织金洞地区的喀斯特地貌与洞穴成因

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摘 要

织金洞由于洞穴内碳酸钙沉积形态多样，洞外喀斯特景观组合完好，成为我国著名的旅游洞。本文通过分析该地区新构造抬升及河流下切引起的水动力效应，探讨喀斯特发育与洞穴形成演化的成生联系。

由于新构造运动强烈的间歇性抬升，区域侵蚀基面下降，喀斯特回春峰，从洼地、峡谷向深发育，谷坡洞穴层层分布。在岩层平缓、节理发育的条件下，地下河下切与崩塌作用相结合是地下喀斯特向地表喀斯特转化的重要方式，即对洞穴通道的扩大和峡谷的形成起着决定性的控制作用。第四纪以来的水系变迁与河流袭夺是该区洞穴形成发育的根本动力。结合织金洞大形态的地质构造控制特点和碳氧同位素年代测定与古环境分析，发现：在早更新世中晚期，随干流六冲河的下切，以结河下游潜伏地下形成夹岩洞和龙吸洞，新寨河下游相应形成黄家岩洞；中更新世早期，该河流继续下切、变迁、袭夺并伴有崩塌作用，形成了横跨在峡谷上的双层天生桥，织金洞主洞和黑洞也属这一期的产物；中更新世中期，新寨河逐渐被以结河袭夺，织金洞由于较大的枯洪水位变幅引起频繁的崩塌，形成大厅；中更新世晚期，洞穴脱水，碳酸钙沉积形态广泛发育，直至全新世。

KARST GEOMORPHOLOGY AND SPELEOGENESIS OF THE ZHIJIN CAVE AREA[①]

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ABSTRACT

The Zhijin Cave is a quite well-known tourist cave in China for its large size, beautiful decorations and fantastic karst and caves around. This paper looks at the genetic relationship between karst development and caves formation and focuses on the hydraulic effect of karst landscapes in response to the neotectonic uplift and the rivers incision in the Zhijin Cave area. With the intense, intermittent uplift accompanied by the frequent lowerings of local base-level, karstification in the area adjacent to those major rivers has been rejuvenated, which gives rise to a deepward development and accordingly a stepped occurrence of karst landscapes. The passage-leveled caves with phreatic features on the valley slope are also produced in this way. When possibility is great which is achieved by a combination of gentle dip and heavy joint of the limestone, the incision and collapse processes are of very important ways for underground karst toward surface landscape and also of great contribution to cave passage enlargement. The river capture from evidences of fossil drainage system suggested that it was a long time for the origin, formation and development of caves in the area. Examining geological control on the Zhijin Cave passages and variations of oxygen and carbon stable isotopes from the speleothem, the paper concludes with a growth model for the karst and caves in the area.

INTRODUCTION

The Zhijin Cave, previously known as the Daji Cave, 21 km northeast of the Zhijin County Town in the western part of Guizhou Province, China, is situated in a very karstic area with the finest and the most notable suite of surface and subsurface karst landforms to be found in any

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small areas in this province. The cave area lies on the lower reach of Yijiehe—the downstream of Zhijinhe feeding immediately into the Liuchonghe River. As a typical subtropical karst mountain-plateau, general topography of the area ranges from 940 m to 1550 m above sea-level with a relative height of 300-400 m, which gives rise to a high available relief and a great hydraulic gradient. The mean annual temperature and rainfall are respectively estimated as 14℃ and 1340 mm.

Carbonate rocks supporting the karst and caves in this area are mostly the Lower-Middle Triassic interbedded limestone and dolomite, some are the Lower Permian limestone. Clastic formation, with some volcanic rocks, forms only a small proportion of the very thick carbonate sequence. Folds and faults mainly trending SW-NE constitute a complex structural pattern with alternating carbonate and non-carbonate outcrops. As a result, the area has been influenced by both diffuse autogenic and concentrated allogenic recharges in the erosion of relief, which is of great potential for formation and development of nice karst and large caves. The geology also provides the rocks with much joints for well developed secondary porosity although the dip is normally 12°～20°. The neotectonic uplift has affected the area throughout the last 50 million years, and the active movement on some structures has continued into the Quaternary.

