

The main entrance (2 080 m a.s.l.) of Jinfodong Cave is located 200 m away from the western escarpment of Jinfoshan (Figure S1a). It has a total passage length of 11 630 m, with two major directions, that is, the trunk passage mainly striking in NE and the branch passages mainly striking in SE (Figures S5a, S5b). The most

typical feature of the cave passages is the wide trunk passage, associated with lower maze-like branch passages (Figures S2, S6a, S6c). The trunk conduit ranges from 30 to 50 m in width, with the widest part 122 m, and the height ranges from 15 to 20 m, with the highest part 40 m (Figure S6a). The ends of the trunk passage were filled with mudslide deposits (Figure S6d). The entire cave floor has a very low inclination less than 10° . It is also higher in the northeast and lower in the southwest, resulting in the development of small streams in the southeast passages with relatively lower cave altitudes (Figures S2, S5). The trunk passage with a flat cave roof, shows typical vadose features, but phreatic features are extremely rare, which could be caused by the bedrock collapse of the cave roof (Figures S6a, S6b).

Conversely, the branch passages are only several meters wide, even narrower than 1 m in width (Figure S6c). The narrower branch passages are composed of more phreatic features and the transition evidence from phreatic zone to vadose zone with keyhole form (Figure S6c). Moreover, phreatic tubes, ceiling meanders, pendants, and scallops are well developed in the branch passages (Figures S6c, S6e). Widely developed cylindrical shafts provide the connection tunnels for the main passage to the lower level passages and range from 30 to 100 m in depth (Figure S2). Whereas well developed avens in the cave roof of Jinfodong Cave formed in the vadose zone have become the modern water supply channels. The largest aven is the cave entrance of Jinfodong Cave which is 83 m long and 70 m deep (Figure S6f).

3.2 Sediment Sequence and Sampling Profiles

Cave passages are filled with fluvial deposits and breakdown, while speleothems are relatively rare but cover them (Figure S6a). Almost the cave floor is covered by thick alluvial sediments (clays and fine sands), with a thickness of about 1–8 m or even up to the cave roof in some branch passages, and the clay sediments in the trunk passage are overlain by the flowstones (Figure S7). In addition, the youngest mudslide filling is also presented at the ends of the trunk passage (Figure S7a), which also appeared in Gufodong Cave and Guanyindong Cave.

Two profiles under the trunk passage floor were excavated for ESR samples. Sampling profile K2 is located in the northern section of the main passage of Jinfodong Cave, and is composed of 2.8 m thickness of fluvial deposits below the cave floor and 5 cm thickness of residual flowstones suspending 40 cm above the cave floor (Figure 3a). This profile is the underground fluvial alluvium, composed of a set of silty clay and sand, and interspersed with gravels which consist of limestone, chert and sandstone. Profile K3 is located near K2, with a total thickness of 6 m (Figure 3b). It consists of 1.5 m of loose deposit above the cave floor, and then 4.5 m of fluvial sediments, with numerous thick flowstones on and in the fluvial sediments. The fluvial deposits are dominated by silt-clay or clay with horizontal lamination and inter-

persed with rock debris, mainly limestone and siltstone gravels (Figure S7b).

However, the fluvial gravel deposits (loose gravel and cemented gravel) are scarce, and only two sections were preserved by the protection of collapse stone, some of which has been cemented (Figure S7e). JF45 profile is near the intersection of the trunk passage and a branch passage in the southeast (Figure S2). It consists of a set of semi-cemented gravel layers with thin clay and mud-bearing sand layer (Figures S7d, 3c). The visible length of the residual profile is about 3 m, with a thickness of 2.9 m. The upper part and sides of the profile are covered by clay layers up to 11 m thick, with the lower part of the profile wedged by multi-phase sand and gravel layers (Figures S7d, 3c).

Cemented fluvial deposits are preserved only in the largest branch passage of Jinfodong Cave, 100 m away from the main cave (Figure S2). The total section covered by breakdown sediments is about 10 m in length, and the total thickness is 3.3 m (Figure 4). It consists of two different materials one is the cemented conglomerate, including sandstone and limestone gravels with fine sand, and the other is the loose fine sand and clay deposited between layers of the cemented conglomerate (Figure 4).

