Journal of Zhejiang University SCIENCE
ISSN 1009-3095
http://www.zju.edu.cn/jzus
E-mail: jzus@zju.edu.cn

Effect of soil-rock system on speleothems weathering in Bailong Cave, Yunnan Province, China*

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Received Nov. 19, 2003; revision accepted Mar. 22, 2004

Abstract: Bailong Cave with its well-developed Middle Triassic calcareous dolomite's system was opened as a show cave for visitors in 1988. The speleothem scenery has been strongly weathered as white powder on the outer layers. Study of the cave winds, permeability of soil-rock system and the chemical compositions of the dripping water indicated: (1) The cave dimension structure distinctively affects the cave winds, which were stronger at narrow places. (2) Based on the different soil grain size distribution, clay was the highest in composition in the soil. The response sense of dripping water to the rainwater percolation was slow. The density of joints and other openings in dolomite make the dolomite as mesh seepage body forming piles of thin and high columns and stalactites. (3) Study of 9 dripping water samples by HYDROWIN computer program showed that the major mineral in the water was dolomite.

Key words: Soil-rock system, Weathering, Cave wind, Permeability, Dripping water
doi:10.1631/jzus.2005.B0202 **Document code:** A **CLC number:** P931.5

INTRODUCTION

Bailong (White Dragon) Cave locates in the Bailong hill occupied by Middle Triassic calcareous dolomite in Mile County, 200 km south to Kunming, Yunnan Province, China. The cave entrance is located in N 24°11′55.2″, E 103°20′59.7″, 1500 m above sea level. The tourist trail in the two-level cave is 1118.8 m long: the upper level is 477 m long and the lower level 641.8 m long. The cave is in subtropical semi-humid and plateau climate zone with annual average temperature of 17.3 °C and average precipitation of 970 mm.

"Heaven Hall", the largest chamber in the cave, connects the lower level and upper level passages. The "Heaven Bridge" is about 20.45 m high and 19.41 m long and was built to link the southern and northern parts of the upper cave level (Fig.1). Near "Heaven Hall", the chambers are narrow, only about 1−1.5 m wide. Cave winds are strong generally from south to north. The outer layers of speleothems such as draperies, stalactites, columns and stalagmites have been weathered into white powder or skin broken. Visitors have a good feeling in the upper cave because the wind frequently blows from outside into the cave entrance and from the cave to outside through two top windows.

The tourism of Bailong Cave is underdeveloped, with maximum annual tourists number being not more than 70000 since 1992. Even on the National day in 2003 the number of tourists was only 200.

MECHANISM OF SPELEOTHEM DEVELOPMENT

The critical condition for speleothem formation is the equilibrium of CO_2 partial pressure (P_{CO_2}) between cave water and atmosphere. The CO_2 in the

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* Project (Nos. 90202017 & 40071017) supported by the National Natural Science Foundation of China

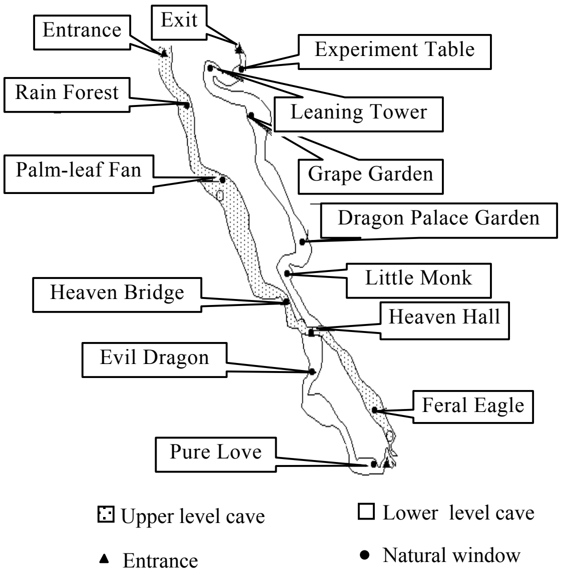

Fig.1 The sketch map of Bailong Cave

karst water is produced by microbes in the soil or breathed out from the roots of plants. When the soil water dissolves the soil CO_2, it will become carbonate acid solution to strongly corrode carbonate rocks. The dynamics of the physico-chemical processes involves three phases of reactants ($CaCO_3$ (s)-CO_2 (g)-H_2O (aq)) in the soil-rock system. The main chemical reactions in the soil-rock system providing the necessary Ca^{2+} for speleothem formation are:

$$CO_2\,(g) \rightleftharpoons CO_2\,(aq) \tag{1}$$

$$2H_2O_2+CO_2 \rightleftharpoons 2H_2CO_3 \tag{2}$$

$$CaCO_3+H_2CO_3=Ca^{2+}+2HCO_3^- \tag{3}$$

$$\Delta P_{CO_2}=\Delta P_{CO_2\,(water)}-\Delta P_{CO_2\,(atm.)} \tag{4}$$

In Eq.(4), if $\Delta P_{CO_2}>0$, the CO_2 dissolved in the water will transfer to the cave air and the Saturation Index of Calcite (SIC) in the water will increase till calcite precipitates appear. If $\Delta P_{CO_2}<0$, the CO_2 in the air will be dissolved into water to corrode the carbonates of the old speleothems. The CO_2 solubility is determined by temperature and the CO_2 solubility in water is decreased with the increase of temperature (Bögli, 1978). The tourists breath and body energy emission, light from lamps and other tourist facilities releasing heat are the most important heat sources that increase the temperature of show caves (Dragovich and Grose, 1980; Craven, 1996; Baker and Genty, 1998; Cigna, 1993; Huppert *et al*., 1993; Villar *et al*., 1986). The number of tourists visiting Bailong Cave was so small that the tourism effects could be ignored.

STUDY METHODS

Wind speed

A made in Tianjin EY3-2A portable anemograph with precision of 0.01 m/s was used to measure the cave wind. We recorded cave wind on Oct. 6 and Oct. 7, 2003 inside the cave. Each time, we first measured the wind outside, then that observed in the cave. The cave wind was measured at the site of the main tourist scenery.

Soil properties and soil CO_2 concentration

The soil was sampled and CO_2 contents were measured in the stone teeth landscape just above the "Experiment Table" of Bailong Cave (Fig.2). This site was covered by 1.5–2.5 m high bush reforested in 1990. The soil was about 0–50 cm thick and filled to 50–120 cm in the limestone solution fissures. The soil was sampled at intervals of 10 cm from the surface down. Soil CO_2 content was measured by using GXH-3010D Infrared Analyzer in April and October, 2003 and CO_2 was measured at 10 cm depth intervals and was stopped on contact with bedrock.

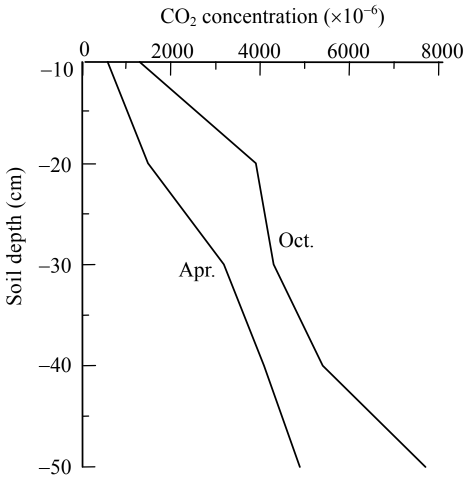

Fig.2 Soil CO_2 concentration in Bailong Cave

Dripping water chemistry

A 125 ml plastic bottle equipped with a funnel was used to collect the dripping water. The pH, conductivity and temperature of water were measured by pH-HJ90B and DDB-6200 respectively, the concentrations of $[Ca^{2+}]$, $[HCO_3^-]$, $[CO_3^{2-}]$, $[Mg^{2+}]$ were titrated with the classical method in the field laboratory, $[Cl^-]$ and $[SO_4^{2-}]$ were analyzed by titration and $[Na^+]$, $[K^+]$ by ICP spectrum apparatus in the IGSNRR (Institute of Geographic Sciences and Natural Resources Research)'s laboratory. All the SIC and soluble minerals in water were calculated by using HYDROWIN computer program.

