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CAVE DEVELOPMENT AND ITS SYSTEMATIC EVOLUTION IN AN UNDERGROUND RIVER SYSTEM

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1 INTRODUCTION

As far as concerned, karst underground rivers are extensively developed in China and most of them are concentrated in seven southern provinces. According to hydrogeological statistics in southern China region, there are totally 2497 underground rivers and 2450 very large karst springs with individual output more than 50 l/s in these provinces. They are the main water sources in the vast southern karst area of the country. Some of them are super underground rivers with individual catchment area larger than 1000 km^2 and minimum annual water resource more than 1×10^8 m^3, including Luilangdong and Nandong undergound rivers in Yunnan, Disu and Poyue in Guangxi, etc..

Most underground watersheds are complex systems both hydrogeologically and speleologically. How the system started and developed? What is the genesis and developing process of karst aquifer characteristics (fissures, conduit, etc.) and also the cave development in this system? These problems are essential to karstology and karst hydrogeology, but still in researching stage, which cannot meet the demand of karst water investigation and exploitation. Moreover, there is no any theory or model about cave development and evolution on the basis of considering an underground watershed as an input-output system[1,2,4].

For several years, we have applied systematic concepts to study underground rivers and caves, such as Nandong researching project and Sino-British cave co-expedition, and estabilished a theoretical model of aquifer-controlled systematic evolution of cave in an underground river system. In this paper, karst water movement, cave formation and development in the input and output parts of the system are discussed in detail.

2 INPUT-OUTPUT TYPES OF MATERIAL AND ENERGY IN AN UNDERGROUND RIVER SYSTEM

Karstification always proceeds in an input-output process of energy and material and exists in an open system with dissipative structure. An underground river system or watershed is just a typical example. According to its input form, the system can be classified into three types: lateral, planar and multiple input(Fig. 1).

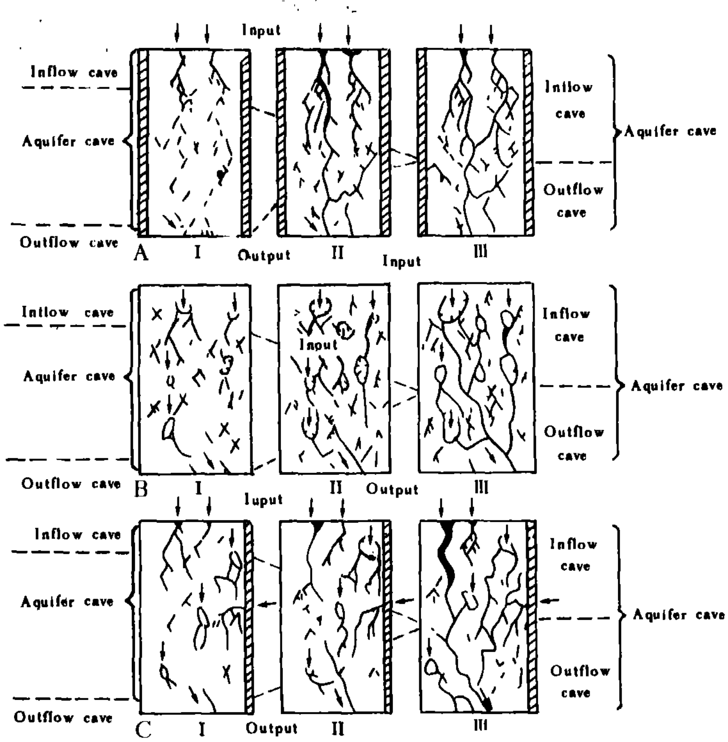

Fig. 1 The model of cave development and its systematic evolution in an underground river system

A—Lateral input; B—Planar input; C—Multiple input; I、II、III—Evolution stage

2.1 Lateral Input

Surface water flows into karst aquifer from one side or several sides, it is mostly concentrated flow (i. e. entering karst aquifer as swallet streams) and inflowing water is allogenic mainly. Karst aquifer between input and output points is usually covered by waterproof strata and bordered by nonkarstified rocks. Among three inputting types, the lateral input is most favorable for forming well developed and highly ordered cave system(Fig. 1—A).