From the spatial relationship, the loose gravel deposits have been covered by 10 m thick clay deposits (Figure S10). Otherwise, the rockfall is generally widespread and with large volumes more than hundreds of meters long and 10 m high (Figure S7g). Although the depositional relationship between large collapse and thick clay sediments is not clear in Gufodong Cave and Jinfodong Cave, the clay deposits about 3.8 m thick cover the large collapse in Yanzidong Cave (Figure S7i). Moreover, the cave chemical deposits on the collapse and the mudslide are only preserved in relative limited area, which provide the upper limit of collapse and mudslide events. Several large stalagmites and stone column were deposited on the main cave floor and are up to 13 m high and 3 m in diameter (Figure S7g). Instead, stalagmites deposited on the collapse and the mudslide are relatively small, most of which are lower than 1 m (Figure S7a). Therefore, a relatively clear deposit sequence from older to younger can be determined as follows: (1) cemented gravel layer, (2) large collapse, (3) loose gravels, (4) thick fluvial clay sediments, (5) flowstones/small collapse, (6) mudslide deposits, and (7) small stalagmite.

3.3 Cave Chronology

3.3.1 Ages of loose fluvial sediments

The sand and clay deposits in K2 profile yielded two ages of 668 ± 87 ka (K2-ESR-1) and 715 ± 129 ka (K2-ESR-2), and K3 profile provided an age of 600 ± 102 ka (K3-ESR-1). The pebble beds in JF45 profile provided an age of 786 ± 118 ka (Figure 3, Table 1). It is, therefore, more likely that the high energy gravel sediments were deposited first and that lower energy fluvial sedimentation occurred 100 ka later, which was proved by the sedi-

ment sequence (Figure S7d).

3.3.2 Ages of cemented gravel sediments

Two quartz samples were collected from the cemented profile for burial dating. ^{10}Be concentration, ^{26}Al concentration, and ^{27}Al concentration in quartz (measured via ICP) are shown in Table 2. Based on the burial age dating methodology laid out in Granger and Muzikar (2001), the concentrations result in a burial age of 6.40 Ma for sample JF-C1 from the cemented layer, with 1σ probability confidence interval of (5.47 Ma; 8.13 Ma). The other age is 3.64 Ma for JF-C2 from the loose sand layer, with 1σ probability confidence interval (3.03 Ma; 4.51 Ma) (Figure 4, Table 2). The constants assumed for these calculations are ^{26}Al mean life = 1.02 Ma, and ^{10}Be mean life = 2.005 Ma (Chmeleff et al., 2010; Nishiizumi, 2004). The burial age of sample JF-1 is beyond the upper limit of $^{10}\text{Be}/^{26}\text{Al}$ burial dating, and thus the cave is older than 5 Ma. The inconsistency of the two ages may be caused by different sediment stages.

3.3.3 Ages of cave minerals

Eight samples of the flowstones and the stalagmites on the collapse and loose sediments provided ages beyond 380 ka using alpha spectrometry test (Table S2). Only two samples on the mudslide sediment yielded two ages of 96.6 ± 9.2 and 90.2 ± 6.6 ka, respectively (Table S2). Seven samples from three stalagmites on the collapse were collected for U-Th dating to confirm the ancient process of the collapse event (Table S2). Five of them on the large collapse yielded ages beyond 500 ka. These results have large dating errors because they are older or near the U-Th dating limit (Cheng et al., 2016). To constrain the minimum age of the collapse event, we used the U-Pb method to date the giant stalagmite on the large collapse. A linear regression with its associated 2σ uncertainty envelope is also shown passing through the individual blank corrected U-Pb analyses (Woodhead et al., 2006). The calculated age is derived simply from the intersection of the two ratios of elements (Figure S4). Based on an estimate of the initial $^{234}\text{U}/^{238}\text{U}$ (1.064 ± 0.24