NEOTECTONIC UPLIFT AND KARST REJUVENATION

Epeirogenic and orogenic activities in the Late Cenozoic Era have given us a landscape of exceptional diversity, complexity and beauty (Bloom,1978). The last tectonic movement in the geological history of the Zhijin Cave area, neotectonism, has greatly played an important part in controlling the development of karst landforms by determining the relief, and in turn hydraulic conditions.

With an intense uplift accompanied by active incision of the Liuchonghe River and the Yijiehe system, karstification in the area adjacent to the downstreams of major rivers has been rejuvenated to enhance a deepward development to follow a lowering of the base-level and a thickening of the vadose zone. Under the conditions of this increasing available relief and hence the potential energy driving groundwater circulation, it is possible for any type of karst landforms at any stage to evolve toward fengcong-depression/gorge in an abnormal sequence (Fig. 1). The fengcong-depression karst is mainly located on the interfluve areas of the Yijiehe system. The cones are connected at a common base of karst upland with a divide bounded by the rivers. Their summits show different heights ranging from 1300 m to 1650 m and slope towards the gorges. The depressions with variable size are characterized by close and polygonal features. Their floors are at different heights, from 1250 m to 1500 m, far above the local base-level and become lower towards the land slope too. The higher available relief enable some dolines and sinkholes to overlap in most of the depressions although some of them are covered by weathering residuals and slope washes at the shallow and flat bottoms. One of the biggest collapse sinkholes, Dachilong Hole, leading downwards to underground river is about 350 m long, 240 m wide and 120 m deep, with a round plan and vertical walls. The fengcong-gorge karst is distributed on the valleyslopeareas of the Yijiehe system and the Liuchonghe River. The cones with a mean hill-sided slope of 43.6° are connected at a common base and the summits show different heights with a relation of normally 150～250 m and slope towards the rivers. The river beds of the Yijiehe range from 1000 m to 1200 m above sea-level, and the cone summits range 1300～1500 m, which means the Yijiehe Gorge reaches to 300 m deep. Accordingly, the Liuchonghe River is at 940～965 m and the cones on the banks range 1300～1450 m, which gives rise to the Liuchonghe Gorge up to around 400 m deep.

With an intermittent uplift, frequent changes of the base-level have resulted in alternated karstifications in either vertical or lateral ways, and hence the stepped occurrence of spatial zonation of the karst was formed, which is another feature of the area. Due to an rapid uplift by the neotectonism and a downcutting by the rivers, the karst will be rejuvenated and adjusted to this increasing available relief toward fengcong karst, conversely, the landscape will be inheritaged and adjusted to the decreasing available relief toward fenglin karst. Each uplift leaves a knickpoint on river and it retreats toward the headwater during the tectonic stillstand. The frequent changes of the base-level following the neotectonic pulses caused the frequent headwater erosions. This effect spreads from the lower reaches of the major rivers to the upper reaches and from the valleys to the interfluves. The river profiles are accordingly of a stepped type (Yang Mingde, 1982), i. e. the sections of normal and abnormal profiles separated by the knickpoints, one following another, make up the entire river profile, with gentle gradient and steep gradient sections occurring alternatively. Rock-cut terraces are thus left on the valley-slopes (Fig. 1), and passage-leveled caves with phreatic tubes on the slopes are also produced in this way.

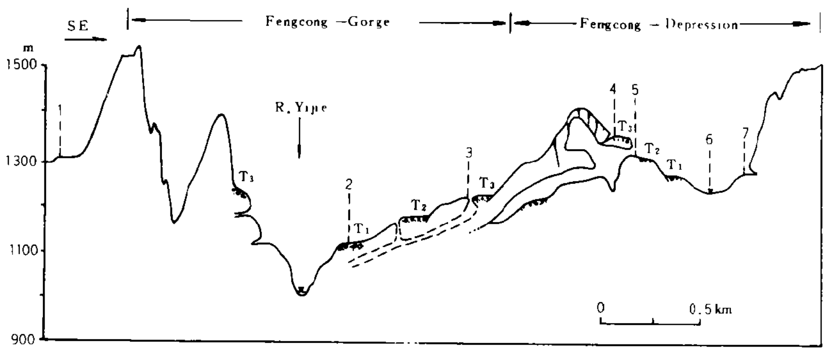

Fig. 1　Geomorphic section of the Yijiehe system

(1. Bapu Vallage; 2. rock-cut terrace and the order; 3. Jiayan Cave; 4. Huangjiayan Cave; 5. Zhijin Cave; 6. Xinzhaihe River and 7. Mawo Cave)