The famous Mammoth Cave underground water basin in Kentucky, USA, can be taken as an example for lateral input type (Fig. 2). The main karst aquifer in the basin is carboniferous limestone which is covered by sandshale. The Green River lying in the north determines regional drainage base level. There are tens of outlets along its left bank, which forms a complicated output cave system. And all these caves can be grouped into four layers. The total explored cave is more than 550 km in length. In the southern part of the basin, because upper waterproof sandshale was moved away by denudation, the limestone aquifer has outcropped and become a recharge area. Input points are in hundreds, including swallet streams and dolines. The output caves along the Green River including multi-layered fossil caves, subterranean streams and karst emergences are in their different development stages, which shows that the whole Mammoth Cave System has gone through a long and multi-cycled development history.

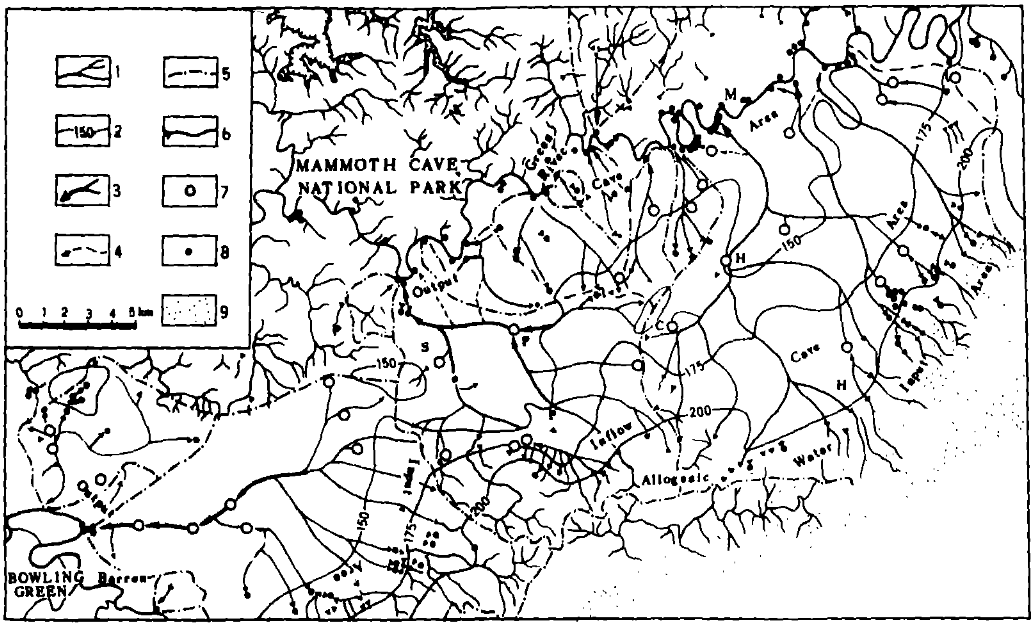

Fig. 2 Mammoth Cave System of lateral input type of material and energy

(The basic map from Ford. D. C.)

1. River or stream; 2. Piezometric contours(m); 3. Flow routes; 4. High level overflow routes; 5. Groundwater divide; 6. Stream sink; 7. Cave with stream passage; 8. Perennial spring or springs; 9. Lower St. Louis formation & older rocks; S—Smiths Grove; P—Park city; C—Cave city; H—Horse Cave; H—Hiseville; M—Munfordville

2.2 Planar Input

For a relatively isolated underground watershed in a vast area covered by soluble rocks, water feeding will be in diffuse flow instead of concentrated flow. In this case, the input caves are sinkholes mainly. Planar input is of advantage for development of aquifer caves. Nevertheless, it is difficult to form well developed and interlinked cavern system. Output caves have more outlet sumps and branches. Because of less material and energy inputting, the formation and ordered process of the cave system are slower compared to lateral input type. Fig. 1—B represents a typical process of cave deveolpment for this input type.

2.3 Multiple Input

Both lateral and planar input or their combination exist in one underground river system. It is the most popular inputting type in the karst region of southern China. The caves between main lateral input and output points develop first, which makes the cave system heterogenous and more complicated in development degree and dimension (Fig. 1—C).

In natural condition, a hydrologic input-output system for instance Mammoth Cave, the world longest cave, is usually not only a system but a combination in which subsystems in different sizes or grades are superimposed, combined or incorporated. In this case, low graded and small or incorporated systems usually develop first.