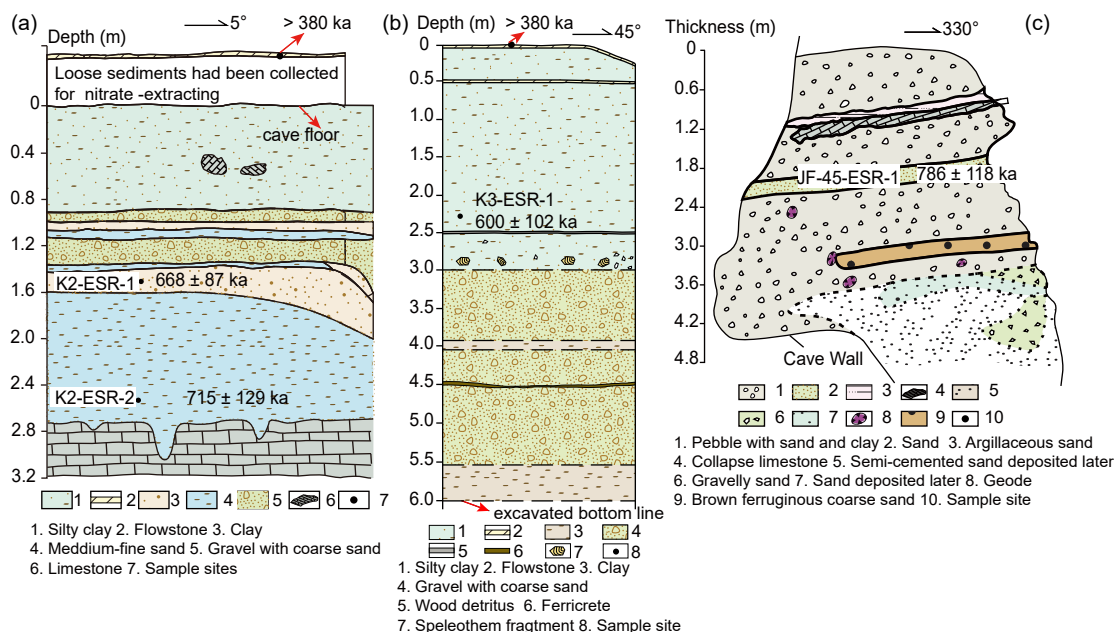


Figure 3. Map of the loose fluvial deposit sections showing the sediment types and the ESR Dating results in them. (a) K2 profile deposit sequence and dating results; (b) K3 profile deposit sequence and dating results; (c) JF-45 profile deposit sequence and dating results.

Table 1 ESR Dating Results of samples in Jinfodong Cave

No.	U (ppm)	Th (ppm)	K ₂ O (%)	Water content (%)	De(Gy)	Age (ka)
K2-ESR-1	10.8	11.9	0.47	14.8	2 459.12 ± 319.69	668.46 ± 86.9
K2-ESR-2	6.78	13.2	0.53	15.1	2 060.24 ± 370.84	715.469 ± 128.78
JF-45-ESR-1	4.81	10.1	1.20	9.26	2 264.7 ± 339.71	786.089 ± 117.9
K3-ESR-1	10.4	10.8	1.48	7.28	2 762.83 ± 469.54	600.39 ± 102.07

Table 2 Cosmogenic nuclides $^{26}\text{Al}/^{10}\text{Be}$ dating results of Jinfodong Cave

No.	Coordinates	Elevation (m)	Mass (g)	^{27}Al concentration (ppm)	^{10}Be concentration (10^3 atoms/g)	^{26}Al concentration (10^3 atoms/g)	$^{26}\text{Al}/^{10}\text{Be}$	Buried age (Ma)
JF-C1	107.17°E,	2 080	139.68	42.2	8.44 ± 0.59	2.60 ± 1.46	0.308 ± 0.174	$6.40 \pm 1.73, -0.93$
JF-C2	29.01°N		120.23	40.0	6.40 ± 0.54	7.48 ± 2.49	1.169 ± 0.401	$3.64 \pm 0.87, -0.61$