COLLAPSE PROCESS AND GORGE DEVELOPMENT

Zhang Yingjun (1984, 1990) suggested a model for geomorphogenetic processes of karst valleys in the Guizhou Plateau, i. e. sinking stream→underground river and karst window→gorge and natural bridge→karst valley. Of the karst in the Zhijin Cave area, karst gorges are the most dominate and notable features coexisting with entrenched rivers, water caves, natural bridges, and karst windows, etc. (Fig. 2).

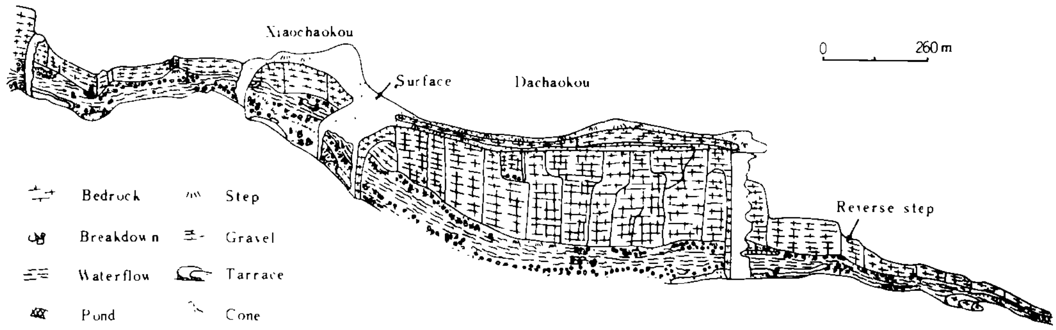

Fig. 2 Karst features and caves of the Yijiehe Gorge

Most of the karst gorges in the area, all with great gradient along the riverbeds, are extremely narrow and deep and found to be of 3 styles of cross-sections, V-shaped valley with straight slopes, box-shaped valley with vertical slopes and fissure-shaped valley with convex slopes. The river downcutting in response to the great uplift has lowered the base-level and caused the karst rejuvenation to produce many bare gullys and deep depressions alongside the gorges. There are many large breakdowns at the gorge floor, notable bedrock steps at the slope base and reverse steps on the slope side. The riverbeds are very rough due to occurrence of the knickpoints, ponds and certainly rockfalls. The underground karst is hence dominated by massive vadose canyon water-passages and the abandoned phreatic caves are hanged on the gorge sides. Any traces of phreatic origins are lost in the high roof, normally up to several tens of meters, of the large canyon passages, and the roof profile is stepped and lowered gradually from the entrance with stepped arch-shaped cross-section to the inside of the passage with water-filled phreatic tubes and ponds. There are some double natural bridges, a case of a through-cave over the present natual bridge, across the gorge. Between the bridges are karst windows. It is clear that the natural bridges are remains of the water cave roof and the karst windows are collapsed parts of the roof.

From the evidences above, formational processes of the karst gorge in the Zhijin Cave area are presented. Incision and collapse, comprising all processes which cause walls and ceilings of and underground cavity to break down naturally, are enhanced when the possibility is greater which is achieved by a combination of gentle dip and heavy joint of the limestone in the area. In case caves with interior rooms are big enough, collapse will be very frequent, and is also of great contribution to the passage enlargement, which normally gives a rectangular cross-section of passages such as the Dragon's Breath I Cave (Fig. 3). Another example is the Zhijin Cave in which breakdowns occur nearly everywhere in the passages, especially the breakdown deposits in the Mouse passage reach to 40000 m^3 in volume and those at the end of the Main passage, Shiwanda

