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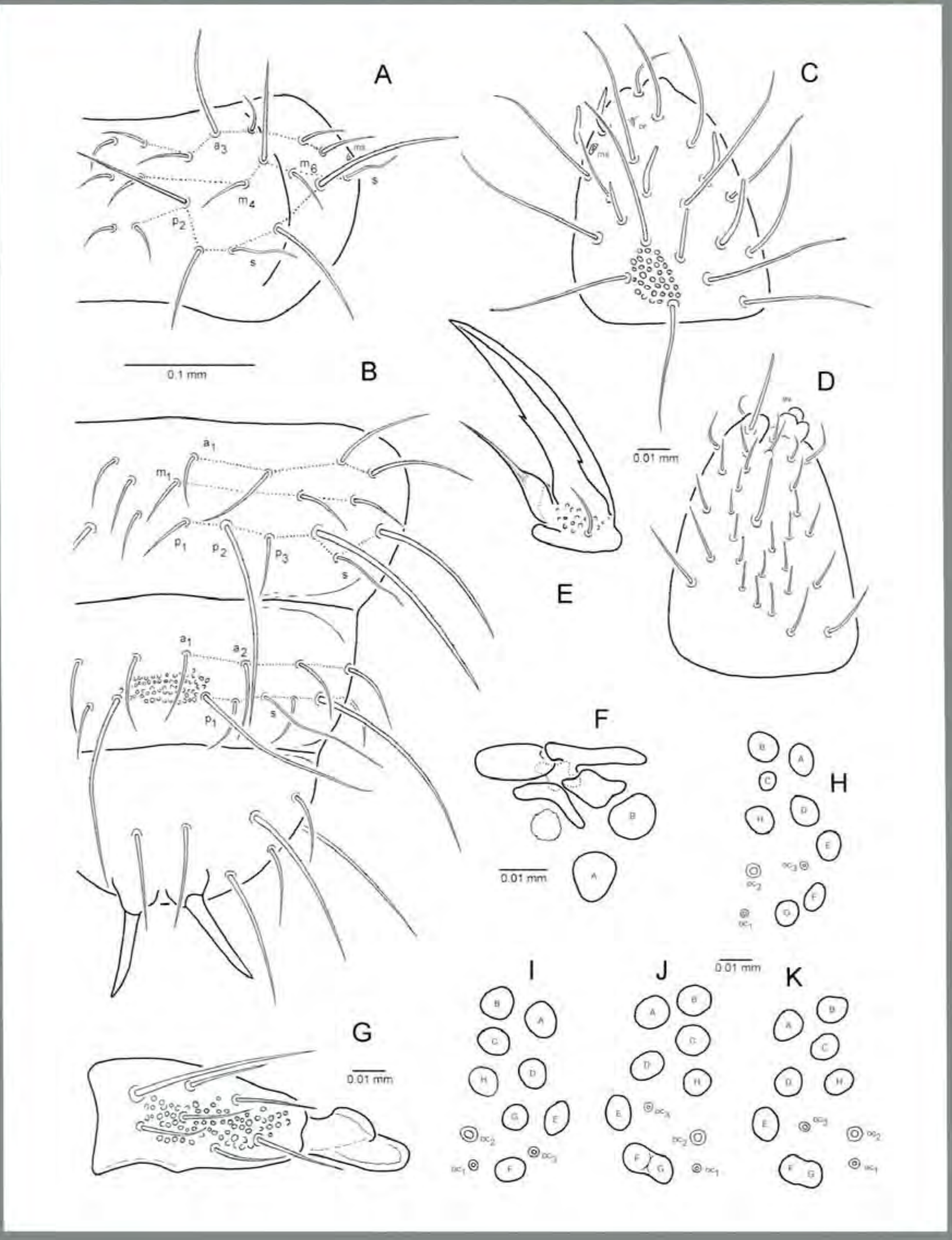

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T. Dogwiler, C.M. Wicks, and E. Jenzen – An assessment of the applicability of the heat pulse method toward the determination of infiltration rates in karst losing-stream reaches. *Journal of Cave and Karst Studies,* v. 69, no. 2, p. 237–242.

AN ASSESSMENT OF THE APPLICABILITY OF THE HEAT PULSE METHOD TOWARD THE DETERMINATION OF INFILTRATION RATES IN KARST LOSING-STREAM REACHES

TOBY DOGWILER[1], CAROL M. WICKS[2], AND ETHAN JENZEN[3]

Abstract: Quantifying the rate at which water infiltrates through sediment-choked losing stream reaches into underlying karstic systems is problematic, yet critically important. Using the one-dimensional heat pulse method, we determined the rate at which water infiltrated vertically downward through an estimated 600 m by 2 m sediment-choked losing-stream reach in the Devil's Icebox Karst System of Central Missouri. The infiltration rate ranged from 4.9×10^{-5} to 1.9×10^{-6} m s^{-1}, and the calculated discharge through the reach ranged from 5.8×10^{-2} to 2.3×10^{-3} m^3 s^{-1}. The heat pulse-derived discharges for the losing reach bracketed the median discharge measured at the outlet to the karst system. Our accuracy was in part affected by significant precipitation in the karst basin during the study period that contributed flow to the outlet from recharge areas other than the investigated losing reach. Additionally, the results could be improved by future studies that deal with identifying areas of infiltration in losing reaches and how that area varies in relation to changing flow conditions. However, the heat pulse method appears useful in providing reasonable estimates of the rate of infiltration and discharge of water through sediment-choked losing reaches.

INTRODUCTION

Stream reaches that lose water diffusely through their substrate into underlying aquifers are common in karstic basins (White, 1988). In Missouri, 389 of 502 watersheds (~77%) have losing stream reaches, many of which are choked with sediment (Jacobson and Gran, 1999). Losing stream reaches are often hydrologically complex and typically lose water through diffuse infiltration over a length of streambed, direct flow into swallets, or a combination of both. Losing stream reaches are common in both karst and non-karst terrains and in all cases play an important function in aquifer recharge and ground-water – surface-water interactions (Babcock and Cushing, 1942; Burkham, 1970; Silliman and Booth, 1993). A number of studies have been performed to understand the flow dynamics of losing- and gaining-stream reaches (e.g., Constantz et al., 1994; Silliman et al., 1995; Constantz and Thomas, 1996; Ronan et al., 1998). Gaging flow through losing-stream reaches is difficult for a number of reasons. In many sediment-choked reaches, loss occurs via diffuse seepage into the streambed rather than at a discrete point. Furthermore, zones of infiltration can shift longitudinally due to seasonal changes in the adjacent aquifer levels. In karst losing reaches, discharge regimes are typically flashy, and stream sediments are mobile and subject to scour and fill sequences during high flow events (Dogwiler and Wicks, 2004). These characteristics limit the effectiveness of permanently installed continuous monitoring stage-based gaging stations (Constantz and Thomas, 1996).

As such, there is a critical need for a method of understanding and monitoring the flow dynamics of losing reaches. Numerical modeling of ground-water flow and contaminant transport in these hydrologic environments is dependent upon the ability to accurately determine infiltration rates in losing reaches (Wang and Anderson, 1982; Silliman et al., 1995). Furthermore, bigger-picture hydrologic characterizations of karst systems require a detailed understanding of the fluxes and mass balances of water, solutes, and sediments through these systems (e.g., Silliman and Booth, 1993; Wicks and Engeln, 1997; Halihan et al., 1998; Dogwiler and Wicks, 2004; Lerch et al., 2005). These needs are even more pressing in rapidly urbanizing areas like the Devil's Icebox Karst System (DIB) of Central Missouri.

METHODS

In this study, we have applied the heat pulse technique to a karst losing reach. Our study site, the Bonne Femme Creek Losing Reach, is a sediment-choked losing stream reach that recharges, in part, the DIB in Central Missouri (Figs. 1 and 2). Wicks (1997a, 1997b) and Lerch et al.

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Figure 1. (A) The Bonne Femme Creek losing reach during a low flow period and (B) approximately 24 hours after a significant storm event.

(2005) provide thorough hydrologic descriptions of the DIB basin. Bonne Femme Creek is the source of allogenic water to the cave stream that flows through DIB (Lerch et al., 2005). This portion of the losing reach is bounded on the upstream side by a 1 m deep pool that represents the limit of perennial surface-water flow, and on the downstream side by a large swallet. Except during extreme high-flow events, surface water is lost diffusely through the sediment substrate and no surface flow enters the swallet at the downstream end of the reach.

The heat pulse method provides a means of monitoring infiltration rates through losing-stream reaches using thermal variations in the stream substrate as a proxy for infiltration rates. The technique was developed and has been used in ephemeral streams in the arid southwestern U.S. (Constantz et al., 1994; Constantz and Thomas, 1996) and perennial streams in the humid Midwestern U.S. (Silliman and Booth, 1993; Silliman et al., 1995). The heat pulse method employs tracing thermal pulses, which occur in the surface water due to diurnal forcing or the rapid influx of thermally unequilibrated waters during storm events, through the recharge zone. Because suitable high-resolution temperature loggers are economical and readily available, the heat pulse method is an attractive approach for monitoring infiltration rates through losing-stream reaches. This study utilizes a portion of a dataset generated by Dogwiler (2002) and analyzed, for a purpose separate from this study, in Dogwiler and Wicks (2005). Here we have re-examined these data and applied the heat pulse method to them in order to determine infiltration rates through the Bonne Femme Losing Reach.

The temperature series data[1] were collected using Stowaway Tidbit temperature dataloggers positioned at different depths in the stream substrate at three stations in a portion of the ~600 m Bonne Femme Losing Reach from May 27, 2000 to July 10, 2000 (Fig. 2). Station 1 was located approximately 8 m downstream of the end of the perennial stream reach. Stations 2 and 3 (most downstream station) were spaced longitudinally downstream in 15–20 m intervals. The depths at which the dataloggers were placed are in the general range recommended by Silliman et al. (1995). In placing the temperature dataloggers, there is a trade-off between detecting the magnitude of the pulse, which decreases with depth, and the phase shift of the signal, which increases with depth (Silliman et al., 1995). Additionally, as depth increases, the assumption that flow is one-dimensional becomes more unreasonable. Many karst streams, including Bonne Femme Creek, have thin veneers of bed sediment. Therefore, relatively shallow placement of temperature sensors is both ideal and necessary. We positioned the temperature dataloggers at each station at depths of 1–3, 7–10, and 15–20 cm. The range for each depth represents both the difficulty of precisely burying the dataloggers in a streambed, as well as the actual thickness of the dataloggers. For the purpose of our calculations (described below), we have focused on the data from the upper and lower dataloggers at each station and quantified the depths as 2.0 cm and 17.5 cm, respectively. Each datalogger was programmed to record temperature at 15 minute intervals.

At each of the three stations, we identified heat pulses and used them to track the thermal fluxes through the recharge zone. The rate of thermal flux, which is assumed to be controlled by downward advection of the surface water, becomes a direct proxy for infiltration rate toward the underlying aquifer (Silliman et al., 1995). The heat pulse method involves measuring the lag time between a maximum (or minimum) surface temperature and a corresponding maximum (or minimum) subsurface temperature and the distance between the surface and subsurface monitoring locations (Taniguchi and Sharam, 1990). The velocity v_t at which a heat pulse migrates downward through sediment is proportional to the rate q_i at which water infiltrates through that sediment according

[1] Available as a comma-delimited ASCII file on the *JCKS* website or through the NSS archives and library.