3 BASIC CAVE TYPES IN UNDERGROUND RIVER CAVE SYSTEM

As mentioned above, any karst watershed or underground river system can be considered as an input-output system of material and energy. And in one system there are different water circulation or movement, such as inflowing, outflowing and movement in karst aquifer. In normal condition, the location of inflow and outflow depends on local topography and hydrological condition. Whereas water movement in aquifer is controlled by lithologic character, strata occurrence and geological structure. The formation and development of underground watershed or river system is mainly controlled by geological structure of aquifer and surface water network, and represents a result of ordered evolution in history.

The three types of water circulation and movement (i. e. inflowing, outflowing and movement in aquifer) result in three types of caves, i. e. inflow, outflow and aquifer caves correspondingly. They combine together to form a genetic system of caves and its formation and evolution follow the principle of disorder-order transformation, self-organizing and coordination.

3.1 Inflow Cave

Inflow cave is formed under such condition that concentrated surface flow directly enters karst aquifer. Its entrance may be sinkhole, doline or shaft. But most important and popular types are swallet stream and footcave in fenglin karst (tower)area[6,7,8]. Because the capability of material and energy inputting through sinkhole or doline is relatively low, cave entrance is often vertical and extends to a limited depth. Swallet holes and footcaves in various forms are most significant in southern China karst region.

Both site investigation and lab modelling show that if water is injected at a certain point, cave will develop from this point towards internal part, i. e. the cave will extend following the same direction as water flows[3~5](Fig. 3). As for karstification and water corrosion, inflow cave has a potential advantage of physical, chemical and biochemical energy and generally forms first and develops faster. The characteristics of inflow cave are as follows[9,10].

a. It often has large scale bell-shaped entrance.

b. In early stage, its spatial dimension reduces and more branches occur following the cave extension. Finally it immerges into inlet sump. But for cave in its mature stage, there is no such characters.

c. Various speleogens such as scallops, pocket, ceiling groove, pendant, etc., develop intensively. Flow marks show that water flows into cave.

d. Coarse allogenic deposits are found frequently.

e. In comparison with outflow cave in the same system, inflow cave is less layered.

f. Generally, main inflow cave (swallet caves specially) developed earlier and faster than main outflow cave in the same system. Inlet sumps at the end have also been lowering in pace with cave deepward development.

Inflow cave is mainly located in the recharge part of an underground watershed. A major lateral input cave is often feeded by allogenic water. In such case, plenty of water carrying large number of mechanical particles (sand, gravel, etc.) has intensive aggression on bedrock. If steeper slope exists at the cave entrance, the physical erosion of inflowing water will be much stronger than that in any other type of caves. Usually allogenic water is strongly aggressive water. Moreover, there is considerable biochemical activity near ground surface. These are the reasons that inflow caves are quite more in number and larger in dimension than outflow caves in the same system as shown in Fig. 1—A.

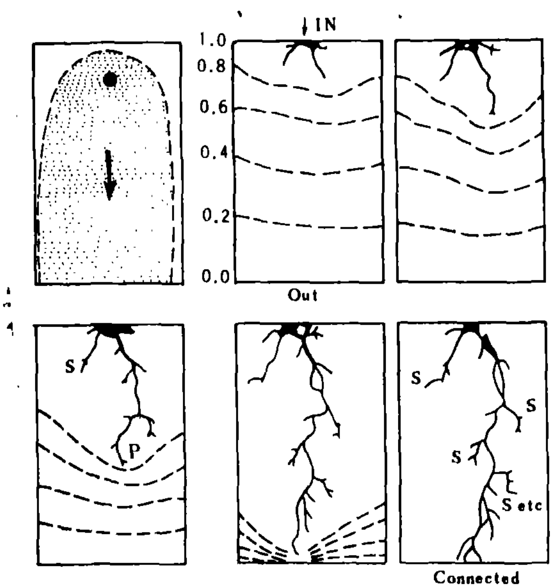

Fig. 3 The development of original solution passage under the single point lateral input

(From Ewers 1982)

P—Principal (or victor) tube; S—Subsidiary tube; Dash line—Piezometric contour

From preliminary estimates, there are more than ten thousands of traverse caves in 5×10^5 km^2 karst area of southern China and about 70%~80% of them are inflow caves.