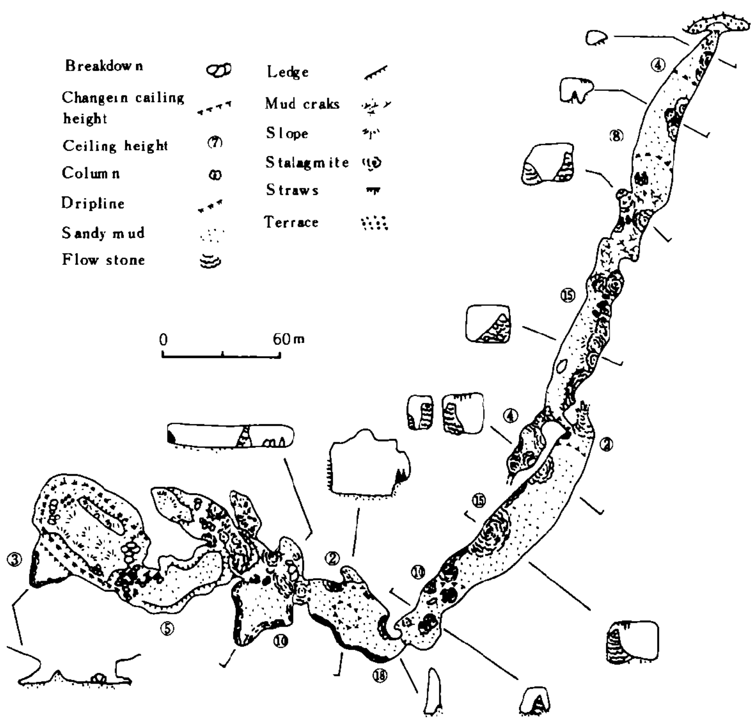

Fig. 3　The Dragon's Breath Cave with rectangular cross-sections

Mountain spot reach to 600000 m^3. For those with both river incision and big rooms it is quite easy for collapse to open underground cavity to form gorges and related karst features such as the Yijiehe gorge. It always happens when the river cave entrances have become so extended by erosion and/or corrosion that the rock strength is overtaxed. Each collapse will result in a stepped arch-shaped cross-section at the entrance, and accordingly a step-lowered profile of the ceiling from the entrance to the interior passage. This process is sometimes enhanced by lateral undercutting of the river again. With lateral extension and longitudinal retreat of the cave entrance, the collapsed passage become a gorge. Karst window will be produced where vertical distance between the ceiling and the surface is thin enough for collapses and natural bridge formed where the retreat processes are in both ways downstream and upstream. The gorges at this time are characterized by reverse stepped walls with active rockfalls. Since then onward, the gorge sides are getting into vertical and parallel retreat by both collapse and undercutting. However, the undercutting will be getting slower and replaced by the downcutting as more and more rockfalls are accumulated at the basis of both slope sides, but breakdowns on the upper walls are still proceeding. It is in this way that the bedrock steps covered by rockfalls at the basis are formed. which is different from those rock-cut terraces produced by frequent headwater erosion following the base-level changes and the intermittent neotectonic uplift as discussed above.

RIVER CAPTURE AND CAVE FORMATION

River capture and drainage change, above and below ground, are the recurring features in the Zhijin Cave area, and are spectacularly developed along the incised rivers (Fig. 4) in response to the neotectonic uplift. This hydraulic effect can be seen to be of considerable importance in terms of origination, formation and development of the caves in the area.