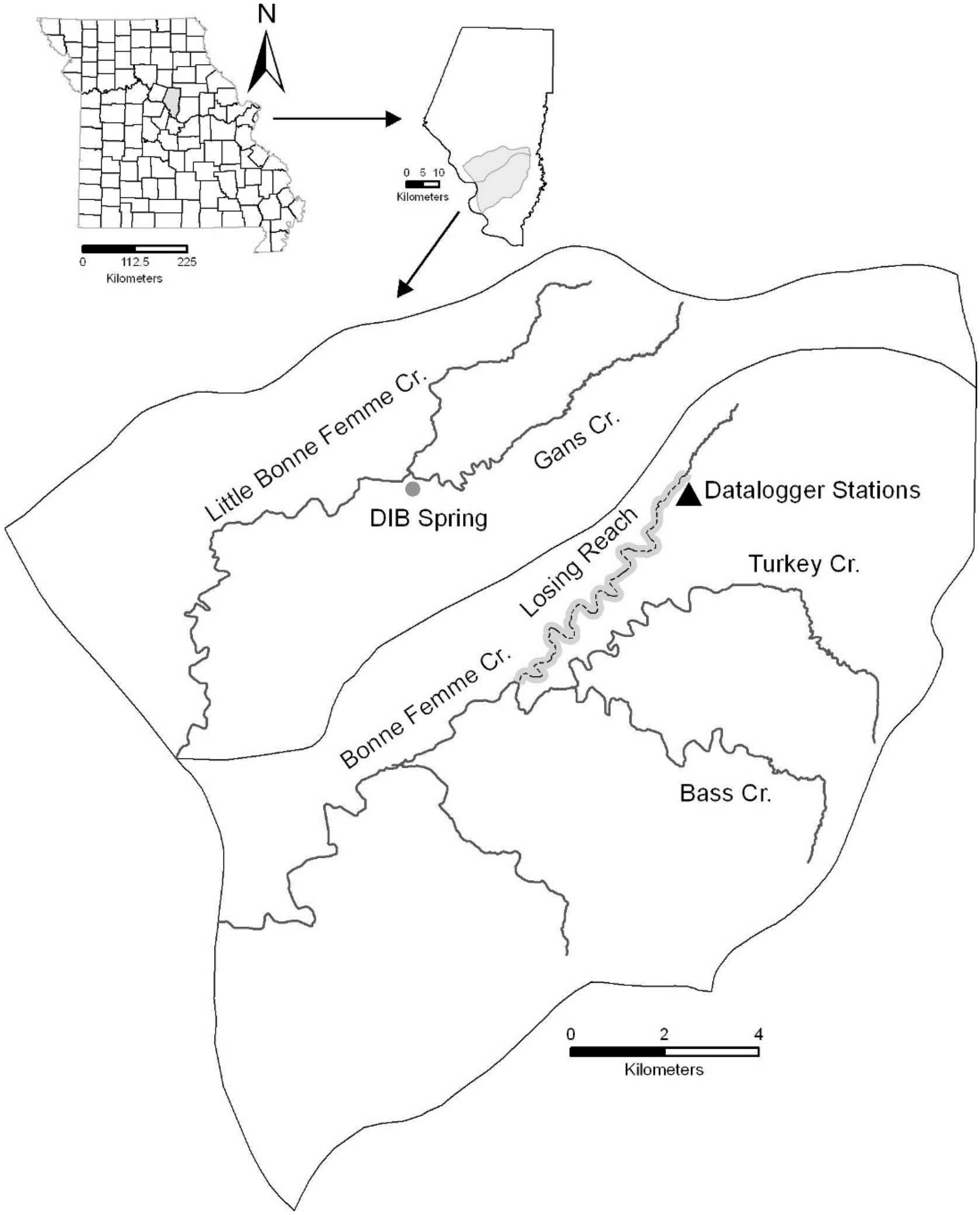

Figure 2. Location and hydrologic setting of the Devil's Icebox Karst System (DIB), including the Bonne Femme Creek Losing Reach (indicated by gray highlighting and dashed line). The total recharge area for the DIB is approximately 34.0 km^2 (Lerch et al., 2005). Water is pirated via the losing reach under the topographic drainage divide that separates the Bonne Femme Creek and Little Bonne Femme Creek. Ultimately, the water drained by the DIB re-emerges as surface flow at Connor's Cave Spring (indicated as DIB Spring on the map).

to

$$q_i = v_t \left(\frac{c_s \rho_s}{c_w \rho_w} \right) \quad (1)$$

where c_w and c_s are the specific heats of the water and wet sediment, respectively and ρ_w and ρ_s are the density of water and bulk density of the wet sediment, respectively (Constantz and Thomas, 1996). Thus, c_s ρ_s and c_w ρ_w are the volumetric heat capacities of the water and wet sediment, respectively (see Table 1 for values used for these constants).

Results and Discussion

For all depths and at all stations, diurnal variations were noted in the temperature data, although during some

Table 1. Constants used in heat pulse calculations (see Equation 1 in the text).

Parameter	Value	Units	Description
c_s	0.840	kJ kg^{-1} °K^{-1}	Specific heat of wet sediment
ρ_s	2,820.0	kg m^{-3}	Bulk density of wet sediment
$c_s\ \rho_s$	2,368.0	kJ m^{-3} °K^{-1}	Volumetric heat capacity of wet sediment
c_w	4.184	kJ kg^{-1} °K^{-1}	Specific heat of water
ρ_w	1,000.0	kg m^{-3}	Density of water
$c_w\ \rho_w$	4,184.0	kJ m^{-3} °K^{-1}	Volumetric heat capacity of water

time periods precipitation-induced flow temporarily reduced the variations (Fig. 3). Variations of up to ~7°C were common at a depth of 2.0 cm at all stations, whereas the maximum variation observed at 17.5 cm depth was ≤ 4°C. At the 2.0 cm depth, the maximum and minimum daily temperatures typically occurred between 3:00 and 6:00 p.m. CDT and between 6:00 and 9:00 a.m. CDT, respectively. The maximum and minimum daily temperatures at the 17.5 cm depth generally lagged approximately five to six hours behind those recorded at the 2.0 cm depth. In addition to the observed diurnal variation, there were weekly cooling (or warming) trends.

Using data from the 2.0 cm and 17.5 cm depths, 190 heat pulses were noted in the record. Equation (1) was applied to all 190 recognizable heat pulses, and Table 2 contains a summary of the descriptive statistics for the calculated υ_t and Table 3 contains the same analysis for q_i. The overall median heat pulse velocity υ_t was 1.1×10^{-5} m s^{-1} and the derived overall median infiltration rate q_i was 6.5×10^{-6} m s^{-1}. The rates of infiltration we found are comparable to rates determined in investigations utilizing the heat pulse method in other geologic settings (i.e., Constantz and Thomas, 1996; Constantz et al., 1994; Ronan et al., 1998; Silliman, 1993; Silliman, 1995), and therefore, appear reasonable.

An important assumption in the heat pulse method is that the rate of thermal flux υ_t is controlled by the downward advection of the surface water and is therefore a proxy for the infiltration rate q_i. The relative importance of conduction and convection in the substrate of the losing reach can be assessed based on the calculated Peclet number. Following the approach of Silliman et al. (1995), we calculated the range of Peclet numbers for the losing reach as 0.3 to 4.0 with a mean of 1.2. For infiltration rates greater than 3.7×10^{-6} m s^{-1}, the Peclet number is greater than 1.0 and advection dominates. At the lower end of our range of calculated infiltration rates, we push the assumption of dominantly advective transport. Of the 185 heat pulses we tracked, only 20 (11%) of the resultant q_i values are less than the 3.7×10^{-6} m s^{-1} threshold for advectively dominated transport. All of our median and mean q_i values are well above the threshold for advective transport (Table 4).

Based on the range of our derived q_i values, the volumetric discharge of water through the ~600 m by 2 m losing reach was between 2.3×10^{-3} and 5.8×10^{-2} m^3 s^{-1} with a median of 7.8×10^{-3} m^3 s^{-1} (Table 4). Over the same period, the median discharge from DIB (Fig. 3 and Table 4) was 4.2×10^{-2} m^3 s^{-1} (Lerch et al., 2005). Thus, the heat pulse-derived discharge range reasonably brackets the measured discharge at DIB. However, the median heat pulse-derived discharge through the losing reach is much

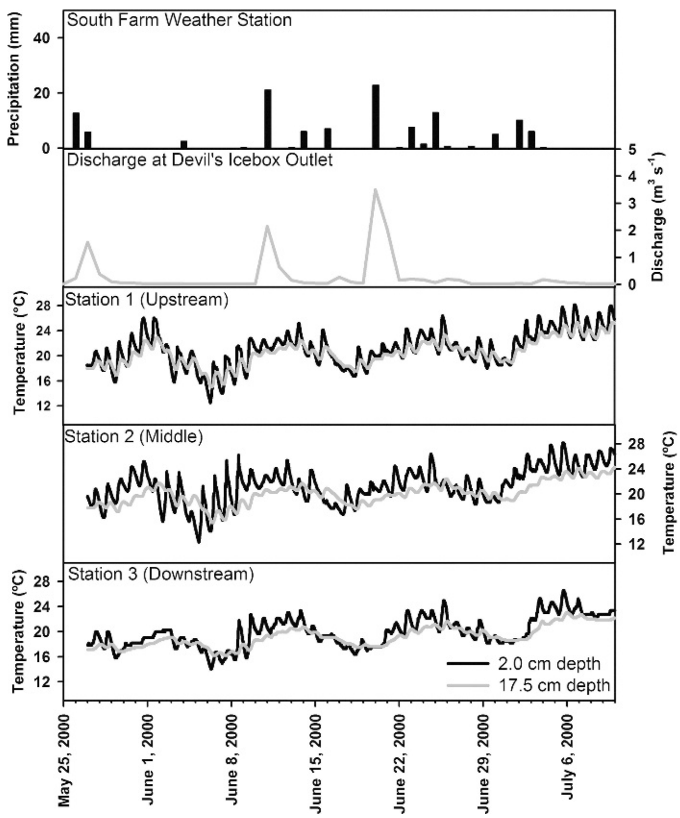

Figure 3. Graph of the time-series data utilized in this study. The uppermost plot shows 24-hour precipitation totals from the University of Missouri South Farm Weather Station located ~1 km north of the Bonne Femme Creek losing reach. The second plot from the top shows the discharge measured at the DIB spring (see Figure 2). The lower three plots depict water temperature at the 2.0 cm and 17.5 cm depths for the three datalogger stations. Note that Station 1 is the upstream-most station and Station 3 is furthest downstream.

Table 2. Calculated heat pulse velocities v_t in the Bonne Femme Creek Losing Reach.

Station	Median ($m\ s^{-1}$)	Mean ($m\ s^{-1}$)	Range: Low ($m\ s^{-1}$) High ($m\ s^{-1}$)	Stan. Dev. ($m\ s^{-1}$)	No. of Pulses
1	1.6×10^{-5}	2.2×10^{-5}	$6.9 \times 10^{-6} – 8.6 \times 10^{-5}$	1.7×10^{-5}	73
2	1.0×10^{-5}	1.4×10^{-5}	$3.4 \times 10^{-6} – 8.6 \times 10^{-5}$	1.3×10^{-5}	62
3	8.4×10^{-6}	1.1×10^{-5}	$3.5 \times 10^{-6} – 3.4 \times 10^{-5}$	6.9×10^{-6}	55
Overall	1.1×10^{-5}	1.6×10^{-5}	$3.4 \times 10^{-6} – 8.6 \times 10^{-5}$	1.4×10^{-5}	190

smaller than the median measured discharge from DIB. The mismatch between the median calculated and measured discharges is likely due to uncertainty relating to the area through which infiltration occurs, rather than due to poor assumptions or parameterization of our infiltration calculations. As Figure 1 suggests, estimating the infiltration area of the losing reach is difficult. Future work is needed to define the area of streambed that serves as an infiltration boundary and to determine how that area varies as a function of flow conditions.

Under low flow conditions, the volumetric flux of water through the losing reach should equal the discharge from DIB (Lerch et al., 2005). However, a total of 124 mm of precipitation fell at the University of Missouri South Farm Weather Station on 17 rain days during the 47 day study period (Fig. 3). At least some of the difference between the median calculated losing-reach discharge and the median measured outlet discharge is attributable to diffuse recharge from elsewhere in the karst basin during precipitation events. We tested this hypothesis by filtering the DIB spring discharge data to isolate flow rates for days representing baseflow conditions. Two different filters were applied to the data. Based on the discussion of the discharge rating curve for the DIB spring in Lerch et al. (2005), we used their criteria for low flow (based on their Equation 1) and re-calculated the flow statistics for days during our study period with flows of 0.43 $m^3\ s^{-1}$ or less (Table 4). We also filtered the data by identifying all days with, or preceded by, 2.54 mm or more of precipitation and defining those as days with above baseflow discharges. Both filtering methods improved the statistical overlap of the calculated and measured values of discharge at the losing reach and spring, respectively (Table 4). Although the filtered data still range higher than the heat-pulse derived estimations of discharge, the ability of the method to bracket the median discharge values measured at the DIB spring is encouraging with respect to the applicability of the method to karst systems.

Table 3. Calculated heat pulse-derived infiltration rates q_i in the Bonne Femme Creek Losing Reach.

Station	Median ($m\ s^{-1}$)	Mean ($m\ s^{-1}$)	Range: Low ($m\ s^{-1}$) High ($m\ s^{-1}$)	Stan. Dev. ($m\ s^{-1}$)	No. of Pulses
1	9.3×10^{-6}	1.2×10^{-5}	$3.9 \times 10^{-6} – 4.9 \times 10^{-5}$	9.7×10^{-6}	73
2	5.7×10^{-6}	7.8×10^{-6}	$1.9 \times 10^{-6} – 4.9 \times 10^{-5}$	7.5×10^{-6}	62
3	4.8×10^{-6}	6.0×10^{-6}	$2.0 \times 10^{-6} – 1.9 \times 10^{-5}$	3.9×10^{-6}	55
Overall	6.5×10^{-6}	9.1×10^{-6}	$1.9 \times 10^{-6} – 4.9 \times 10^{-5}$	8.1×10^{-6}	190

Table 4. Comparison of total discharge through the Bonne Femme Creek Losing Reach as calculated with the heat pulse method and actual measured discharges at the DIB spring. The discharge data for the outlet is also presented using two filtering techniques to isolate baseflow discharges from storm-induced discharges. Because the losing reach has been shown to contribute nearly all of the flow to the DIB during baseflow conditions (Lerch et al., 2005), the filtered data provide the best comparison with the heat pulse-derived discharges.

Measurement Method	Median Discharge ($m^3\ s^{-1}$)	Mean Discharge ($m^3\ s^{-1}$)	Range: Low ($m\ s^{-1}$) High ($m\ s^{-1}$)
Losing Reach			
Heat Pulse Method	7.8×10^{-3}	1.1×10^{-2}	$2.3 \times 10^{-3} – 5.8 \times 10^{-2}$
DIB spring			
All Discharge Data	4.2×10^{-2}	2.8×10^{-1}	$1.3 \times 10^{-2} – 3.5 \times 10^{0}$
Baseflow Data (Rating Curve Filter)	3.8×10^{-2}	7.6×10^{-2}	$1.3 \times 10^{-2} – 3.7 \times 10^{-1}$
Baseflow Data (Precipitation Filter)	2.3×10^{-2}	4.9×10^{-2}	$1.6 \times 10^{-2} – 1.6 \times 10^{-1}$

SUMMARY AND CONCLUSIONS

Because the hydrology of the DIB is well-understood from previous investigations, the Bonne Femme Losing Reach provides an excellent opportunity for assessing the utility of the heat pulse method. This study suggests that the heat pulse method can be applied to sediment-choked losing stream reaches in karst areas to determine infiltration rates and approximate discharges. We found reasonable agreement in the mass balance of calculated discharge input to the system through the losing reach and the measured discharge at the outlet of the karst basin. Future work should focus on defining the infiltration area within losing reaches and assessing how that area varies with changing flow conditions.