RESULTS

Cave wind

The floor of Bailong Cave along the tourist trails was like a string of calabash. The entrance and exit of each calabash hall were narrow and the central hall was wide; the two end parts were more or less higher than the central hall. For example, the "Rain Forest" hall's entrance was 1−1.5 m wide and nearly 10 m higher than the central hall, which was 18.35 m long, 14.7 m wide and 15.07 m high. In the east side of the hall were developed about 100 bigger or smaller columns whose exit end was higher than the central hall and close to the "Palm-leaf Fan". The cave wind speed was measured on Oct. 6 and Oct. 7, 2003 (Fig.3). The outside wind speed was 0.09–0.16 m/s, temperature was 17 °C–22 °C on Oct. 6, and 0.7–1.7 m/s and 18 °C–23 °C on Oct.7. Fig.3 shows that the soil-rock system configuration had obvious affects on the cave wind. Because the cave dimensions narrowed abruptly and airflow flux was higher due to the cave rock configuration, wind speed in some places was distinctively higher. For example in "South Palace Entrance" ("S. P. Entrance") it was 2.4 m/s whereas in "Stone Waterfall", it was only 0.05 m/s. The ground wind velocity did not have obvious effects except in the natural windows that were exits in the past time. The wind near the biggest one with diameter of 13 m above "Palm-leaf Fan" was nearly 0 m/s mainly because the natural plants on the ground covered it and prevented the air exchange.

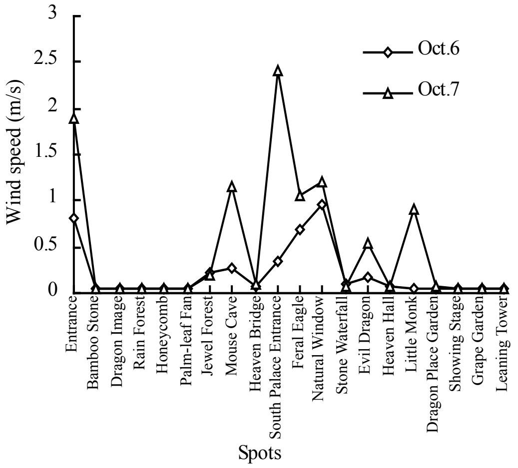

Fig.3 The cave wind speed in Bailong Cave

Soil-rock system effects on speleothem growth

One cause of the speleothem weathering was the relatively high cave wind speed; the other was the poor condition for new speleothem growth. The soil-rock system functions affecting speleothem growth include its permeability that controls the cave humidity and its provision of the Ca^{2+}. They are determined by the soil granularity, physico-chemical properties of carbonate rock crannies and organizational structure of carbonate rock and soil. The permeability coefficient of clay is less than 1/10 that of grit, so if the soil contains 50% or more clay, the permeability of the soil will be low (HPBG, 1978). The soil-rock system will be the main penetrating zone of surface water. The fissure with soil filling is the principal water seepage zone. The potential capacity of soil water to dissolve carbonate rocks is controlled by the CO_2 content in the soil and fissures, and the permeability and recharge rate. If the system permeability is very low, the system will contribute little to the speleothem development.

Soil granularity

Soil samples were taken from 10 cm to 50 cm below the soil surface to analyze their granularity by Mastersizer 2000 in the Igsnrr Laboratory. The soil granules were divided into 3 grades: clay (d<2.0 μm), fine sand (2.0 μm<d<50 μm) and coarse sand (50 μm<d<2000 μm). The soil granularity distribution with depth is shown in Fig.4.

Permeability of soil-rock system

A water percolation experiment was conducted on June 1, 2003. The total rainfall was 49.51 mm on June 2. Until 19:00 June 3 the conductivity of the

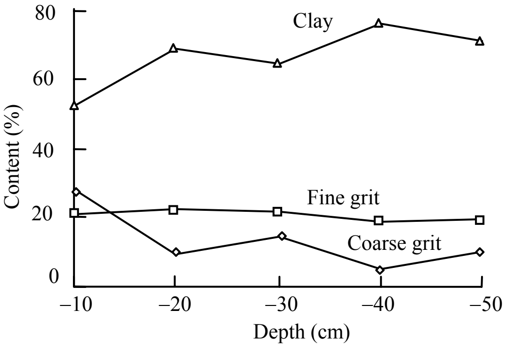

Fig.4 Soil properties

dripping water started to increase only at “Heaven Bridge” but there were no variations of water drop velocity and conductivity at other sites. At 19:00, June 4, the dripping velocity at “Experiment Table” increased from 3 drops per minute (drop/min) to 5 drop/min and at “Leaning Tower” the individual drops had become clusters of drops. On June 5, the dripping water velocity at all sites varied and on June 6, the velocity was very much faster than before. For example, it was very difficult to precisely count the drops at “Leaning Tower” and water samples were somewhat feculent. The dripping velocities variations are shown in Fig.5.