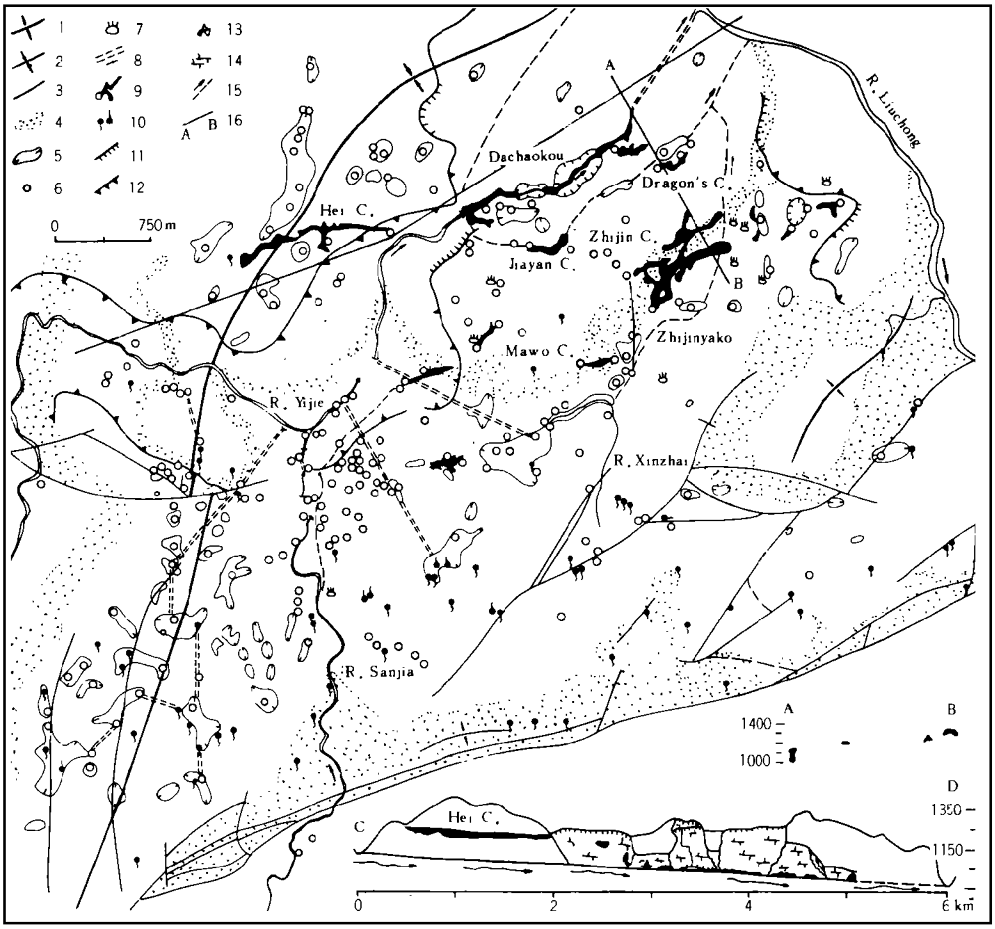

Fig. 4 Karst hydrogeology with the fossil drainage system of the Zhijin Cave area

(1. anticline; 2. syncline; 3. fault; 4. non-karst; 5. depression; 6. doline and/or sinkhole; 7. blowing cave; 8. inferred underground river; 9. mapped cave passage; 10. springs; 11. cliff; 12. washing slope; 13. breakdowns; 14. bedrock; 15. fossil course of river; 16 geomorphic section line)

Evidences from the fluvial deposits on surface, over the Jiayan Cave, at the top edge of Xiaochaokou Hole, from the downstream of Xinzhaihe to Zhijinyako, for instance, suggested that there are at least two visible former river courses, where the 3rd terraces exist at present day, in the fossil drainage system. One trending NE is at altitudes ranging from 1250 m to 1300 m above sea-level for the Yijiehe, another in NNE at 1350 m for the Xinzhaihe. The dating analysis indicates that both river courses were surface streams at that elevation from about the Pliocene to the beginning of the Early Pleistocene. It was not until the middle-late part of the Early Pleistocene, as the trunk river—Liuchonghe incised and underground water captured surface water, that the Yijiehe downstream passed underground to form the Jiayan Cave and maybe the Dragon's Breath I Cave. At the same time the former downstream of the Xinzhaihe also went underground to form the Huangjiayan Cave and its present collapsed passage at Xujiayako, which is the former top-level passage of the Zhijin Cave, just above the Mouse passage of the Cave.

It was at the beginning of the Middle Pleistocene that, as the local water-table was still lowering in response to the neotectonic uplift, the Yijiehe kept incision along the stratigraphic dip and gave rise to the through-caves over the present natural bridges and 2nd terraces at about 1170～1190 m above sea-level. The Xinzhaihe was captured again by underground water to form the main passages of the Zhijin Cave and the Benta Cave and the related 2nd terraces at 1330 m. The Hei Cave with beautiful phreatic tubes (Fig. 5) used to be a cave route of the Yijiehe before and probably abandoned as a fossil cave at that time. Up to the middle period of the Middle Pleistocene, incision of the Yijie had reached an altitude of 1125 m with the 1st terraces on, and the Xinzhaihe River was captured, due to its slower downcutting rate, by the underground water system of the Yijiehe. The Xinzhaihe at that time was at about 1300 m and the entrenched flow course was also impeded by shale near the Mawo Cave. As a result, the river had to changed the course from NE to NW to follow the land slope and limestone dip, and to passed underground as a tributary of the Yijiehe. Since then onward, incisions of both rivers were continued to reach the present levels respectively at around 1000 m for the Yijiehe and 1240 m for the Xinzhaihe.