The ability to estimate infiltration rates is critical to parameterizing the boundary conditions in numerical flow models (Wang and Anderson, 1982). Thus, the heat pulse method will provide better data that could lead to more robust modeling of karst systems. Additionally, the heat pulse method offers an alternative approach to quantifying discharge in karst stream reaches where traditional gaging strategies have proven inadequate due to the dynamics of flow, sediment transport, and the difficulty of maintaining rating curves in these highly variably fluvial systems.

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P. Audra and F. Hobléa – The first cave occurrence of jurbanite [Al(OH SO_4) · $5H_2O$], associated with alunogen [$Al_2(SO_4)_3$ · $17H_2O$] and tschermigite [$NH_4Al(SO_4)_2$ · $12H_2O$]: thermal-sulfidic Serpents Cave, France. *Journal of Cave and Karst Studies,* v. 69, no. 2, p. 243–249.

THE FIRST CAVE OCCURRENCE OF JURBANITE [Al(OH SO_4) · $5H_2O$], ASSOCIATED WITH ALUNOGEN [$Al_2(SO_4)_3$ · $17H_2O$] AND TSCHERMIGITE [$NH_4Al(SO_4)_2$ · $12H_2O$]: THERMAL-SULFIDIC SERPENTS CAVE, FRANCE

Philippe Audra[1] and Fabien Hobléa[2]

Abstract: Serpents Cave, located in the French Alps, contains a sulfidic-thermal (41 °C) karst spring. Degassing of the sulfidic vapor produces diverse sulfate minerals. The reaction with the limestone host-rock produces gypsum, anhydrite, sulfur, and magnesium calcite. The reaction with an artificial material (aluminum door) produces alunogen, tschermigite, and jurbanite. Microbial activity is suspected in the genesis of sulfur and tschermigite. Aluminum sulfates have usually been reported in mines, in volcanic settings, and in rock-shelters in phyllites. Some of these alum minerals such as tschermigite are rarely observed in caves, and jurbanite is identified here for the first time in a cave. Serpents Cave is therefore an important site for sulfate minerals in caves, even if the aluminum sulfates should be considered border minerals because they originate from sulfur vapor reaction with artificial media.

Introduction

The chemistry of development of hypogenic caves by the oxidation of sulfur compounds to sulfuric acid, with the resulting corrosion and gypsum replacement of limestone, has only relatively recently been defined (Morehouse, 1968; Egemeier, 1981). The replacement corrosion process occurs according to the following reactions: (1) H_2S originating from degassing oxidizes, (2) then sulfuric acid reacts with the limestone rock to produce gypsum ($CaSO_4 \cdot 2H_2O$) as a by-product, and finally (3) CO_2 can again dissolve the limestone rock according to the classical reaction of limestone dissolution.

$$H_2S + 2O_2 \Rightarrow H_2SO_4 \quad (1)$$

$$H_2SO_4 + CaCO_3 + H_2O \Rightarrow CaSO_4 \cdot 2H_2O + CO_2 \quad (2)$$

$$CaCO_3 + CO_2 + H_2O \Rightarrow Ca(HCO_3)_2 \quad (3)$$

Sulfidic hypogenic caves have been studied in the Guadalupe Mountains, USA (Hill, 1987), in the Frasassi Caves, Italy (Galdenzi and Menichetti, 1995; Forti, 1996), and in France (Audra, 2005; Audra et al., 2002, 2007; Audra and Häuselmann, 2004; Audra and Hofmann, 2004). The active participation of microbial processes was identified in Movile Cave, Romania (Sarbu et al., 1996), in the Frasassi Caves, Italy (Sarbu et al., 2002), and in Villa Luz Cave, Mexico (Hose and Pisarowicz, 1999).

Aix-les-Bains is a thermal resort in Savoy, France, located between the Bourget Lake shore and the foot of the Bauges massif at the front of the Northern French Prealps overthrust. Serpents Cave, a water-table cave, harbors the Alum Spring, a sulfidic and thermal spring (about 41 °C). Since the early mention of sulfidic origin of the cave by Martel (1935), it has been studied to define the origin of the thermal flow-path (e.g., Carfentan et al., 1998); it is only recently that Serpents Cave has been studied for its karst processes (Hobléa, 1999). Within the cave, sulfidic degassing produces replacement-corrosion with a H_2S-rich corrosive atmosphere and deposition of gypsum.

Chevalley Aven and Serpents Cave belong to the same system (Fig. 1) (Hobléa, 1999; Gallino, 2006). Chevalley Aven is a blind chimney developed above the water table, made of stacked spheres arranged in a bush-like pattern, originating mainly from condensation-corrosion (Audra et al., 2007). Chevalley Aven contains gypsum as crust, flowstones, stalactites and stalagmites, made by replacement corrosion originating from the thermal pool which is degassing H_2S. Biofilm develops on the walls where condensation moisture occurs. The active Alum thermal spring flows into the cave at the upstream head. The thermal characteristics of the spring are responsible for major condensation-corrosion activities as evidenced by the development of spherical ceiling cupolas.

The discharge of Alum Spring ranges from 8 to 42 L s^{-1}; the temperature oscillates seasonally between 33.5 and 46.6 °C due to some mixing with meteoric water (Muralt, 2003). Water has a high concentration of calcium,

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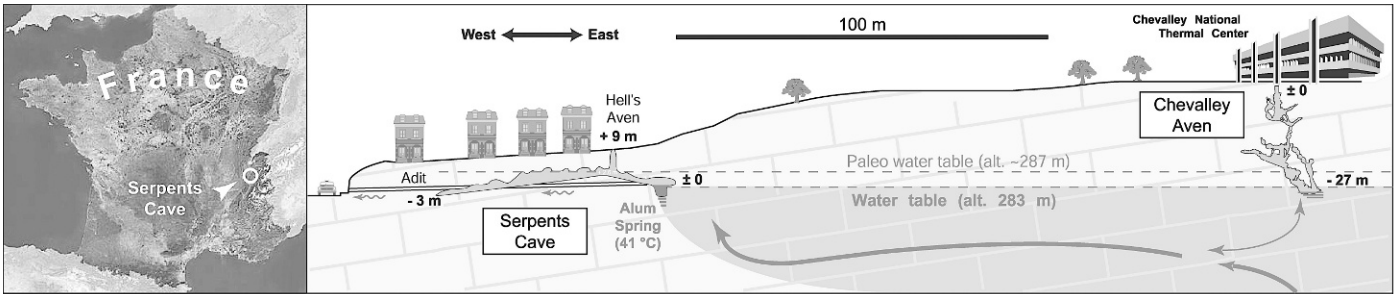

Figure 1. Profile of the Aix-les-Bains thermal-sulfidic cave system (survey SC Savoy, EDYTEM). Chevalley Aven is a blind chimney developed above the water table; Serpents Cave is a water table cave. The active Alum thermal spring flows into the cave at the upstream head (Audra et al., 2007).

sulfate, and secondary sodium, magnesium, and silica (Table 1). The temperature, high silica and salt contents, and presence of trace elements suggest a deep artesian flowpath (about 2000 m) confined under the Bourget Lake syncline, where Triassic evaporites are leached (Carfantan et al., 1998). The water is flowing out turbulently from the Alum spring and produces a CO_2 and H_2S degassing, this last being evidenced by the characteristic rotten egg smell together with a thick coating of replacement gypsum covering walls around the spring pool (Fig. 2). The spring also brings up microbial soft flakes.

In this paper, we describe the processes responsible for the formation of sulfates in the Serpent sulfidic-thermal cave. To examine the products of the corroding activities, we carried out X-ray diffraction (XRD) of the corrosion products. The results of our studies indicate not only the classical sulfate minerals deposited through replacement-corrosion, but we also identify aluminum sulfates growing on an artificial door that encloses the spring. Some of these alum minerals such as tschermigite are rarely observed in caves, and jurbanite is identified here for the first time in a cave. Finally, we discuss the role of the artificial aluminum of the door in the formation of the aluminum sulfates, which for this reason, are considered as border minerals.

MATERIALS AND METHODS

SAMPLE SITE DESCRIPTION

Distribution of Gypsum and Aluminum Sulfates Around the Sulfidic-Thermal Spring

The Alum Spring thermal siphon (37–41 °C) is isolated from outside contamination by a glass partition framed with aluminum (Fig. 2). This door separates two types of microclimatic conditions. The inside temperature is about 37 °C, and humidity at saturation produces condensation on the glass; outside of the door, the temperature is about 24 °C, and the atmosphere is less saturated with vapor, thus allowing some evaporation. Degassing in the Alum Spring produces sulfidic vapor which reacts with the surroundings (inside and outside).

Inside the Door. Where temperature and humidity are high, vapor condenses along walls and limestone replacement

Table 1. Main physical and chemical data from the Alum spring, Serpents Cave, Aix-les-Bains.

Physico-chemistry	Values	Reference
Temperature	33.5–46.6 °C	Muralt, 2003
Discharge	8–42 L s^{-1}	Muralt, 2003
Conductivity	576–691 μS cm^{-1}	Hobléa, 1999
pH	6.5	Hobléa, 1999
TDS	496 mg L^{-1}	Muralt, 2003
HCO_3^-	262 mg L^{-1}	Muralt, 2003
SO_4^{2-}	60–230 mg L^{-1}	Muralt, 2003
Cl^-	15–30 mg L^{-1}	Muralt, 2003
Na^+	20–40 mg L^{-1}	Muralt, 2003
Ca^{2+}	100–150 mg L^{-1}	Muralt, 2003
K^+	3–6 mg L^{-1}	Muralt, 2003
Mg^{2+}	10–25 mg L^{-1}	Muralt, 2003
SiO_2	22–26 mg L^{-1}	Muralt, 2003
H_2S	5 mg L^{-1}	Iundt et al., 1987
Trace Elements	Al, Fe, Mn, Pb, B, Sr, Sn, Sb, Ba, Li	Iundt et al., 1987

Figure 2. The Alum sulfidic-thermal spring, in Serpents Cave. The thermal siphon (37–41 °C) is isolated from outside contamination by a glass partition framed with aluminum. Note floating microbial mats at the water surface and gypsum replacement crust on the wall. Studied minerals form on the frame of the glass door.

occurs. Consequently, the walls are covered with a several-centimeter thick gypsum crust. XRD analysis shows the presence of anhydrite, together with gypsum (Fig. 3). In some places, the gypsum crust is covered with a thin (<1 mm) yellowish coating. It corresponds to native sulfur, together with magnesium calcite (Fig. 4). Sulfur crystals are not visually distinguishable. The elemental sulfur may originate from sulfate reduction through microbial activity (Barton and Luiszer, 2005). The magnesium calcite precipitation may be of hydrothermal origin, possibly influenced by microbial activity.

Outside the Door. The gypsum crust quickly disappears at about 1 m from the door because of seepage plus dissolution by condensation from cold surface air entering the cave. However, a peculiar crust has developed on the aluminum frame of the glass door, especially close to the contact between the rubber joint, the glass, and the aluminum (Fig. 5). It occurs as a soft crust, mainly pure white, but sometimes transparent or tinted in grey or brown. The taste, bitter and astringent, is typical of alum. XRD analyses described below show the presence of gypsum with three aluminum sulfates: alunogen, jurbanite, and tschermigite (Fig. 6).

Method

X-ray powder diffraction (XRD) patterns were recorded on a Philips diffractometer using Cobalt radiation (λ = 1.79 Å) with a secondary graphite monochromator. The diffractometer optic used to record all samples was a front fixed slit of 1°, a scattered radiation slit of 1° after the sample, and a 0.2 mm detector slit. The X-ray tube operating conditions were 40 kV and 40 mA and the step-scan data were continuously collected over the range 3.5 to 78° 2θ using a step interval of 0.05° 2θ and a counting time of 2.5 s.

Results

Mineralogical Characteristics of the Jurbanite and Associated Hydrous Aluminum Sulfates

The Alum Spring in Serpents Cave owes its name to the alum mineral, which is a generic term for hydrous sulfates of aluminum and an alkali. Three of these alum minerals evidenced by XRD (Fig. 6), alunogen, tschermigite, and jurbanite, are presented here. Information about the minerals is provided by Jolyon and Ida (2006) for a general presentation, and Hill and Forti (1997) for cave minerals.