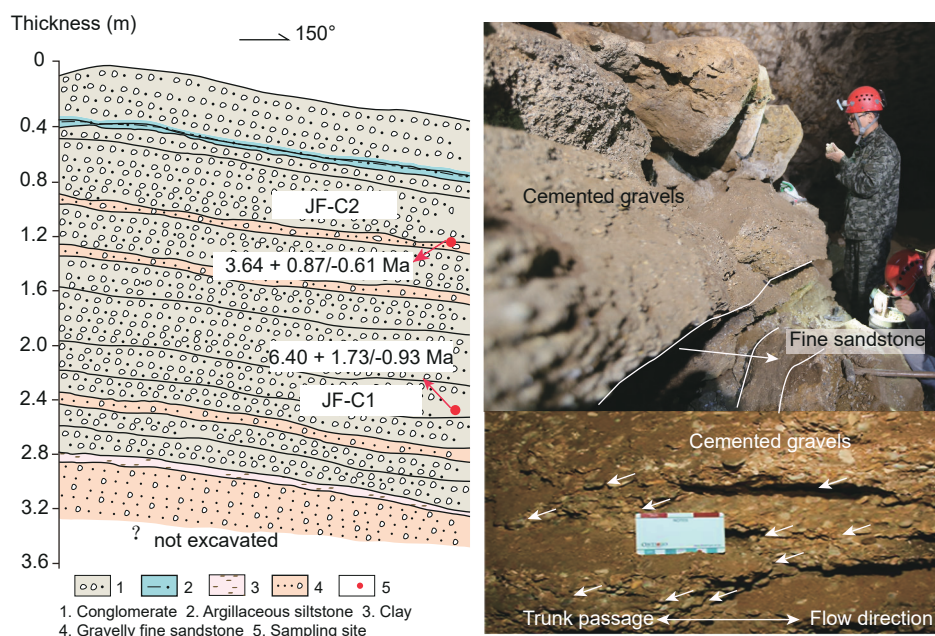


Figure 4. Map of the cemented fluvial deposit section showing the sediment types and the cosmogenic nuclides $^{26}\text{Al}/^{10}\text{Be}$ dating results in it.

for this), we obtained a corrected U/Pb age of 1.56 ± 0.10 Ma. The other two samples on the small collapse, however, yielded ages from 163.46 ± 0.72 to 198.68 ± 1.09 ka (Table S2).

4 DISCUSSION

4.1 Speleogenesis

4.1.1 Phase 1: main horizontal cave level development prior to the Late Miocene

Due to the cave development process, the formation of cave conduits predated the cave deposition (Wagner et al., 2010). Thus, it is likely that this Late Miocene Age only provides the minimum age of the cave passage. The largest branch passage, in which the oldest deposit was emplaced, is lower than the main cave floor (Figure S8). Moreover, the imbricate structure of these sediments also shows that they were transported from the main passage (Figure 4). Because the volume of the relic cemented profile more than 10 m long and 3 m thick, it indicates that not only the trunk passage but also the branch passages reached a large size when these gravels deposited (Figure 4). Therefore, the development history of these caves and karst landform here, can be traced back to the Miocene or even earlier.

Inferred from the development relationship between the surface caprock and the underground cave systems, the denudation of non-carbonate rocks on the surface as the prerequisite of cave development must therefore have occurred before the Late Miocene (Figure S8). With the denudation of clastic caprocks, surface streams started to dissolve rocks along the fissures from sinkholes and phreatic conduits began to develop (Figure S9a). With the expansions of the karst fractures, the scattered cave conduits were finally connected into a unified passage. The huge underground stream correlating to the water table gradually enlarged the cave passages and

large amounts of fluvial sediments were transported into caves and then deposited (Figure S9b).