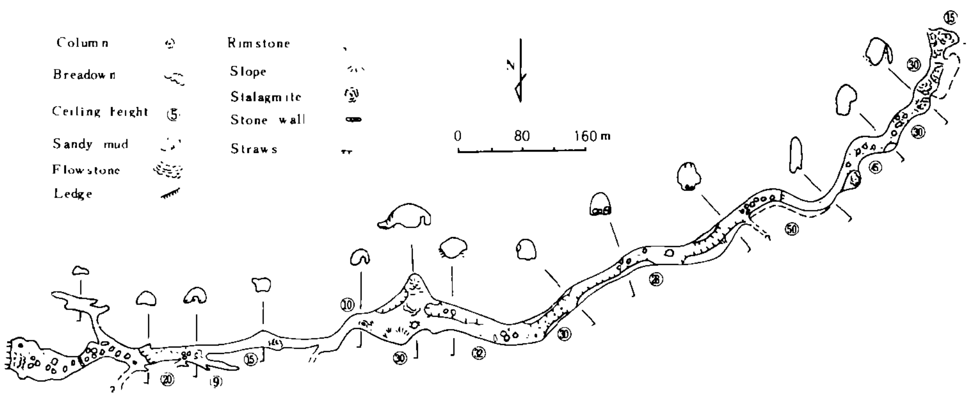

Fig. 5　The Hei Cave with phreatic tubes

STABLE ISOTOPES OF OXYGEN AND CARBON IN THE ZHIJIN CAVE

The Zhijin Cave, with only one entrance, consists of five main passages called Main Passage, Towers Passage, Mouse Passage, Rimstone Passage and Helictite Passage forming its network pattern in plan (Fig. 6). About 4215 m long and 242 m deep passages have been mapped with a total volume of around 5 million cubic meters. The widest section is 150 m, generally 30 ～50 m. The maximum height is 65 m, normally 20～40 m. The largest chamber is about 46200 m^2 in area. The cave contains 4-level of passages in vertical, of which the top one is at an altitude of 1335～1348 m(No. Ⅳ), the next (No. Ⅲ)is at 1250～1260 m, the No. Ⅱ at 1214 m and the lower one (No. Ⅰ) at 1170 m. These levels are connected by some inclined shafts. The cave passageways are complicated and controlled by faults and joints trending NE, NNE, and some in NW. In addition, bedding planes also play an important part in determining those inclined passages. The large forms of the cave include chambers, canyons, domes, rectangular sections and half tubes. The small forms are ceiling channels, anastomoses, pendants, pockets, scallops, splinters and collapse holse. The breakdowns are majority of clastic deposits in the cave, some are fluvial mud, sand and gravels. There is a great variety of speleothem types in the cave. Most of them are of multi-forms with complicated origin, in which mushroom-shaped, petal-shaped and pinecone-shaped stalagmites are the most typical. The petal-shaped one of 14. 7 m in height and 0. 3～0. 2 m in diameter is very beautiful and unusual.