Alunogen

Alunogen ($Al_2(SO_4)_3 \cdot 17H_2O$) is a triclinic hydrated aluminum sulfate generally associated with volcanic fumaroles or decomposition of sulfides in coal mines. It appears as a crust made of small white to transparent crystals, but it is often tinted by impurities. In caves, alunogen is a mineral present in volcanic environments,

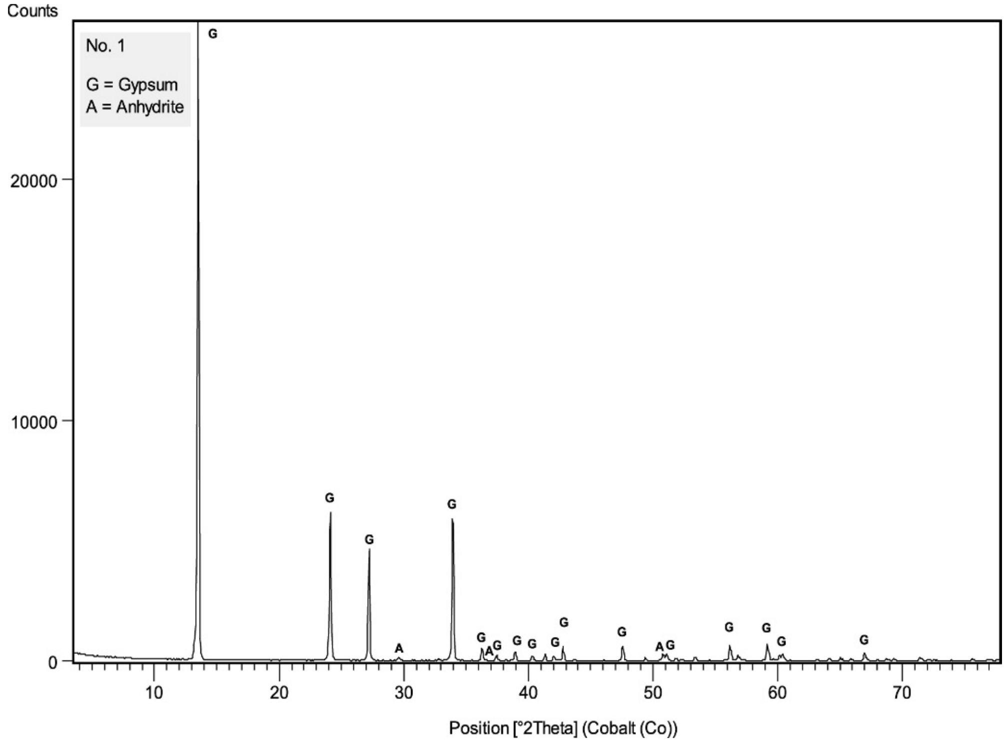

Figure 3. X-ray diffraction diagram of the gypsum crust covering walls inside the chamber isolated by a door. Anhydrite occurs, together with gypsum.

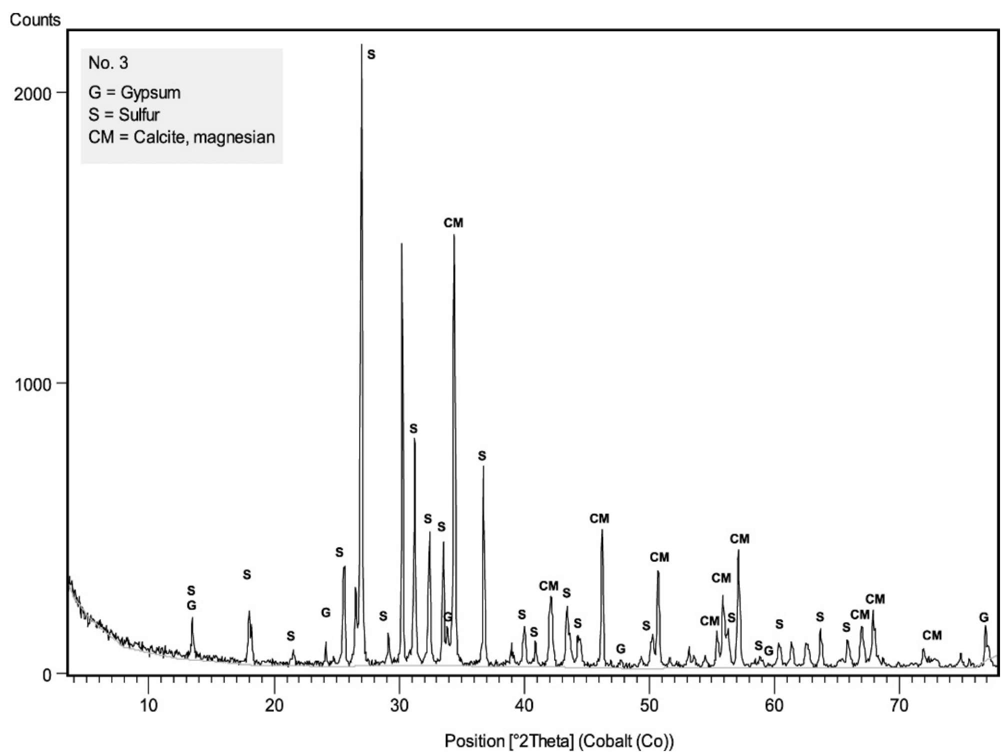

Figure 4. X-ray diffraction diagram of the yellow coating of the gypsum crust. Native sulfur is present, together with magnesium calcite.

Figure 5. Detail of the frame of the glass door. Aluminum sulfate crystals are growing on outer side on aluminum frame, along rubber joints. Outside temperature is 24 °C, inside temperature is 37 °C; humidity at saturation produces condensation on the glass.

either derived from fumarole gases reacting with tuff rock (grotta dello Zolfo, Italy; Bellini, 1901) or from weathering of tuff (Ruatapu Cave, New Zealand; Cody, 1978). It appears that Serpents Cave is the first mention of that mineral in a cave not related to any volcanic influence.

Tschermigite

Tschermigite ($NH_4Al(SO_4)_2 \cdot 12H_2O$) is a cubic ammonium alum that was discovered in 1853 in Cermiky mine in the Czech Republic (called Tschermig at that time, as it was under Austrian domination). It has since been identified in mines or around volcanoes in the Czech Republic, China, Germany, Italy, Hungary, Russia, Slovakia, and the USA. It is reported in Lone Creek Fall Cave, South Africa, as white to yellow sugary efflorescences associated with Lonecreekite, its iron equivalent (Martini, 1983). In Ruatapu Cave, New Zealand, it may be associated with potassium alum (Cody, 1978). In Lone Creek Fall Cave, sulfates are provided by the oxidation of host rock pyrites, ammonia from bat guano, and aluminum from clay. If one excludes Alum Cave Bluff, Tennessee, which is a rock shelter in metamorphic phyllites in the Great Smoky Mountains, Tennessee (Coskren and Lauf, 2000), Serpents Cave is only the third mention of tschermigite in a cave.

Jurbanite

Jurbanite ($Al(OH\ SO_4) \cdot 5H_2O$) is a rare monoclinic hydrated aluminum sulfate. It occurs as short prismatic crystals, commonly in crusts and stalactites, in humid tunnels and in oxidized portions of sulfide deposits in aluminous rocks. It was discovered in 1976 in San Manuel Mine, Arizona (Anthony and McLean, 1976). The name was given by a mineral collector, J. Urban, who first

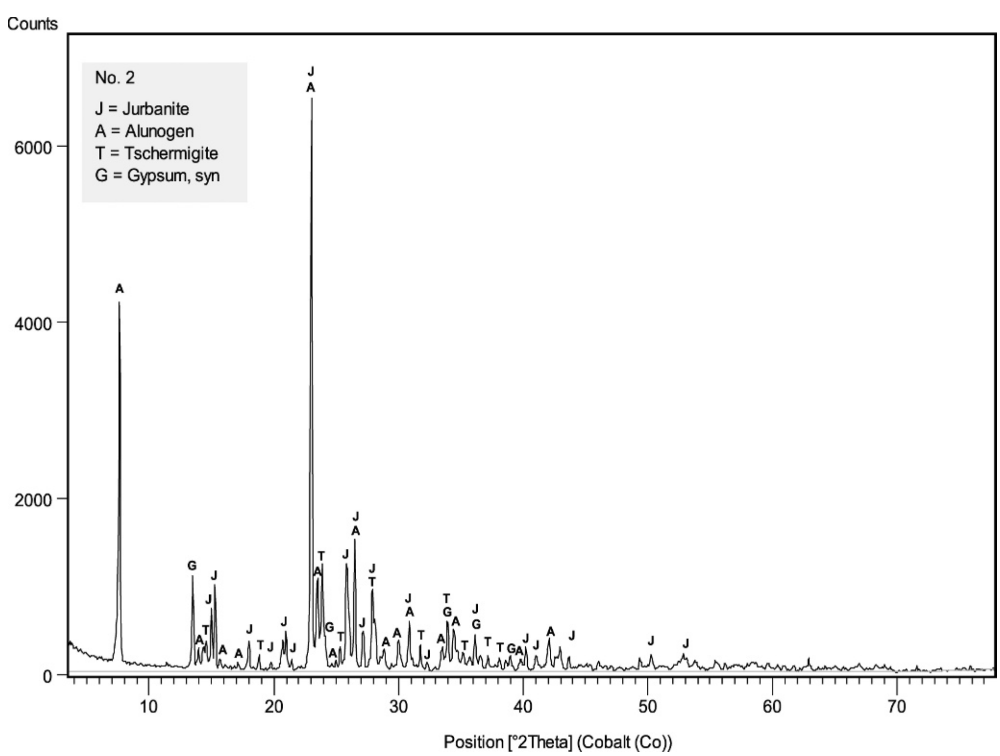

Figure 6. X-ray diffraction diagram of the soft crust growing on the aluminum frame of the door. Together with gypsum, three aluminum sulfates are present: alunogen, jurbanite, and tschermigite.

observed the natural material. Since its discovery, it has been documented in only a few sites worldwide, and exclusively in mines, including Nejedly I Mine, Czech Republic, and Cetine Mine, Italy (Jolyon and Ida, 2006). In addition, jurbanite is suspected to be present in Alum Cave Bluff. Consequently, since Alum Cave Bluff is neither a real cave, nor a karst phenomenon, and since other localities are mines, jurbanite occurrence in Serpents Cave is the first mention in a karst cave.

DISCUSSION

ORIGIN AND POSSIBLE ANTHROPIC INFLUENCE ON THE GROWTH OF THE ALUMINUM SULFATES

In Serpents Cave, we observe the following association of sulfate minerals originating from the reactions driven by H_2S release from the sulfidic spring:

1. Calcium sulfates such as gypsum and anhydrite over limestone cave walls; and
2. Aluminum sulfates such as alunogen, tschermigite, and jurbanite over the aluminum frame of the door.

Due to their location well above the water, all these minerals are formed by reactions between gases, liquid (condensation), and solids. On the wall, H_2S is dissolved into condensation water, then is oxidized into sulfuric acid by reaction with atmospheric oxygen (Egemeier, 1981). This acid attacks the local media, either the limestone or the aluminum of the door frame. Sulfates for the minerals come from the sulfuric acid. Ammonia could be due to microbial metabolic activity such as nitrification processes involving *Crenarchaeota* which use ammonia as an energy source through oxidation (Weidler et al., 2007). The presence of ammonia could show a biogenic component for the formation of tschermigite and should be confirmed by further studies. The sulfur coating on gypsum crust may also have a microbial origin. Aluminum probably comes from the door frame. For this reason, alunogen, tschermigite, and jurbanite have to be considered here as border minerals since they are formed by a combination of natural processes and human intervention; the aluminum is introduced artificially by the presence of the door. However, in other sites, they are considered as true minerals since there is no human intervention, the aluminum being provided by the host rock or by clay. Similarly, some minerals naturally produced on archaeological stain artifacts were considered as border minerals and consequently accepted by the Commission on New Minerals and Mineral Names of the International Mineralogical Association (Organ and Mandarino, 1970).

CONCLUSIONS

The sulfidic vapor degassing from Alum Spring in Serpents Cave produces sulfate minerals when it reacts with the host rock of the cave. The replacement-corrosion of the limestone wall produces gypsum, anhydrite, sulfur, and magnesium calcite. The reaction of sulfuric acid with the aluminum door produces border minerals in the form of aluminum sulfates: alunogen, tschermigite, and jurbanite. Jurbanite is described within such a cave environment for the first time in this paper. Serpents Cave is an important site for the study of sulfidic karst processes and sulfate minerals in caves. Because microbial communities are present as soft flakes in the phreatic zone and as biofilms on walls where condensation occurs, and because the microbial activity is suspected to influence some mineral precipitation such as native sulfur, magnesium calcite and tschermigite, the Serpents Cave may also be an important site for the study of microbial activity related to karst solution and mineralization processes. Further studies will continue to assess the potential of this cave as a source of information on speleogenetic processes, mineralization, and microbiology.

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L.M. Mejía-Ortíz, G. Yáñez, M. López-Mejía, and E. Zarza-González – Cenotes (anchialine caves) on Cozumel Island, Quintana Roo, México. *Journal of Cave and Karst Studies,* v. 69, no. 2, p. 250–255.

CENOTES (ANCHIALINE CAVES) ON COZUMEL ISLAND, QUINTANA ROO, MÉXICO

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Abstract: Cozumel Island is a Caribbean locale having karst as the main component of its surface. Known caves are steep-sided, water-filled sinkholes (cenotes), and almost all of them are considered to be anchialine caves because they have seawater connections. In order to identify the location of as many cenotes as possible on the island, we based our study initially on aerial photographs. This was followed by visits to each site for field verification and collection of physical data and biological specimens. We explored several cenotes to record physical data such as temperature, salinity, dissolved oxygen, depth, pH, light, and to collect the animals living there. As a result, we report on eighteen cenotes on Cozumel Island, their location and fauna. Physical data from three cenotes showed that the freshwater is very thin at the top of the water table. Most of the systems are marine water-filled. Varying degrees of connection exist between these sinkholes and the ocean. In addition, other water bodies were found not to be cenotes, but aguadas (shallow water basins).