4.1.2 Phase 2: cave collapse prior to 1.56 Ma

Combined with the deposit sequence of the giant stalagmite and the breakslaps, the U-Pb age of the giant stalagmite provides us with a minimum age of the collapse event before 1.56 Ma (Figure S7g). Moreover, U-Th ages of small stalagmites on large collapse also confirmed this event before 500 ka (Table S2). When caves developed into a relatively large volume, the bedrock on the cave roof collapsed due to the loss of supporting stress (Figure S9c). Inferred from the detailed cave survey, this large collapse event provided abundant breakslaps occurring in more than half of the cave floor. Also, it has shaped the cave morphology and destroyed some phreatic features formed in earlier stages. Meanwhile, the large collapse event as the common feature in the top-most caves was more likely caused by the same forcing drivers, such as tectonic movement and water table lowering as a result of river incision (e.g., the Yangtze River) (Deng et al., 2015). Thus, we infer that the tectonic movement may have induced the fractures between the beddings, and the unsaturated water from the upper coal layer dissolved the soft bedding and caused this common large collapse event, along with fluvial incision and water table lowering.

4.1.3 Phase 3: cave infilled with thick clay sediments

Based on the stratigraphical features and ESR ages of K2 and K3 profiles, these sand and clay deposits were filled into the caves in a relatively short time by some extreme climatic event in the Middle Pleistocene (Figure S9d). Reddish clay and gravels on cave roof show that the fluvial sediments filled the whole cave passages not

only in the trunk passage but also in the branch passages (Figure S10). This deposit feature also occurred in Guanyindong Cave at the south region of Jinfoshan Plateau. These large-scale fluvial clay sediments indicate that the outer areas of this present karst platform have a large catchment area and the surrounding Lower Silurian canyons were not formed yet (Figure 2). Thus, large numbers of clastic deposits can be transported into caves. Previous study has confirmed that the formation of 1 m thick weathering crust requires about 627 m thick pure limestone for providing original materials (Wei et al., 1983). Therefore, we inferred that these thick fluvial sediments should be denudated from the non-carbonate strata, most probably the Silurian strata in the anticline area which can provide a large amount of materials (Figure S10). Cave dissolution morphologies also provide information about sedimentology and paleocurrent. Ceiling meanders were typically developed on the branch passages of Jinfodong Cave, indicating that the cave was in the phreatic zone (Calvet et al., 2015; Calaforra and De Waele, 2011; Stock et al., 2005; Zhu, 1982). It was formed when the whole cave was filled with clastic sediments, illustrating that there was no space for cave streams to flow and it started to dissolve the roof of Jinfodong Cave, which is similar to paragenesis (Figure S6e) (Farrant and Smart, 2011). These features may show that a large amount of clastic materials eroded from the non-carbonate strata was transported into caves.

4.1.4 Phase 4: cave mineral deposited and main cave fossilized

U-Th ages of stalagmites on the large collapse and flowstones on the loose clay deposit proved that several wet periods in the Jinfoshan area, also provide the upper limit of these events. The small collapse stones on clay and gravel sediments proved that it happened after the deposition of loose sediments (Figure S6d). Based on the deposit sequence when small collapse and stalactite deposition occurred in the cave, the clay deposition ceased (Figure S9e). Two U-Th ages of the stalagmite on the small collapse stone suggested that the stalagmite is older than 198.68 ± 1.09 ka (Table S2). Therefore, based on the overlapped relationship between the loose sediments and the stalagmite, the small collapse event occurred between 199 and 600 ka. Moreover, the mudslides on both ends of Jinfodong Cave caused its fossilization due to the loss of its hydrological energy. Results of two stalagmites on the mudslide sediments supported that the mudslide event happened before 90 ka and that Jinfodong Cave had completely evolved into the fossil cave stage before 96.6 ka (Table S2).