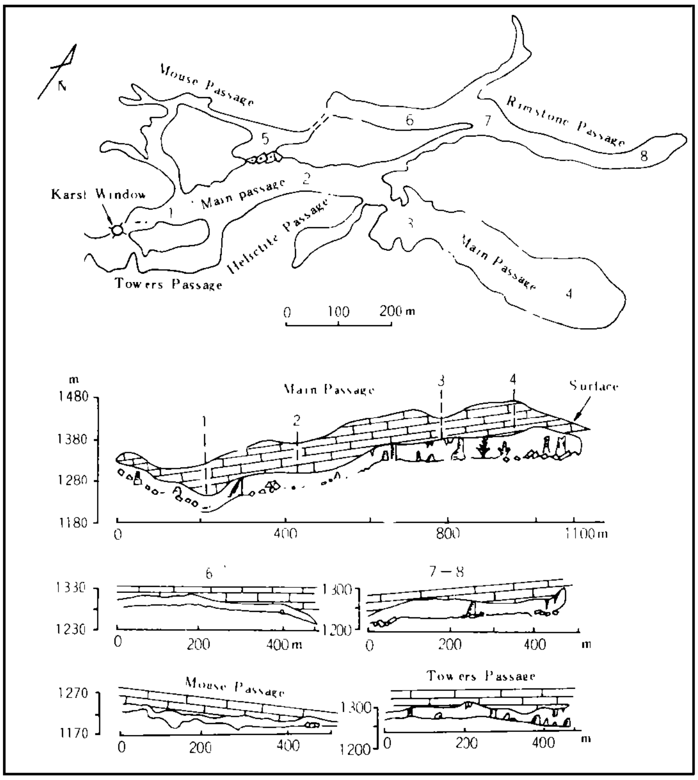

Fig. 6 Plan and profile of the Zhijin Cave

(1. Sun-Moon Pool; 2. Mountain Lake; 3. Moon Palace; 4. Shiwan Mountain; 5. Collapsed Hall; 6. Water Village; 7. Banquet Hall; 8. North Sea Ridge)

From variations of stable isotopes of oxygen and carbon and the data of U-series dating from a fallen stalagmite of 45 m in length and 70 cm in diameter, supplemented by other speleothem and their characteristics, the results (Tab. 1) are obtained as follows.

a) The higher $\delta^{18}O$ the speleothem contains, the lower temperature it reflects when formed, and accordingly, the lower $\delta^{18}O$ indicates a relatively high temperature of speleogenetic environment. This situation is corresponding to what Wang Xunyi (1985) did in Guilin area.

Tab. 1 $\delta^{18}O$ and $\delta^{13}C$ variations and relevant data in stalagmite and speleothem collected from the Zhijin Cave

Sample No.	Sample Location	$\delta^{18}O$% (PDB)	$\delta^{13}C$% (PDB)	Date (ka)
85-Z1	Stalagmite base core	-10.34	-8.06	254.1+24
85-Z2	1.4 m from the base	-7.12	-10.63	100.2+9
85-Z3	4.7 m from the base	-10.30	-10.45	50.1+2
85-Z4	9.3 m from the base	-10.79	-8.45	40.1+2.4
85-Z5	19.2 m from the base	-10.15	-9.27	35+3
85-Z6	33.4 m from the base	-9.92	-8.15	34.1+3.3
85-Z7	44.3 m from the base	-10.92	-8.64	7.5+6
88-Z1	Calcite on cave floor	-7.87	-5.38	>350
89-Z2	Calcite on stalagmite	-10.06	-8.55	71+7

b) Minimum of oxygen isotope is respectively at 254.1 ka, 40.1 ka, 50.1 ka and 7.5 ka B.P.. The data suggests that the palaeoclimate in the Zhijin Cave area was warm and wet at those time, consequently they are important periods for the speleothem formation.

c) Taking the speleothem texture into account, we find that most of the speleothem were formed around 250 ka B.P.. They are quite big cap-shaped stalagmites, several tens of meters in diameter, made of sand-bearing calcite. The cave columns have same characters, these evidences indicate that it is in this period that heavy rainfall or thick water-stored layers provided the cave with much dripping water of high frequence. It is after 250 ka B.P., especially 100 ka, that the calcite forms formed are mostly small in size, less than one meter in diameter, less sand-bearing and pure in composition. It is clear that the materials feeding into the cave were smaller and smaller in quantity, so that the ground over the cave had undertaken a very serious denudation.

Zhao Shusen (1988) did a study on U-series in the karst cave of East China and noted that the periods when speleothem is great in development are those respectively at 4～13 ka, 35～60 ka and 75～120 ka B.P. when the palaeoclimate is warm and wet. However, the variation of isotope in the V28-239 rock core from deep sea illustrates a cold stage falling in the fifth warm period of 90～100 ka B.P.. Xu Xin and Shan Zida (1990) found that a new warm period (i.e. the best suitable climatic time) is 6～4 ka B.P..