Introduction

In México about 20 percent of the land consists of karst, and by 1981 about 1024 caves were known around the country (Reddell, 1981). Particularly on the Yucatán Peninsula, the underlying rock is exclusively calcareous. In that region, cenotes are the main water bodies. Gaona-Vizcayno et al. (1980) defined them as subterranean water bodies with some connection to the surface. Hall (1936) classified the cenotes on the peninsula into four types: cenotes-cántaro (surface connection narrower than the diameter of the water body), cenotes-cilíndricos (vertical walls), cenotes-aguadas (shallow water basins), and grutas (horizontal entrance with dry sections).

The topography of Cozumel Island is mainly karstic, and it has all four kinds of cenotes. When these conduits have sea connections, we know them as anchialine caves. The local people use the freshwater from these holes to satisfy their basic water necessities. Some cenotes on Cozumel Island have been previously reported, such as Cueva Rancho Santa Rita (Reddell, 1977), Cueva Quebrada Parque de Chankanaab (Bowman, 1987; Holsinger, 1992), Cenote Xkan-ha and Cenote Aerolito (Kensley, 1988). On Cozumel, we also find shallow sediment-floored bodies of superficial water called aguadas. Cozumel Island is covered by tropical forest, so the shallow water bodies (aguadas) and the deep holes (cenotes) are not always easily found. Inaccessibility is the main reason that few cenotes have been previously catalogued.

This work aimed to identify the cenotes and aguadas on Cozumel Island, their geographic location, fauna, and some physical qualities. We also conducted surveys to obtain vertical profiles of physical data in two deeper holes (Tres Potrillos and Xkan-ha), and one from the Quebrada System (a horizontal cenote).

Study Area

Cozumel Island lies between 20°16′12″ and 20°35′15″ N latitude, and between 87°01′48″ and 86°43′48″ W longitude, and has an area of 482 km^2. The Island is off the northeastern tip of the Yucatán Peninsula, in the Mexican part of the Caribbean Sea, and its main freshwater sources are the cenotes and subterranean water conduits (Fig. 1).

Cozumel is part of the East Maya Plate with sedimentary rocks formed on a wide platform. Wurl and Giese (2005) report that core drillings indicate that the island is formed from reef sediment with a thickness of 100 m or more, which dates from the Oligocene and Quaternary Epochs. A karstic aquifer has been developed in these limestone beds.

Materials and Methods

We analyzed aerial photographs taken during the dry season (Feb. 9, 2000) at 1:75,000 from Instituto Nacional de Estadística Geografía e Informatica: Sistema Nacional de Fotografía Aérea (INEGI SINFA), and identified bodies of surface water. In addition, we reviewed the literature of species descriptions from Cozumel, and we listed the cenotes reported. Subsequently, we made several visits during 2005 to those places to corroborate their geographic

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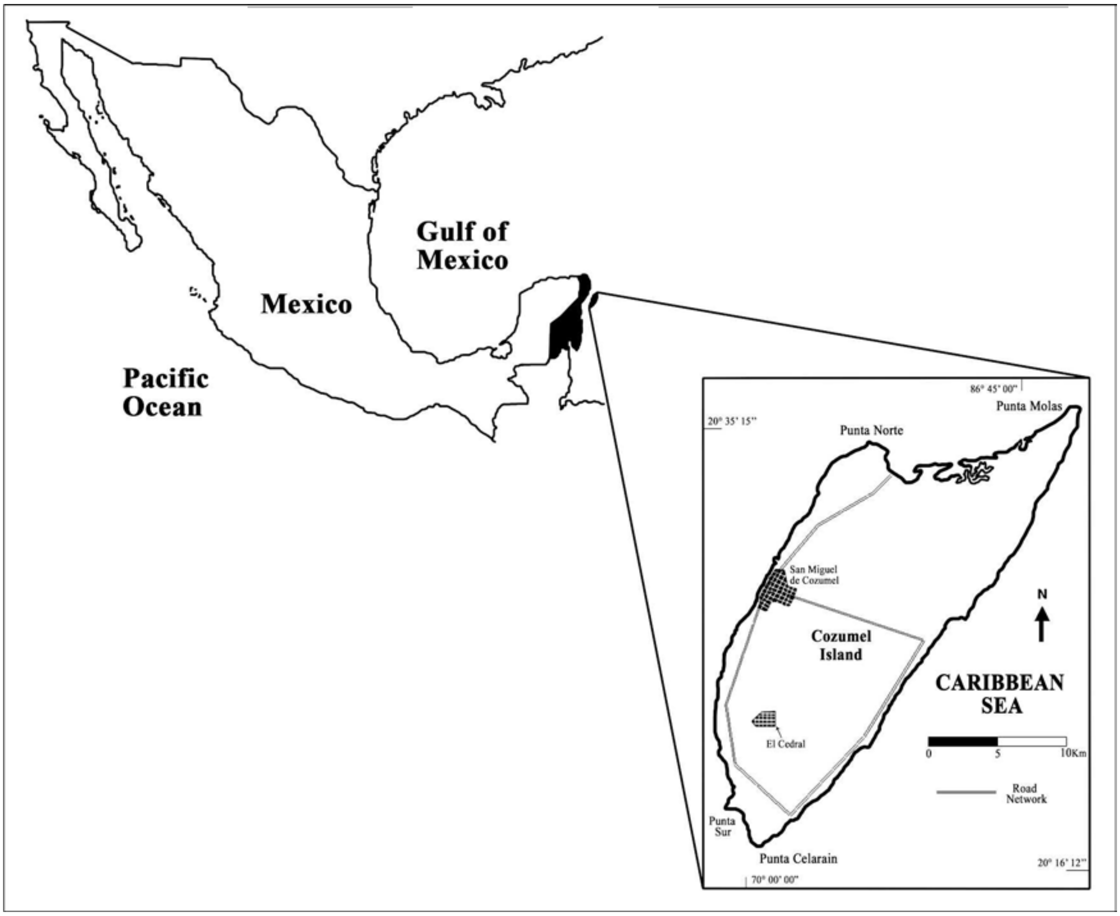

Figure 1. Index maps to the state of Quintana Roo and Cozumel Island.

locations and examine the main features. Geographic positions were registered using a Garmin Global Positioning System (GPS Summit 12 channels) using the NAD 27 Map Datum, and all positions were rounded to the closest 5 seconds. We obtained maps for three large cenotes from the literature, and then we explored them in order to corroborate the map surveys of these sinkholes. We also recorded physical data using a Hydrolab DataSonde 5 to measure temperature, salinity, dissolved oxygen, depth, light, and pH, and collected animals living there. All the cenotes were plotted on a map and listed.

Results

We registered 18 cenotes, most of them having salt water in their deeper layers, which are listed in Table 1, including their geographic locations and fauna. We also registered 250 shallow water bodies (cenotes-aguadas), from which only the larger are shown on Figure 2. The main water bodies are close to the coast, and others that lie in the inner part of the island are difficult to identify because the tropical forest is very dense. During our explorations, we found freshwater fish and turtles as the main fauna in almost all the aguadas. In most of the cenotes, however, we recorded salt or brackish water at deeper levels. As examples, we show here vertical and horizontal profiles from three cenotes: Tres Potrillos, Xkan-ha, and Cenote Km 1 (Quebrada System) (Figs. 3 and 4 respectively). During the analyses we found light penetration to occur only in the superficial water (2–3 m) of the vertical cenotes, and also to a very shallow depth (3 m) of the horizontal system. The halocline appears on the graphs, and dissolved oxygen was recorded at very low concentrations (Figs. 3 and 4). Only the Quebrada and Aerolito Systems have direct sea connections from where we collected crustaceans, echinoderms, worms, and mainly marine species of fish.

Discussion

This study deals with several water bearing features around Cozumel Island. Other authors have reported previously on different features on the island (Yañez-Mendoza, 1999; Bowman 1987; Kensley, 1988; Reddell, 1977, 1981). Here, we report the precise location of these features, the physical parameters of three of them, and

Table 1. Cenotes on Cozumel Island.

Cenote[a]	Latitude (°N)	Longitude (°W)	Length (m)	Depth (m)	Fauna	Reference
(a) Rancho San Miguel Cenote	20° 30′ 40″	86° 53′ 55″	8.0	3.0	Freshwater fish	
(b) Rancho San Miguel 1	20° 30′ 15″	86° 53′ 55″	9.0	2.0	Freshwater fish	
(c) Cenote del Dr. Villanueva	20° 30′ 20″	86° 53′ 10″	12.0	4.0	Cave crustaceans	
(d) Cenote Bambu	20° 29′ 35″	86° 52′ 30″	61.0	51.8	Freshwater fish, turtles, snakes	
(e) Universidad de Quintana Roo	20° 29′ 30″	86° 56′ 45″	15.0	1.5	Freshwater fish, land crabs, turtles	
(f) Cenote Chu-ha (San Francisco)	20° 29′ 25″	86° 57′ 20″	38.1	18.3	Freshwater fish	Milhollin, 1996
(g) Aerolito[a]	20° 28′ 00″	86° 58′ 45″	18.3	7.0	Cave crustaceans, marine fish, Cave echinoderms, cave worms	Kensley, 1988; Mejía-Ortíz et al., 2006, in press
(h) Xkan-ha	20° 27′ 55″	86° 57′ 15″	80.0	35.0	Cave crustaceans, freshwater fish, turtles	Kensley, 1988; Mejía-Ortíz et al., 2006
(i) Tres Potrillos	20° 27′ 05″	86° 59′ 15″	94.0	38.1	Cave crustaceans, freshwater fish	Yañez-Mendoza, 1999; Mejía-Ortíz et al., 2006
(j) Km 1 (Quebrada System)[b]	20° 26′ 40″	86° 59′ 45″	6.0	5.0	Cave crustaceans, freshwater fish	Bowman, 1987; Holsinger, 1992; Sternberg and Shotte, 2004; Mejía-Ortíz et al., 2006
(k) RokaBomba (Quebrada System)[b]	20° 26′ 40″	86° 59′ 40″	2.0	5.0	Cave crustaceans, freshwater fish	Bowman, 1987; Holsinger, 1992; Sternberg and Shotte, 2004; Mejía-Ortíz et al., 2006
(l) Cilpa (Quebrada System)[b]	20° 26′ 45″	86° 59′ 20″	2.0	4.0	Marine crustaceans, freshwater fish	Bowman, 1987; Holsinger, 1992; Sternberg and Shotte, 2004; Mejía-Ortíz et al., 2006
(m) Cenote Cocodrilo[b]	20° 23′ 00″	87° 01′ 10″	2493.0	17.4	Cave crustaceans	Mejía-Ortíz et al., 2006
(n) San Andrés El Cedral	20° 22′ 50″	87° 00′ 30″	15.0	4.0	Freshwater fish, crustaceans	
(o) Rancho Juvencio El Cedral	20° 21′ 20″	86° 59′ 55″	8.0	3.0	Freshwater fish, crustaceans	
(p) Cenote 1, Rancho El Chino El Cedral	20° 20′ 20″	86° 59′ 40″	12.0	5.0	Freshwater fish, turtles	
(q) Cenote 2, Rancho el Chino El Cedral	20° 19′ 10″	86° 56′ 05″	3.0	1.0	Freshwater fish, turtles	
(r) Cenote 3, Rancho el Chino El Cedral	20° 21′ 20″	86° 55′ 20″	5.0	1.5	Freshwater fish, turtles	

[a] Letters in front of each cenote corresponds to location on Figure 2.
[b] Denotes sea connection.

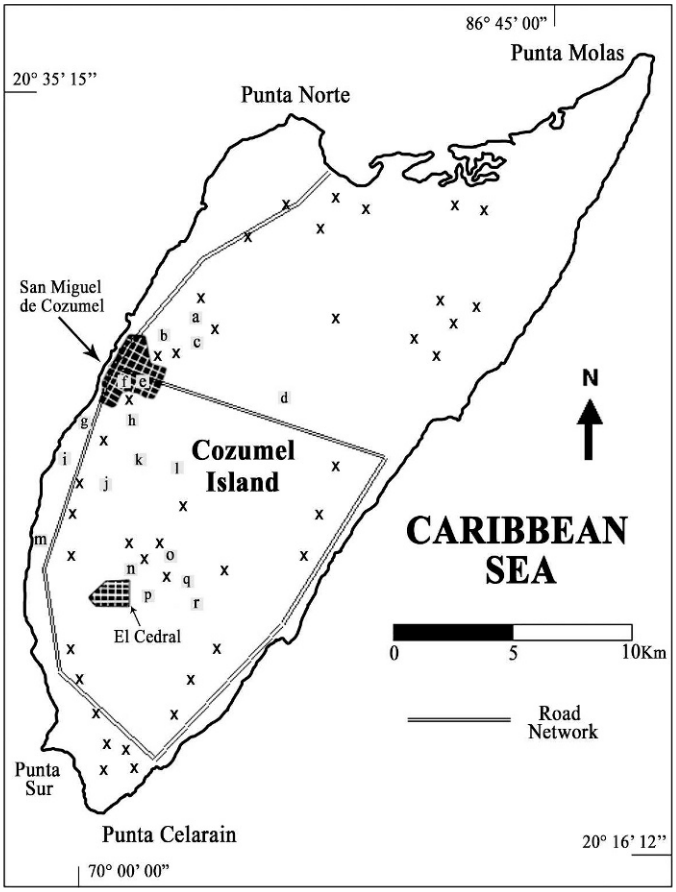

Figure 2. On Cozumel Island, crosses locate the largest aguadas (shallow water bodies), and letters keyed to Table 1 locate cenotes.

a record of other features not previously reported. We also found a significant number of aguadas. It is evident that the dense tropical forest makes the cenote entrances difficult to find. Despite the fact that the road network correlates somewhat with the previously known cenotes, our approach resulted in identification of the biggest sinkholes on the west side of the island. The island is mainly composed of limestone (Wurl and Giese, 2005), and the formation of all the cenotes is due to carbonate dissolution. We have insufficient data to suggest a pattern of distribution of these systems on the island.