Those inflow caves like dolines and sinkholes are popular in karst area. Because the input of material and energy (water flow mainly) is limited, the development of caves is very slow and it is impossible to form a major water passage. More frequently, in a certain depth the caves disappear into bedding plane or structural fissures abruptly. Except for large scale collapses or karst windows, the dimension of the caves is corresponding to the amount of energy input.

3.2 Outflow Cave

Outflow cave is formed under concentrated draining of underground water and most are developed in the discharge part of karst aquifer, specially along major river valleys. It is directly influenced or controlled by drainage base level (river valley or related aquifuge). The cave development starts from the resurgence entrance and goes upwards gradually in the reversed direction of water flow. As mentioned above, the development of outflow cave is always behind that of inflow cave. In early stages, outflow cave occurs as karst spring whereas inflow cave in the same hydrogeological system has already been in a considerable scale. Characteristics of outflow cave are described as follows.

a. Outflow cave often has small scale entrance with oval cross section (major axis is horizontal) comparing to inflow one.

b. Speleogens are less developed. Flow marks (scallops) show water flows out of cave, but usually it is difficult to recognize.

c. The dimension and form of cave along its extension often change quickly and abruptly. It usually disappears into fissures or outlet sumps.

d. There is no or just fine mechanical deposit inside cave, which depends on regional geological and hydrological conditions.

e. Cave entrance is susceptible to the falling of drainage base level, i. e. the falling of drainage base will causes the development of outflow cave at a lower position. So, it is often noticed that there are layered cave or fossil cave with different elevation along a river valley.

f. Cave developing stages can be clearly identified. In early stage, they often occur as fissure springs and some marked U-shaped karst siphon. Initial underground river is its mid stage in which the cave often disappears into outlet sump. Up to mature stage, the cave develops upwards and finally joins up with inflow cave.

Outflow cave is mainly located in drainage part of an underground river or water-shed. It is or used to be major draining passage and on the edge of drainage base. In general, inflow cave has obvious advantages in comparison with outflow cave in both number and length.

The water amount flowing out from an outflow cave may be much more than the water entering into one inflow cave in an underground river system. But the water aggression or cave development capability is much less than that of one or several inflow caves. The larger the catchment area, the more obvious this effect. This is because in early stage, when the water just enters the aquifer through inflow cave it will be dispersed into fissures and its chemical erosiveness will greatly reduce at the drainage part. The physical corrosion capability of water is dependent on its hydraulic gradient and flow velocity. At the beginning, physical corrosion is concentrated on the emergence where the outflow cave started. And only when the flow becomes turbulent, cave development can be quickened by physical dynamics. Therefore, the development of outflow cave is in reverse direction of water flow, i. e. so-called "headward erosion". For the time being, inflow and outflow caves become nearer and nearer, and finally link up with each other to form an underground river passage.

3.3 Aquifer Cave

Aquifer cave means the syngenetic cavern network developed between inlet and outlet sumps in the whole karst aquifer of an isolated underground watershed. Being controlled by various developing conditions such as vast developing space, dispersed water, conveyance fissures, disordered flow field, slow and space-limited water flow and so on, aquifer cave has its own properties which include

—small scale in dimension;

—complicated cavern system;

—various forms or patterns;

—rugged (rolling) bottom;

—no integrated groundwater table;

—phreatic and confined water co-existing.

With the change in recharging and the development of inflow and outflow caves, "selective" mechanism plays a great role in the development of aquifer caves, *i.e.* those caves with strong material and energy exchanges will develop first and others will less develop. Most single passages will have no chance for successive development. Therefore, cavern formation principles such as "development stage", "processing order" and "ordered process" have no meaning for aquifer cave due to the lack of steady and continuous input-output of material and energy. But it is still possible for some caves to develop further and form labyrinth cave system under following favorable conditions (Mammoth Basin as a good example).

—Aquifer is thick enough and lies horizontally;

—Fissures and fractures are well developed in aquifer strata;

—Karst aquifer is covered by watertight strata;

—Recharging is from only one side;

—There is sufficient feeding of material and energy;

—Multi-typed outflow exists;

—Draining passages are relatively stable for a certain time;

—Cave system development has a long history.