4.2 Morphology and Its Geomorphological Significance for Water Table Lowering and Planation Surface

Alluvium-filled horizontal passages in limestone karstic networks are associated with ancient water table (Sartégou et al., 2018; Rossi et al., 2016; Calvet et al.,

2015). The large size of horizontal conduits may be related to allogenic recharge and relatively long-term base level stability (Figure S1). According to the limited present-day outcrop area of the carbonates, the small area of autogenic recharge cannot account for the formation of such large horizontal cave systems (Rossi et al., 2016). Based on the spatial distribution of Jinfodong Cave and Yanzidong Cave, they are likely to be the same cave system, but were separated by the escarpment retreat (Figure S1). Thus, the allogenic paleocurrents should have a large catchment area and this isolated planation that was enclosed by escarpments at Jinfoshan has not been developed yet when the large horizontal passages were formed. Therefore, changes in cave morphologies from large horizontal passages to meander branch passages and lower conduits indicate that the hydrological dynamics have altered from a large amount of allogenic supply to the limited autogenic recharge (Figure S2).

The top cave level located at 2 100 m a.s.l. has been abandoned by base level lowering, which was likely caused by the uplift and/or valley incision (De Waele et al., 2009). When rivers entrench, renewed cave formation occurs very rapidly, resulting in the formation of a lower level (Columbu et al., 2015). Therefore, three cave levels ranging over a vertical relief of ~1 500 m also confirmed that the regional base level in Jinfoshan area has periodic decline and stability (Figure S11). Based on the development process of large horizontal cave systems, the cave level corresponded to the location of the valley floor (Figure 5) (Audra and Palmer, 2011). It follows that the elevated cave level preserved on the erosion surface—such as the Exi Surface, was not shaped at high elevations (Li et al., 2001). They were formed, instead, close to the base level and then uplifted in successive stages by tectonic processes or river incisions (Calvet et al., 2015; Clark et al., 2005). The topmost horizontal cave level recorded the history when the base level was in lowland, but the abandonment of this cave level was probably triggered by the uplift and the subsequent river incision (Figure 5).

4.3 Periods of Cave Incision and Aggradation and the Causes

The development of a karst system especially the cave system can be frozen and then rejuvenated several times. When new energy is added into the cave system, it may trigger the reactivation of cave enlargement and deposits. Instead, these fossilization processes can be caused due to the loss of its hydrological energy. Thus, the periods of cave clastic deposition, erosion, and speleothem formation provide valuable information for karst landform evolution and paleo-environment changes (De Waele et al., 2009). The cemented gravels, sub-cemented gravels, clay, and sand, or even the mudslide sediments indicate the cave hydrodynamics has changed. Based on the cave deposition and dating results, the cave infill was not a steady process and recorded periods of aggradation and river erosion since 6.4 Ma.

The causes of river incision and aggradation are composed of tectonic, base level-related, and climatic forcing signals (Calvet et al., 2015; Columbu et al., 2015). Kirby et al. (2002) argued that the initiation of major river incisions began between 12 and 5 Ma, coinciding with the development of high topography in the region southeast of the Tibetan Plateau near the Sichuan Basin. The uplift of the eastern Tibetan likely intensified precipitation in the area. Consequently, the combined effects of increased elevation and enhanced precipitation contributed to higher river incision rates (Zheng, 2015; Clark et al., 2004). Moreover, thermo-chronologic results indicate that the onset of karstification on highlands began at 19 Ma (Cui et al., 1996). Thus, karst landform evolution along the Sichuan Basin was probably affected by the combined effect of tectonic uplift and intensive monsoon, which influenced the denudation of the top caprocks and accelerated the development of cave passages (Figure S9) (An et al., 2005, 2001; Clark et al., 2005). Based on the multi-stage structural evolution of Daloushan Mountain system (including Jinfoshan Mountain), the third phase of NE-SW deformation during the Late Paleogene (40–20 Ma) may induce the NE-SW faults and fractures (Deng et al., 2015). Thus, the large horizontal caves were more likely formed under these geological conditions but after the tectonic event. With the influence of tectonic uplift, regional rapid river incision began before 10 Ma, but later than 15 Ma (Ouimet et al., 2010). Other studies also give clues that the surface uplift was prior to the river incision (McPhillips et al., 2016; Clark et al., 2005). Based on these uplift and river incision records, the large horizontal cave systems are more likely to develop before the rapid river incision around 10 Ma but later than the deformation period during 40–20 Ma (Deng et al., 2015). Subsequently, the fourth phase of NW-SE uplift and the erosion event here in the Late Miocene (10–5 Ma), may force the formation of the surface valley in the NW-SE direction (Figure S8). Therefore, the headward erosion of southern valleys probably caused the development of lower branch passages following the new base level (Figure S12) (Deng et al., 2015).