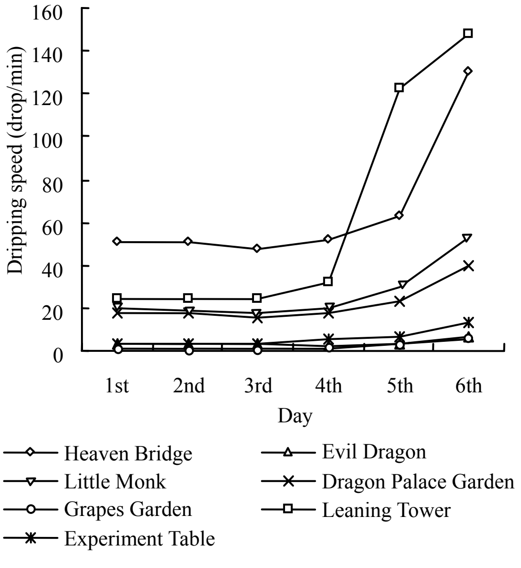

Fig.5 Dripping velocity variation

It was very clear that the variation patterns of dripping water in Bailong Cave may be classified into 3 types: the fast response at “Leaning Tower” and “Heaven Bridge”, the medium-response at “Little Monk” and “Dragon Palace Garden” (“D. P. Garden”) and slow response at “Back Imperial Garden”, “Evil Dragon” and “Grapes Garden”. Under the same precipitation, Baiyun Cave of Hebei Province and Yaolin Cave of Zhejiang Province took 30 h to react to the rainfall, in contrast to Bailong Cave’s at least 50 h. Fig.6 and Fig.7 explain that to some extent that CO_2 expulsion from the dripping water increased with increased dripping speed, which favors calcite deposition by chemical equilibrium:

$$Ca(HCO_3)_2 \rightleftharpoons CaCO_3\downarrow + CO_2\uparrow + H_2O \tag{5}$$

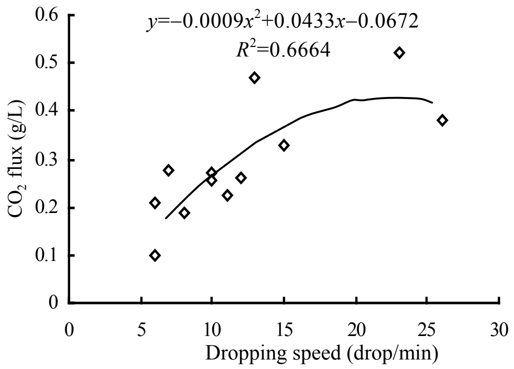

Fig.6 CO_2 flux in “Experiment Table”

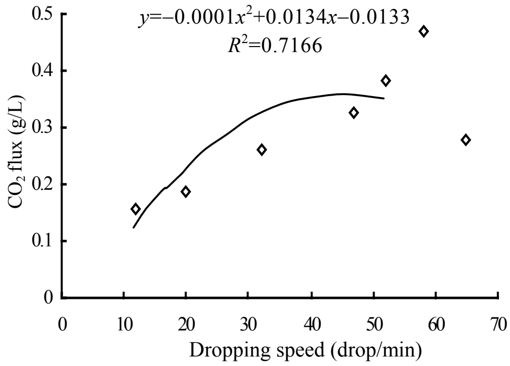

Fig.7 CO_2 flux in “Little Monk”

Ca^{2+} provided by soil-rock system

In the complete chemical processes described below, rainwater first percolates into the soil, flows through the limestone and finally drops down on the cave.

$$H_2CO_3 \rightleftharpoons H^+ + HCO_3^- \tag{6}$$

$$HCO_3^- \rightleftharpoons H^+ + CO_3^{2-} \tag{7}$$

$$CaCO_3 + H_2O + CO_2 \rightleftharpoons Ca^{2+} + 2\,HCO_3^- \tag{8}$$

$$MgCa(CO_3)_2 + 2H_2O + 2CO_2 \rightleftharpoons Mg^{2+} + Ca^{2+} + 4\,HCO_3^- \tag{9}$$

$$Ca^{2+}+2\,HCO_3^- \rightleftharpoons Ca(HCO_3)_2 \qquad (10)$$

The chemical reactions (1), (2) and (6)–(10) occur in the soil-rock system and when the water drops down the chemical reaction (5) will take place in the cave. Besides the calcite and dolomite, gypsum, sodium chloride and other minerals also possibly exist in the soil-rock system. Their dissolution process can be expressed as