4 SYSTEMATIC EVOLUTION OF CAVE DEVELOPMENT IN AN UNDERGROUND RIVER SYSTEM

As shown in Fig. 1, the development of cave in an underground river system can be separated into three stages. The characteristics for each stage are described briefly as follows:

(1) Early stage A karst hydrologic input-output system forms its initial pattern. Input and output points are formed and more or less stable. Inflow cave occurs and has strong potential for further development. Whereas outflow cave is still in the state of karst spring.

(2) Mid stage It is the main stage for ordering process of karst hydrological system. Inflow cave remains in the course of development and outflow cave forms its initial shape.

Development of aquifer cave starts following "selective" principle as described above.

(3) Mature stage Inflow and outflow caves are linked up to form an unobstructed water gallery. Most aquifer caves are abandoned. Later on, karst windows and land collapses occur on the ground along the main water passage. Parts of underground river are even uncovered to become surface river.

In the every stage of the cave development sufficient and long term material and energy input is needed.

For a karst hydrological system, different types of material and energy input will cause system to have different constitutes and structures.

5 CONCLUSIONS AND DISCUSSION

The objective of our study is focused on karst cave types and their mutual relation, formation mechanism, development and evolution process in order to establish a systematic evolution model. These will be helpful in the research on karst underground river system and water resource exploitation. When we use this model, the first is to think about whether an isolated input-output system exists or not, what are its range and constituentes. Moreover, its changing history and current developing stage must be considered. It has a great importance in our studying of cave characteristics and aquifer water-bearing capacity. In the analysis of survey data, a very popular and important method is using the elevation of cave entrance to study cave development history. From this study, we know that without considering cave types, this kind of analysis will be thoroughly no sense. It has scientific significance only for those outflow caves located in a limited area, controlled by the same drainage base level and with no disturbance of aquifuge. Thus, we should use this method very carefully.

Finally, we want to say that our model is a result based upon series studies on underground cave system well developed in southern China and is mainly for peak cluster-depression in geomorphology. It belongs to rainfall karst in the light of precipitation[11]. As we know, there are other cave types in the world, such as geothermal cave represented by Jewel Cave and Wind Cave in South Dakota, USA and mixture (saline-fresh water) karst cave which is represented by the caves (about one hundred in number) developed along the coast of Nullarbor Plain, southwest Australia. The model cannot be directly applied to study the development of these kinds of caves.

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地下河洞穴发育的系统演化*

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摘 要

洞穴成因在岩溶学理论研究中占有极其重要的地位。岩溶洞穴的渗流带、潜流带和地下水面生成理论是众所周知的。Davis W. M. (1930)提出了灰岩洞穴成因的两循环模式,即洞穴的发育早期在潜流带,后期则处于渗流带中。本世纪70年代以来,Ford D. C. 进一步提出了灰岩洞穴自潜流带向地下水面发展的四状态模型(the four-state model),是近代灰岩洞穴成因理论研究的重要进展。

根据我国南方灰岩分布区大量地下河系统存在的事实,本文作者从洞穴发育与形成必定属于某个物质能量输入—输出系统的基本认识出发,并利用Ford D. C. 和Ewers R. O. 的模拟实验研究成果,建立了地下河系统洞穴形成和演化的新模式。将这一系统的物质与能量输入—输出分为侧向输入、面状输入和多元输入三种基本状况。这一生成系统的洞穴则划分为流入型洞穴、流出型洞穴和含水层洞穴三种基本类型。流入型洞穴以渗流带洞穴和地下水面洞穴为主;流出型洞穴以地下水面洞穴占优势;含水层洞穴则常以深潜流洞穴为特征。论文指出,流入型洞穴的发育、扩大与延伸是从输入点开始的。一地下河系统中主要流入型洞穴的发展强度多数比该系统流出型洞穴为大。可能发生的溯源侵蚀作用只会在流出型洞穴发展的后期阶段出现(当洞道产生紊流时)。认为含水层洞穴的发展具有很大的选择性,即随着含水层水流运动从无序逐渐趋向有序化,大多数的含水层洞穴将被淘汰而终止发展。本文还较深入地讨论了同一地下河生成系统各部洞穴的基本特征、相互关系及其分阶段演化规律。

关键词 地下河洞穴 输入—输出系统 类型划分 系统演化

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