Thus, the cave sediment should only provide the minimum age when the planation surface and caves were entrenched by river incision, which was probably caused by uplift movement (Ouimet et al., 2010). When caves lose energy by river entrenchment, some detrital sediments were gradually emplaced in the caves since the Late Miocene. Subsequently, with the reactivity of the cave, the sediments were eroded and new cave levels were formed near the newly developed base level in the relatively stable geological condition (Figure 5).

ESR dating results proved that large numbers of fluvial sediments were transported into caves from 786 to 600 ka. The intensified denudation process of clastic caprocks and river erosion may recharge the previously formed sediments. Based on U-Th ages, there was a wet period from 600 to 380 ka that allowed the growth of stalactites and the deposition of flowstones in Jinfodong Cave. This

period corresponds to the wet period when the most typical paleosol S5 was developed in the Loess Plateau during 600–468 ka (Hao et al., 2012; Ding and Liu, 1991). Although large amounts of speleothem were deposited during this wet period, the deposition of thick fluvial sediments suddenly ceased. This opposite sedimentary evidence infers the disintegration of the catchment basin and the formation of the isolated karst platform during 600 to 380 ka. Because Jinfoshan is only 70 km away from the Yangtze River, its regional water system is controlled by the Yangtze River datum (Figure 5). Reviewing the results of different studies on the down cutting process of the Three Gorges, our results are more consistent with the younger cutting-through time of the Three Gorges cut through timing (Zhang et al., 2021; Richardson et al., 2010; Xiang et al., 2007). The fluvial sediments in the downstream basin of the Yangtze River and terraces on the upstream and downstream of the Three Gorges area support the theory that the integration of the Yangtze River could be in the Middle Pleistocene, rather than the pre-Miocene (Zhang et al., 2021; Xiang et al., 2007). Inferred from the rapid lowering of cave levels associated with local base levels, it is proposed that the formation of the dissection of the karst highland and the changes of cave morphology and sediments are the response to the formation of the Three Gorges (Sun et al., 2021; Zhang et al., 2021). The regional base level adjustment caused the headward capture and rapid retreat of Silurian canyons, accelerating the denudation of Silurian strata (Figure S12). Ultimately, it resulted in the limestone strata in syncline area being higher than the surrounding clastic area, and thus Jinfoshan became the isolated karst platform separated from the regional karst plateau (Figure 5).

5 CONCLUSIONS

Based on cave morphology, sedimentology and geochronology, the geomorphologic evolution and speleogenesis of the top cave level have been reconstructed. Common features of large cave passages, thick fluvial sediments and huge collapse on the karst planations of Southwestern China, provide important evidence to illustrate the forcing mechanism of tectonic, climate and hydrosystem adjustment.

The leveled karst cave and sediments, and cave geochronology preserved on the highest planation reconstructed the karst landform evolution process from prior of 6.4 Ma (most probably around 10 Ma) to 90 ka. Cosmogenic burial ages of quartz samples indicate that formation of caves and karst landform preserved on the first planation is before the Late Miocene. The coupling dynamics of climate and tectonic forcing by the Tibetan Plateau's uplift in the Early Miocene, has influenced the denudation of the top caprocks and accelerated the development of large horizontal passages following the main faults. The rapid uplift of Daloushan Mountain could trigger the intensive river incision and create a new base level. Thus, the obvious decrease of hydrological energy and river headward erosion along the NW-SE fractures fi-