At some sites, the freshwater table is shallow and superficial. This is important, because the human population of the island has been increasing during the past 5 years, with a consequent increase in water demand. At the same time, this increase in population also increases residual waste and contamination that could percolate into subterranean environments. This situation could cause a loss of water quality and also damage underground biodiversity. This could be the reason we found several species living only in the brackish water in almost all of the cenotes.

In the physical analyses, we found that the ground water of Cozumel has several zones. In the Aerolito and Quebrada horizontal systems, the mixing flow to the sea is important. Conversely, in the Tres Potrillos and Xkan-ha vertical holes, stratification with few mixing periods during the year was found. The halocline and thermocline are clearly defined in these systems.

Although freshwater fish are important in the cenotes of Cozumel, they live in the superficial water layer (Schmitter-Soto, 1999). We report a species richness from each sinkhole mainly composed of crustaceans, including species specialized to cave life. These species have slight relationships with species from other places. For example, during the recent explorations, we recorded three cenotes inhabited by members of the genus *Procaris*, but they all are probably different species (Mejía-Ortíz et al., 2006). These species are interesting because they are phylogeneticaly related to organisms from the Bahamas and Hawaii. Until now, these animals have not been recorded on the Yucatán Peninsula (Sternberg and Shotte, 2004), but we cannot exclude that they might be living in underwater caves there.

Several genera of termobaenacens have been reported mainly in Italy, and in some cases, on the Bahamas Islands. Termobaenaceans considered of the monotypic genus *Tulumella* have been reported previously at two localities in México, in nearby systems of Tulum, Yucatán (Illife, 1992 and 1993), and on Cozumel Island, specifically in the Cueva Quebrada System. But individual species have not been determined there. In this study we report a second cenote where these crustaceans live, and determined that they are members of the genus *Tulumella*, but presumably of an undescribed species.

Other interesting crustaceans that we found in a cenote on Cozumel Island are those of the genus *Barbouria*. To date, this genus has only a unique species *Barbouria cubensis*, and it has been reported on other islands (Hobbs et al., 1977). We have also identified organisms of the genus *Bahalana* in sinkholes that are apparently unconnected.

Conclusions

With this study we increase the known number of identified cenotes on Cozumel Island, and for the first time give their exact geographic positions. It is important to say that several cenotes are under cover in the tropical forest, and this inaccessibility has limited surveys there. Because of the human population increase and its increasing water demand, these environments are potentially in danger of severe damage. Also, we report for the first time the physical water parameters of three cenotes on the island, and conclude that the main component of these waters is saline at shallow depths.

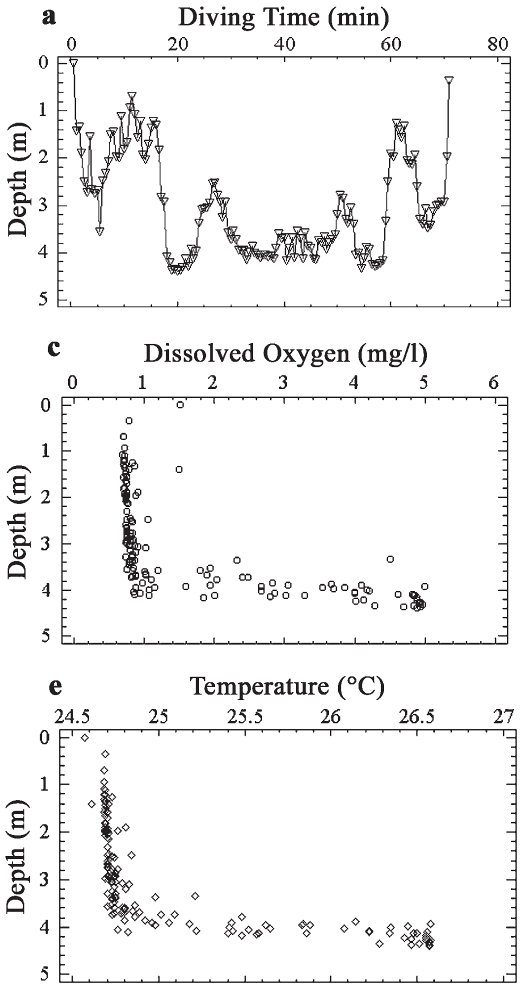

Figure 3. Profiles at an entrance to the horizontal Quebrada System (Chankanaab) for instrument diving time, dissolved oxygen, percentage of oxygen, temperature, salinity, and pH.

ACKNOWLEDGEMENTS

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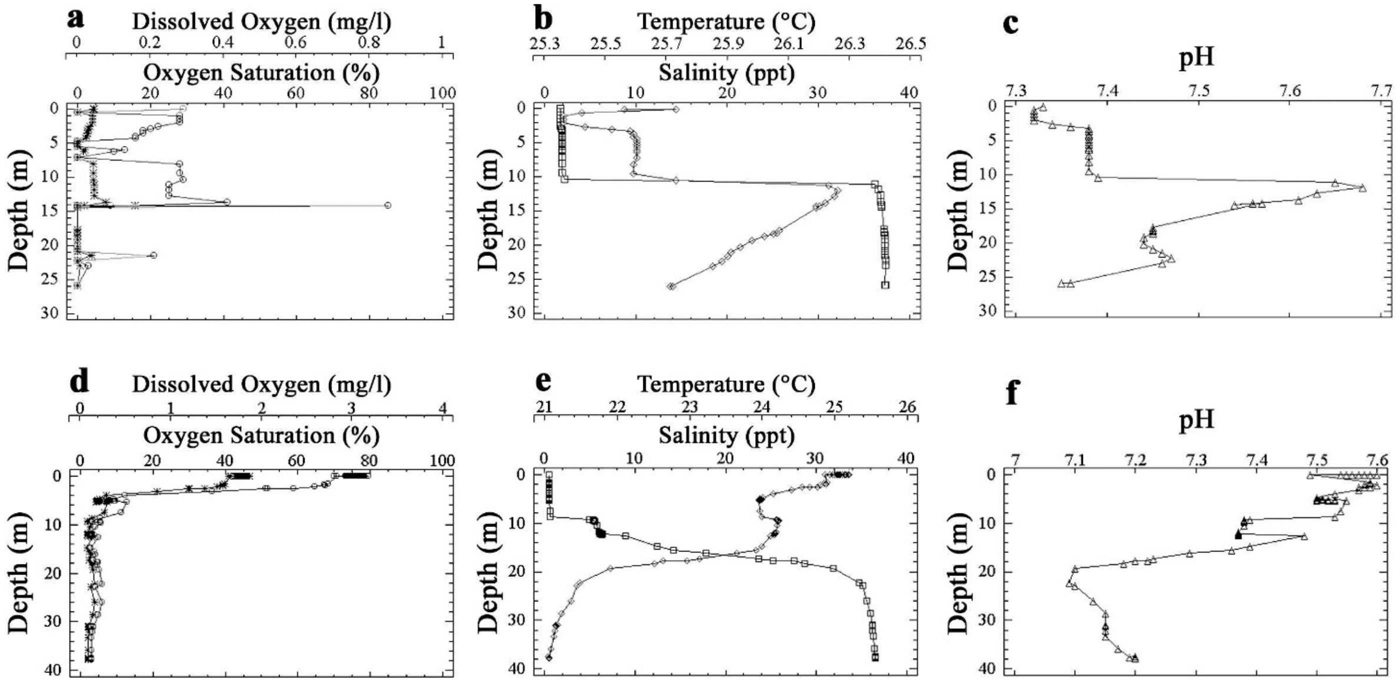

Figure 4. Vertical profiles at Cenote Tres Potrillos (a, b, and c) and Cenote Xkan-ha (d, e, and f) for dissolved oxygen (o) percentage of oxygen (*) temperature (◆), salinity (□), and pH (Δ).

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MONITORING THE DISAPPEARANCE OF A PERENNIAL ICE DEPOSIT IN MERRILL CAVE

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Abstract: Merrill Cave, part of a Pleistocene lava flow within Lava Beds National Monument, is the site of ice deposits that have fluctuated widely in volume between the Pleistocene and Holocene Epochs. Remnant mineral deposition from ice levels on the walls in the lower level of the cave provides insight into the depth of the ice during this time. The disappearance of a large perennial ice deposit in the lower level of the cave was tracked using historical photographs and modern photographic and ice-level monitoring techniques. A major change in airflow patterns and temperatures in an as yet unexplored lower level of the cave are suspected to have initiated the decline in ice levels. Measurements taken of the elevation of the surface of the ice deposit show a loss of over 1.25 m of ice in eight years. Surface and interior losses of ice from evaporation and/or sublimation have resulted in the near total loss of the large main perennial ice pond in the lower level of the cave. Photographs also document a drastic change in ice volume and levels during the same period of time. Several theories for the disappearance of ice have been suggested. One possible explanation for the loss of ice is related to a significant seismic event in the region in 1993 that may have caused rock fall in another, inaccessible section of the cave and precipitated the loss of ice in the accessible lower level. The dramatic loss of ice may also be the result of climate changes that, over time, indirectly influenced ice levels in Merrill Cave. Visitor impacts to the ice deposit after a large cavity breached the surface of the deposit contributed to the decline of ice conditions. Lastly, the presence of western juniper (*Juniperus occidentalis*) in the terrestrial environment above the cave may influence the hydrology of the cave environment.

INTRODUCTION

Lava Beds National Monument is located along the California–Oregon border. It is the site of scores of lava-tube caves and well preserved geologically young volcanic features. The lava flows in the park originated from a variety of vents and covered the entire park, leaving behind nine distinctive lava tube systems that stretch for up to 42 km under the Monument's landscape (Fig. 1). These flows extended to and under Tule Lake, an extensive, shallow Ice Age lake, before it was largely drained in the early 1900s. As these flows cooled, they left behind extensive networks of lava tubes, jumbled aa lava flows, lava lakes, sag basins and inflation plateaus. The basaltic lava flows that created the caves were erupted over 10,000 years ago in the late Pleistocene (Donnelly-Nolan and Champion, 1987; Waters, et al., 1990; U.S. National Park Service, 2003). As of December 2005, field reconnaissance has located 502 caves and other lava tube features within the monument that total over 45 km of underground passage.

The surrounding high elevation desert environment on the northern flank of the Medicine Lake Volcano, a southern Cascade Mountain Range volcano covering approximately 2300 km^2, supports a patchwork of bunchgrass, sage, and juniper in the lower lying areas, while in the higher elevations, ponderosa and lodge pole pine communities predominate. This diverse region of northern California encompasses an awe-inspiring landscape. It lies at the junction of the Sierra-Klamath, Great Basin, and Cascades geographic regions.

BACKGROUND

Water is a scarce natural resource in this semiarid environment. No surface water sources are present within Lava Beds National Monument. However, ice caves within the Monument, replenished by seasonal rains and winter snow melt, provide critical sources of water for wildlife. Ice levels in these caves have been tracked annually since 1990 to monitor the fluctuation of the ice from season to season and year to year.

Merrill Cave, a historically notable cave, was explored by visitors to the Monument in the early 1900s who passed by it on the first wagon road into the area. Although known to prehistoric Indians living in the area, the first documentation made of the cave was in 1888 by a trapper named Tom Durham. It was named after the Merrill Family of Klamath Falls, Oregon. In 1917 Charles H. Merrill homesteaded 160 acres of land in the area that included Merrill Cave. He operated a resort near the cave for four years. The land was donated by the Merrill family to the National Park Service in 1938 (Larson and Larson, 1990).