CONCLUSION

It was about from the end of the Early Pleistocence to the beginning of the Middle Pleistocene that karst development in the Zhijin Cave area was under the control of shallow phreatic condition. Groundwater, some from surface, flowed along fractures, joints and bedding planes. Some favorable places would be enlarged by corrosion and/or erosion to become conduits and hence caves in the limestone. During the first part of the Middle Pleistocene the Xinzhaihe River with greater downcutting from the uplift of land entered the conduits and enlarged the caves, one of them was the Zhijin Cave (Fig. 7)

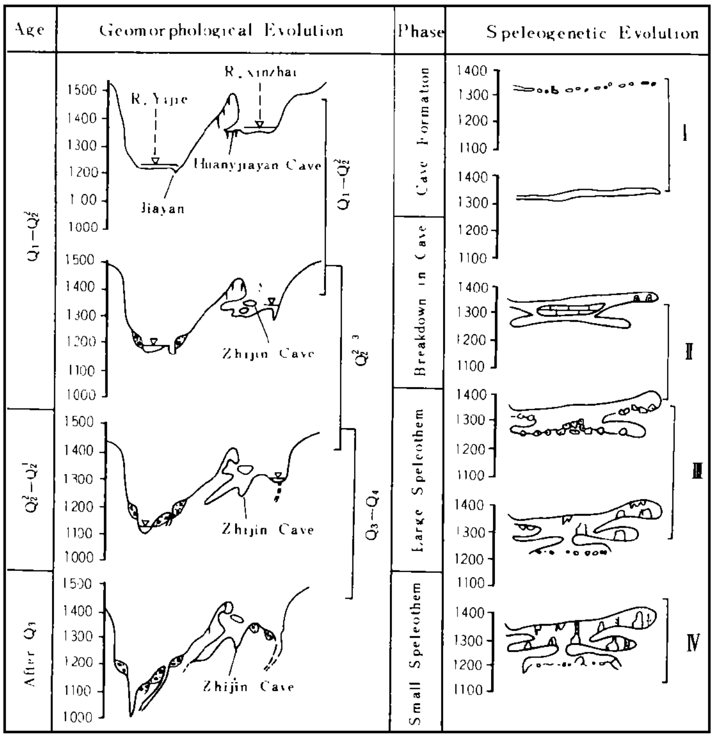

Fig. 7 An evolutional model of the Zhijin Cave

The cave undertook an extensive collapse process in the middle part of the Middle Pleistocene. With a huge range of the cave water-levels between wet-season and dry-season and the intense neotectonics, large-scale breakdowns occured in the large passages whose rate of incision was less than that of the surface rivers. The top-level passage (No. Ⅳ) was partly connected with the next one, which gives rise to some large chambers such as the Mountain Lake and the Sun-Moon Pool. It is possible that the breakdowns in the Huangjiayan Cave probably happened in this period as well. It was not until later part of this period that the passage No. Ⅳ such as the Shiwan Mountain—the Moon Palace and the Banquet Hall—the North Sea Bridge and the passage No. Ⅲ such as the Towers Passage, etc. nearly stopped to be enlarged and started to be deposited.

The late part of the Middle Pleistocene was a time for development of the large stalagmite and column, especially those formed around 250 ka BP. The speleothem is normally several meters to ten meters in diameter, which suggests that this time is an active formational period for speleothem as the Xinzhaihe was already captured by the Yijiehe instead of sinking into the Zhijin Cave. It is only in wet-season that some of flood water from the river passed underground to enlarge the lower-level passages of the cave. The Water Village and the Mouse Passage, for instance, might be water-filled or half water-filled as a sort of active cave at that time.

The calcite deposits formed in the Holocene are mainly those of small, nice, pure speleothem with rod-shaped, bamboo-shaped, petal-shaped and mushroom-shaped forms, some are helictites. Most of them were deposited on the large speleothem and the fallen stalagmites. From the datings, they were formed over last 100 ka BP. The Water Village and the Mouse Passage seemed to stop to be enlarged, but seasonal water in the cave was still developing the lower passages up to now. The shaft at the northern end of the Water Village is a representative. Because of small water quantity, the passage scale is confined and developed along the limestone dip, only with a volume of about one cubic meter.

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