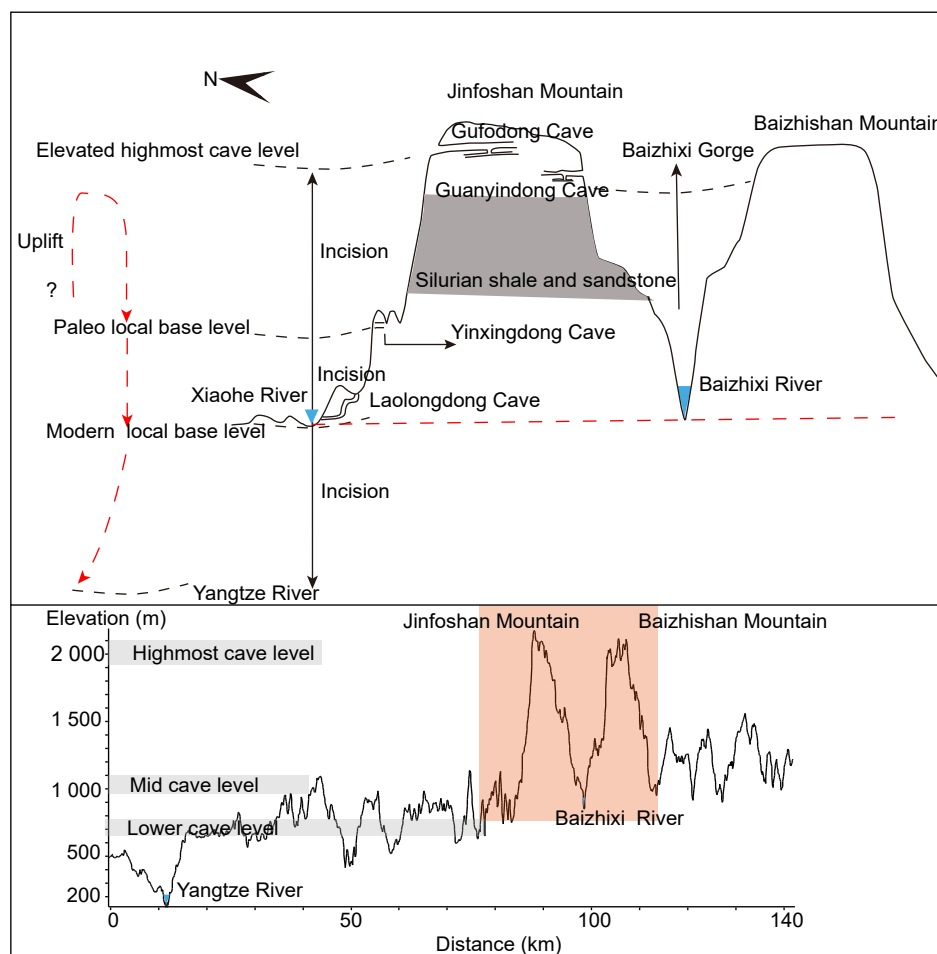


Figure 5. Cave levels distribution and the inferred causes: large horizontal cave passages on the planation recorded the base level was in low-land but uplifted by tectonic movement; the mid and lower cave levels indicated two stable stages of base level and the lowering process were caused by river incision.

nally cause some graves deposited in the SE branch conduit. Based on the cave development process, the horizontal cave passages were formed near the base level. Thus, the burial age of the Late Miocene only provides the late evolutionary stage when this cave level and the planation surface have been elevated and entrenched.

Due to the formation of the Three Gorges in the Middle Pleistocene, the base level dropping induced the river headward erosion and the rapid denudation of the Silurian strata. The continuous retreat and lowering of surrounding Silurian canyons finally triggered Jinfoshan as a karst platform, higher than other areas. With the intensive incision of the regional catchment, the changes of cave morphologies from large horizontal cave passages to maze-like branch passages.

We therefore proposed that the tectonic uplift played a key role on the caprock denudation and created the prerequisites for the development of the initial karst conduits. The river incision caused the base level lowering and the abandonment of earlier horizontal passages. Regional base level adjustment and rapid retreat of Silurian canyons finally triggered the disintegration of ancient catchment basin.

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Conflict of Interest

The authors declare that they have no conflict of interest.

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