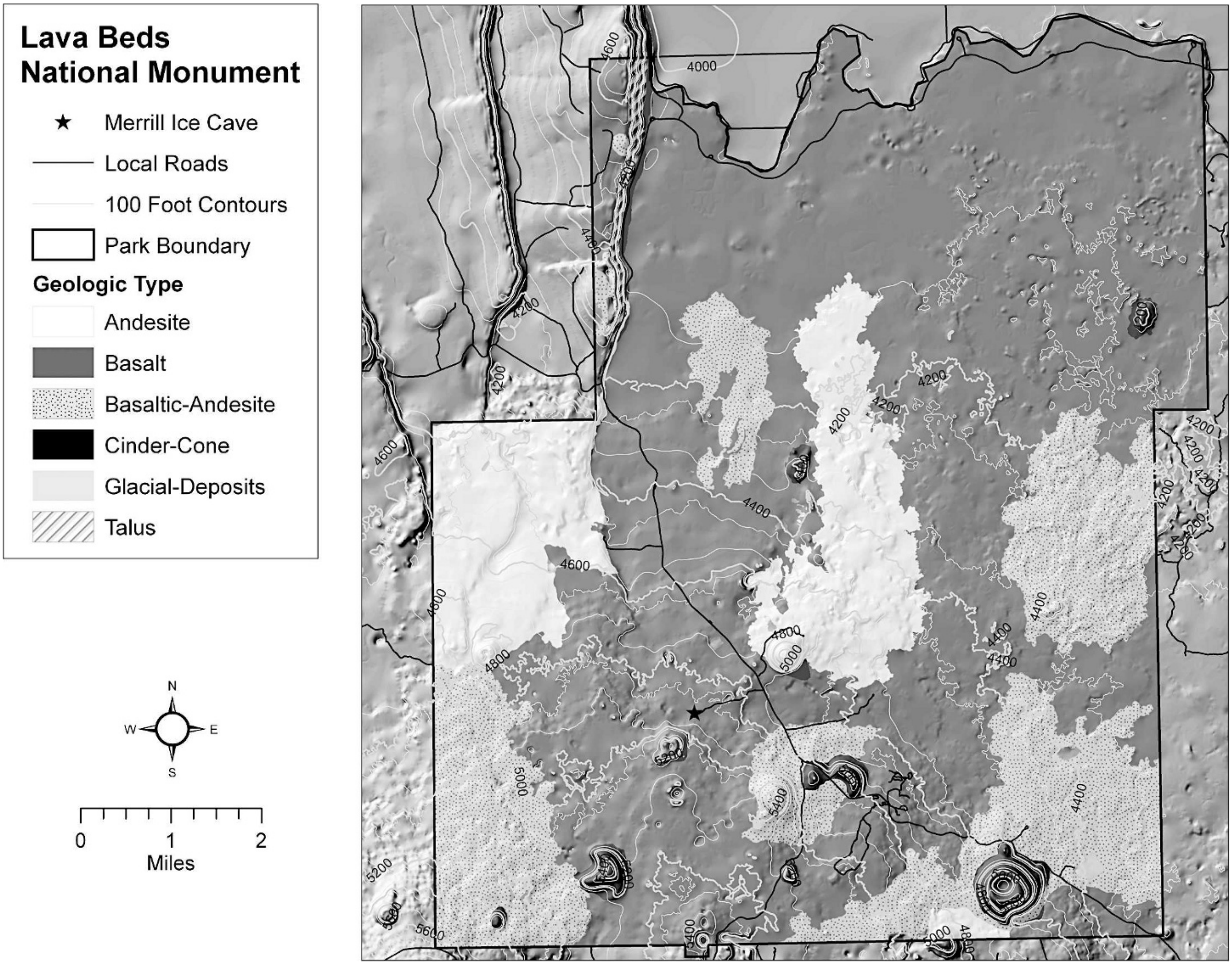

Figure 1. Lava Beds National Monument topographic and geologic map. NPS map by Jason Mateljak.

Merrill/Skull Lava Tube

Merrill Cave (Fig. 2), with an entrance elevation of 1488 m and a total length of 198 m, contains two levels of a master tube known as the Merrill/Skull distributary. The lava flow in which Merrill Cave is found traverses 16 km of the Monument beginning at Modoc Crater and terminating near the pre-settlement shoreline of Tule Lake. The lower level of the cave contains a main ice deposit. Ice caves form in lava tubes when dense colder air settles into a lower level during the winter months and is trapped. Caves with cold-traps may have temperatures around 10 °C below what would be expected at the latitude and altitude where they are found (Moore and Sullivan, 1978). Yonge (2004) discusses seasonal and permanent ice in caves as a result of physical and environmental mechanisms. Water from surface precipitation events is continually deposited in this lower section of Merrill Cave and freezes, forming a perennial ice deposit. The upstream and downstream passages leading to the pond in the lower level also have shallow ice deposits and fluctuate markedly from season to season, dependant upon local precipitation patterns. The main ice pond surface has been fed from these two smaller ice deposits in the lower passage. Developments in the cave that included two stairways leading down to the lower level, walkways on the upper and lower levels, and a catwalk platform over the ice deposit in the lower level were added during the era of the Civilian Conservation Corps in the early 1930s, and improved by the National Park Service in 1957. In 2003, the catwalk platform was removed because its footings were compromised by the receding ice. It was replaced by a viewing platform at the north end of the deposit.

History

There is evidence that the large main ice deposit in the lower 110 m-long passage of the cave has fluctuated dramatically over several thousand years. The climate, and thus the ice, was influenced by Pleistocene glacial

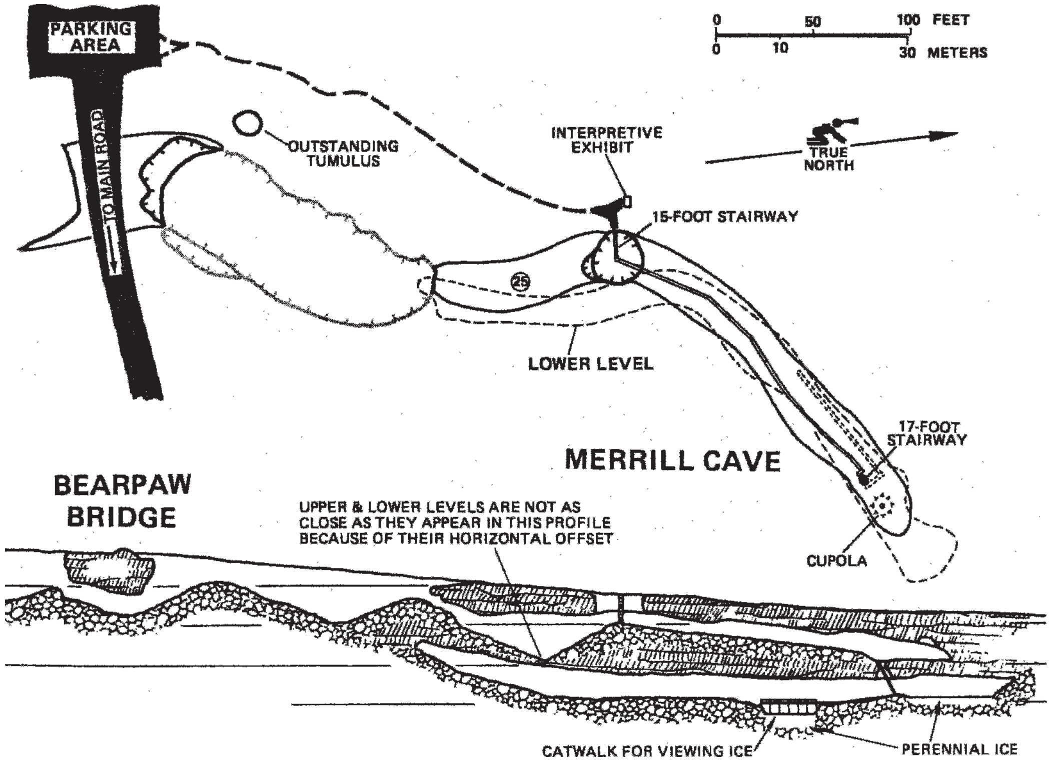

Figure 2. Merrill Cave map showing the upper and lower levels of the cave with cross section and top views (Larson and Larson, 1990).

advances and retreats during the Wisconsin Period 70,000 to 10,000 years ago. Well-defined ice horizon marks in the lower level of the cave, formed by minerals deposited in the ice and seasonal melt water interface, indicate that ice filled most of the lower master tube for an extended period of time in the past (Fig. 3). Over much of the past 40 years, until 1998, photo documentation of the ice has revealed that ice levels have increased. Feeder ice flows at either end of the main ice deposit in Merrill Cave remained relatively constant.

In the spring of 1997, a group of National Park Service employees and Cave Research Foundation (CRF) members noticed a pocket of air beneath the surface of the ice. In November 1997, CRF volunteers taking ice level measurements recorded a small 0.3 m diameter hole that had appeared on the surface of the ice deposit (Sowers and Devereaux, 2000). Below the surface, a large cavity had developed in the ice deposit and a very strong current of air blew out of the hole. The flow of air from beneath the hole, coupled with acts of vandalism, caused the hole to expand rapidly. In addition to the expansion of the cavity in the ice, large amounts of debris had begun to accumulate on the ice. The source of this debris was unknown. One scenario suggested the source of the debris was fallen material from the cave ceiling or reemerged material buried in the ice deposit. Another scenario suggested that visitors to the cave were throwing rocks from breakdown debris deposits onto the floor in an attempt to enlarge the size of the hole by collapsing the edges of it. Precautionary measures were taken to protect cave visitors as well as cave resources. Merrill Cave was closed to all visitors in spring of 1999 for public safety and resource protection purposes. It was reopened in 2003, after the safety issues were resolved and the catwalk platform over the ice deposit was relocated.

Monitoring of the lower level ice deposit was deemed necessary to record the processes taking place, identify the source of rock fall, and investigate safety concerns. Regular photo monitoring of the ice in Merrill Cave began in 1990. In addition, other monitoring activities included rock fall, ice level, and temperature/relative humidity. This report is a summary of the results of these monitoring activities and what has been learned.

A complex relationship of environmental conditions and geological processes is present in Merrill Cave, but not fully understood. The development of a large subsurface ice cavity in the perennial ice deposit and the subsequent near-total disappearance of the ice are perhaps part of a long term cycle of ice recurrence in the cave. However, current speculation explaining the cavity formation in the deposit suggests that airflow from beneath the ice deposit has changed, allowing warmer air to slowly sublimate and evaporate the ice from the base of the deposit. This change of airflow could have been the result of the movement of rocks in a lower, inaccessible level of the cave. However,

Figure 3. Ice level mineral deposits. Field of view is approximately 2.5 m in height. The white mineral stains (indicated with arrows) reveal a history of extensive ice levels in the lower level of the cave.

definite evidence is presently unobtainable because the lower reaches of the passage are blocked with rubble.

Methods

A long term, multi-purpose monitoring program was developed for Merrill Cave by the CRF and the NPS that was cost effective and efficient. All ice level measurements were taken from a pre-established monitoring datum on the cave wall identified by a metal screw (zero line on Fig. 4) installed into the cave wall. This method was implemented by the CRF to monitor and track changes in ice levels in selected caves within Lava Beds National Monument over an extended period of time. Fluctuation in the distances between the datum and the ice deposit indicated increasing or decreasing ice levels. The accuracy of this methodology can be influenced by conditions within the cave such as air flow patterns, temperature changes, and rates of evaporation/sublimation; and extrinsically through the movement of water from the surface through soil substrates and into the cave and the location of the deposition of this water onto the ice. However, for monitoring purposes, this method can provide a useful reference of ice levels over time.

Historical photographs in park archives provided views of the Merrill Cave main ice deposit in the 1960s. The cave photo monitoring program was established by the CRF to provide documentation of changes in cave

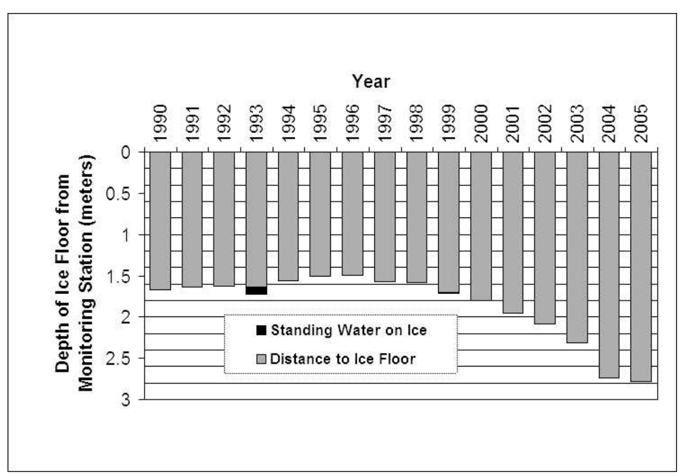

Figure 4. Ice levels of the main perennial ice deposit in Merrill Cave.

environments over time as influenced by natural processes and human activity. Beginning in 1990, the photo monitoring program established a photo point at the down-flow edge of the ice deposit. Photos were to be retaken every five years from the same locations. This schedule was not adhered to until 1998 when additional NPS personnel were available to carry out a regular monitoring schedule. Annual photos were taken after the ice cavity was discovered in Merrill Cave to closely monitor the process and document changes. Photo monitoring points were selected to cover a variety of views of the main ice deposit in the lower level of the cave. Photo monitoring stations were initially set up by the CRF and located by identifying a representative view of the ice floor, measuring from the camera to significant features such as cave walls, marked by plastic survey flagging. All information was recorded on a photo monitoring data form in addition to a sketch of the photo point location. Additional photo monitoring stations were established later by the author using the same methodology. Photos were taken using a Nikon FM 2 35 mm camera with a 28–80 mm lens, 200 ASA film, and remote electronic flash. A Nikon D100 digital SLR camera with a 28–80 mm lens was used to take the 2005 photo from the recently constructed viewing platform.

After rock material began appearing on the surface of the ice deposit, NPS staff deemed it necessary to identify where the material was originating. Initial theories included falling ceiling material, reappearance of rock material from within the ice that had been deposited on the ice floor in the past or moved up through the floor from the bottom of the deposit, and vandalism. A 3×9 m rock fall monitoring station was established in 1999 on the ice below the catwalk over the floor using plastic survey flagging. Photographs were taken of the ice floor within this monitoring station for two years to measure quantities of rock fall and changes in surface ice conditions.