$$CaSO_4 \rightleftharpoons Ca^{2+} + SO_4^{2-} \qquad (11)$$

$$NaCl \rightleftharpoons Na^{+} + Cl^{-} \qquad (12)$$

Table 1 gives the chemical composition of 9 dripping water samples analyzed in June, 2003 at “Rain Forest”, “Experiment Table”, “Leaning Tower”, “Little Monk”, “Heaven Bridge”, “Grapes Garden”, etc. located in the upper level and lower level cave. The main mineral compositions (Table 2) were calculated on the HYDROWIN computer program using data in Table 1. The major minerals were dolomite and calcite.

CONCLUSION

The soil-rock system strongly affects the cave wind speed and the properties of dripping water in the cave. Some conclusions may be drawn from the discussions above:

(1) The cave dimension structure distinctively affects the cave wind; wind at the narrow entrances and exits of the chamber are stronger than that in the central chamber. Most speleothems have been seriously weathered. Outer layers of some stalactites, stalagmites and drapery have become white powder.

(2) According to the different size distribution in the soil, the clay is the highest component at different depth. The response of dripping water to the rainwater percolation is slow compared to that in the limestone areas. The high density of joints and other openings in dolomite make it a mesh seepage body forming the pile of thin and high columns and stalactites.

(3) Study of 9 dripping water samples by HYDROWIN computer program showed that the major mineral in the dripping water was dolomite.

Table 1 Water samples analyzing result in Bailong Cave

Samp.	T (°C)	pH	Cond. (μs/cm)	HCO_3^- (mg/L)	Ca^{2+} (mg/L)	Mg^{2+} (mg/L)	Cl^- (mg/L)	Na^+ (mg/L)	K^+ (mg/L)	SO_4^{2-} (mg/L)
1	16.5	8.22	539	209.45	71.06	10.42	18.44	0.96	0.32	27.09
2	16.8	7.51	968	349.52	88.62	32.1	44.18	0.88	25.86	23.07
3	18.3	7.6	918	357.37	116.2	29.59	34.09	0.78	13.52	24.08
4	16.7	8.26	206	117.82	33.44	14.04	12.87	0.43	0.11	34.11
5	16.6	7.84	731	314.17	102	26.58	14.61	0.43	0.45	50.16
6	17.2	8.33	757	267.05	76.91	35.61	29.92	0.7	10.51	30.1
7	18.6	8.41	705	215.9	62.7	32.1	28.18	0.53	9.02	13.04
8	16.9	7.55	780	324.65	100.32	16.8	24.35	0.31	0.026	22.07
9	16.8	7.64	678	281.44	84.44	7.52	24.35	0.35	0.021	2.01

Table 2 The dripping water type and the major dissolved minerals

Samp.	Water types	Major minerals (arranged by decreasing content)	SIC
1	$Ca\text{-}HCO_3$	Calcite dolomite anhydrite halite	0.872
2	$Ca\text{-}Mg\text{-}HCO_3$	Dolomite calcite anhydrite halite	0.451
3	$Ca\text{-}Mg\text{-}HCO_3$	Dolomite calcite anhydrite halite	0.684
4	$Ca\text{-}Mg\text{-}HCO_3\text{-}SO_4$	Dolomite anhydrite halite	0.36
5	$Ca\text{-}Mg\text{-}HCO_3$	Dolomite calcite anhydrite halite	0.789
6	$Ca\text{-}Mg\text{-}HCO_3$	Dolomite anhydrite calcite halite	1.106
7	$Ca\text{-}Mg\text{-}HCO_3$	Dolomite anhydrite calcite halite	1.044
8	$Ca\text{-}Mg\text{-}HCO_3$	Calcite dolomite anhydrite halite	0.5
9	$Ca\text{-}HCO_3$	Calcite dolomite anhydrite halite	0.525

ACKNOWLEDGEMENTS

The authors sincerely thank Prof. Yang Jingrong, of the Institute of Geographic Sciences and Natural Resources Rearch, Chinese Academy of Sciences, for analyzing the water samples in the laboratory; thanks are also due to Mr. Zhou Guanglin, Song Chao, Li Pingwei and Chen Xikang, Bailong Cave Tourism Administration of Mile County, Yunnan, for their valuable support.

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