During the Summer of 2001 and Spring of 2002 Hobo brand data loggers from Onset, Inc. were used to measure short-term fluctuations in environmental conditions inside the ice cavity and on the surface of the ice deposit in the lower level of the cave. Loggers were set to record temperature and relative humidity conditions every hour in the two locations for eight months.

MONITORING RESULTS

Ice-level monitoring of the ice pond from 1990 to 2005 (Fig. 4) showed increasing ice levels of the ice deposit until sometime between September and November 1997 when the cavity in the ice appeared and measurements revealed a decreasing ice level. Several different methods of monitoring were employed to learn about the processes involved.

Figure 5. Photograph of ice deposit taken in 1962 looking up-flow in the cave. Note fairly low ice level, exposing several large blocks of lava rubble, also called breakdown. Several large, apparently stable blocks are labeled A through E for reference in succeeding photographs. Also note the wooden walkway at the right edge of the photograph constructed in Merrill Cave. In the mid-1960s these structures were replaced by steel and aluminum walkways. Dark colored areas are shallow pools of melt-water in the clear ice; covered blocks of lava can faintly be seen under the clear ice at left. Milky color of the balance of the ice surface is due to minute bubbles of air and fractures in the ice. Also note high water/ice marks on intact tube wall at upper center and extensive mineral covering on walls and ceiling in background.

PHOTOGRAPHIC MONITORING

Photographs show the effects of natural processes and human impacts on the ice in Merrill Cave from 1962–2005. They provide a valuable overview of the changes that took place in ice deposit conditions and the decrease in ice levels in the late 1990s and early 2000s. Historical photographs may be used as a historical reference and monitoring tool (Leutscher, et al., 2005).

Historical photos were taken of the ice floor including a 1962 photo showing the surface of the ice floor (Fig. 5). Dedicated photo monitoring of the ice deposit surface was initiated in 1990 when the floor was unaltered by current conditions. Photographs from early in this time period

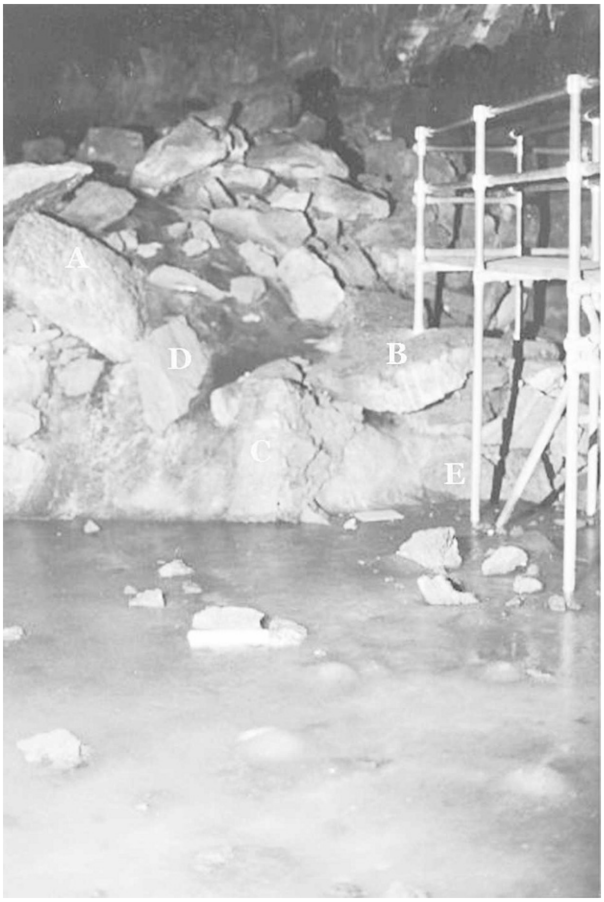

Figure 6. View of ice deposit and upstream ice cascade in Merrill Cave taken in 1990. The ice surface is relatively clear as submerged lava blocks can be seen under its surface; lower ice levels are milky white due to trapped air bubbles and fractures in ice. The large breakdown blocks are partly cemented in a thick ice cascade. Note the bottom of the walkway supports have been engulfed in ice about 20 cm since it was installed in the mid-1960s. White scale bar at center of photo is 30 cm wide. Blocks labeled A through E are the same as those shown in previous photograph.

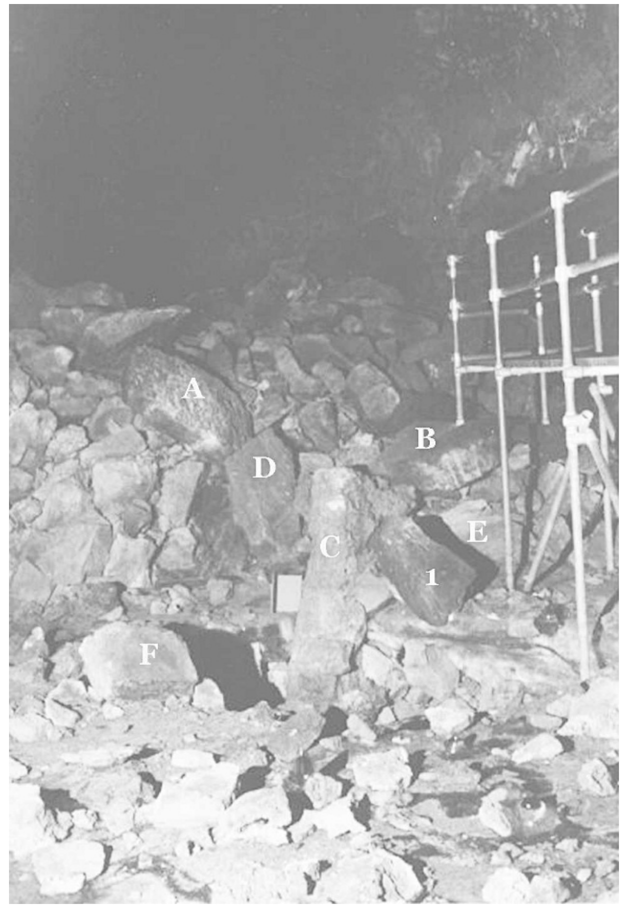

Figure 7. Photograph of the ice deposit in Merrill Cave taken in April of 1999. Note that the ice level has dropped further, exposing more of the upstream rubble pile. Block 1 makes a brief appearance. The origin of this block is unknown. It may have slid down on the pile of rubble above or been moved by visitors from somewhere on the upstream breakdown pile.

reveal a solid ice floor that has very little debris on its surface (Fig. 6). Compared with the 1962 photo, the ice level had risen by 1990.

The same photo retaken in 1999 and 2000 (Figs. 7 and 8) reveals a drastic change in the quality of the ice. Excessive amounts of debris had accumulated on the surface, in addition to the appearance and expansion of a hole in the ice.

The visible degradation of the ice in Merrill Cave began in November 1997 when a small hole appeared in the surface of the ice that grew quickly to 116 cm × 55 cm by March of 1998 (Fig. 9). Beneath this surface hole, a large cavity had formed in the ice deposit. Given the initial diameter of the cavity beneath the surface when it was discovered (4.6 m), the subsurface melting/sublimation phenomenon had probably been at work for an extended period of time. Photo monitoring recorded the changes in the size of the hole in the Merrill Cave ice deposit between March, 1998 and November, 2000. When measured in November of 2000, the size of the hole had grown to 4.4 m × 4.3 m (Fig. 10). As of October, 2005 most of the main ice deposit in Merrill Cave has been claimed by the natural forces at work, with the exception of a 1 m high bench along the east wall and a narrow fissure fill on the northwest corner of the ice pond (Fig. 11).

Rock Fall Monitoring

The accumulation of rock on the ice deposit was a concern because of the potential hazards associated with rock fall. This debris could have originated from: (1) rock fall from the ceiling of the cave; (2) sublimated material re-emerging from beneath the ice in combination with evaporation of ice from the surface; or (3) visitors

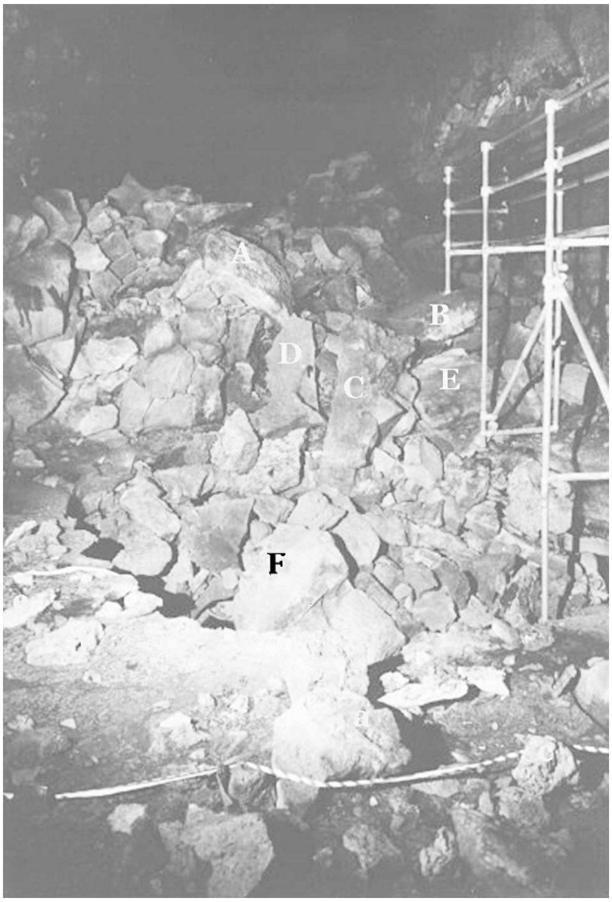

Figure 8. In this photograph taken in November of 2000 note that the ice deposit has substantially melted further. Block F has slipped and/or rolled further down into the cavity. Block 1 has disappeared down into the rubble cavity as well. Smaller boulders near the downstream edge of the ice surface are labeled lower case a to e. Striped plastic tape delineates the reference area for a concurrent rock fall study.

Figure 9. Merrill Cave ice deposit cavity breach, March, 1998.

depositing rocks onto the ice in an attempt to enlarge the cavity hole in the floor or create new holes.

A gate was constructed at the entrance and the cave was closed to the public to provide for public safety, prevent possible further resource damage by vandalism, and give resource managers a chance to study the phenomenon at work. A rock fall monitoring plot, which can be seen in Figure 10, was marked off and cleared on the top of the ice to observe the amount of rock accumulation from natural causes. Observations of the monitoring plot and photo documentation over a period of 17 months (June 1999–November 2000) revealed no natural rock fall on the ice deposit. Based on these observations, the changes in the accumulation of debris material appear to be the result of ice sublimation and evaporation processes. Various sizes of basalt rock material were identified embedded in the cavity walls. Part of the initial deposition of material was apparently the result of visitors throwing rocks onto the ice deposit attempting to increase the size of the cavity hole.

The accumulation of debris before closure of the cave to visitors is therefore attributed to a combination of vandalism and reemergence of submerged material due to loss of ice from sublimation processes and evaporation. Sublimation processes take place very slowly. More rocks and debris material continued to emerge from the ice deposit as the ice evaporated.

Environmental Monitoring

Temperature and relative humidity probes were installed to monitor conditions and obtain an accurate record of environmental fluctuations both inside the expanding hole and on the surface of the main ice deposit in the lower level of the cave. Conditions on the surface of the ice deposit followed seasonal patterns in terrestrial heating and cooling (Fig. 12). In September 1993, a magnitude 6.0 earthquake with an epicenter 22 km west-northwest of Klamath Falls, Oregon (Washington State University, 2006) may have initiated a shift of cave rubble in the lower levels of the lava tube beneath the perennial ice pond in Merrill Cave. A steady airflow from beneath the breakdown rubble affected the temperature and relative humidity conditions inside the cavity during the period of time monitoring took place (Fig. 13). These conditions included higher relative humidity (increased evaporation), and lower temperatures (higher air flow velocity). The location, quantity, and force of the airflow present suggested a source of air from outside the known passages of the cave. This airflow also may have dramatically increased the rate of evaporation of the ice that occurred over a short period of time and the size of the ice cavity when it was discovered. Ambient external terrestrial temperatures are recorded using a National Weather Service weather monitoring station at park headquarters. These data have been collected since 1946. Records show that the average annual high terrestrial temperatures have

Figure 10. Photograph of ice deposit hole in November, 2000, looking along the western wall. Large and small blocks labeled C, D, and F and a through e are labeled as in previous figures. Note stratified nature of ice deposit with clear and milky white, air bubble-filled layers.

increased 0.84 °C over the past 21 years in the local area that includes Merrill Cave (Fig. 14) (U.S. National Park Service, 2005). Average annual precipitation shows a declining trend since 1946 (Fig. 15). A combination of changing airflow patterns influenced by seismic activity, increased terrestrial temperatures and decreasing precipitation levels may be related to the disappearance of ice in Merrill Cave. Changes in cave ice levels can be influenced by climate changes (Luetscher et al., 2005).

Other Influences

Visitation

Visitation to Merrill Cave was measured from 1992 until the cave was closed in 1999 using a seismic trail sensor on the cave trail that monitored visitor traffic. These records from the cave are shown in Fig. 16. The highest visitation levels were recorded during the months June, July and August. A high of over 4,100 visitors was recorded in June of 1995. The cave had an average of 456 visitors per month before the cave was closed. The

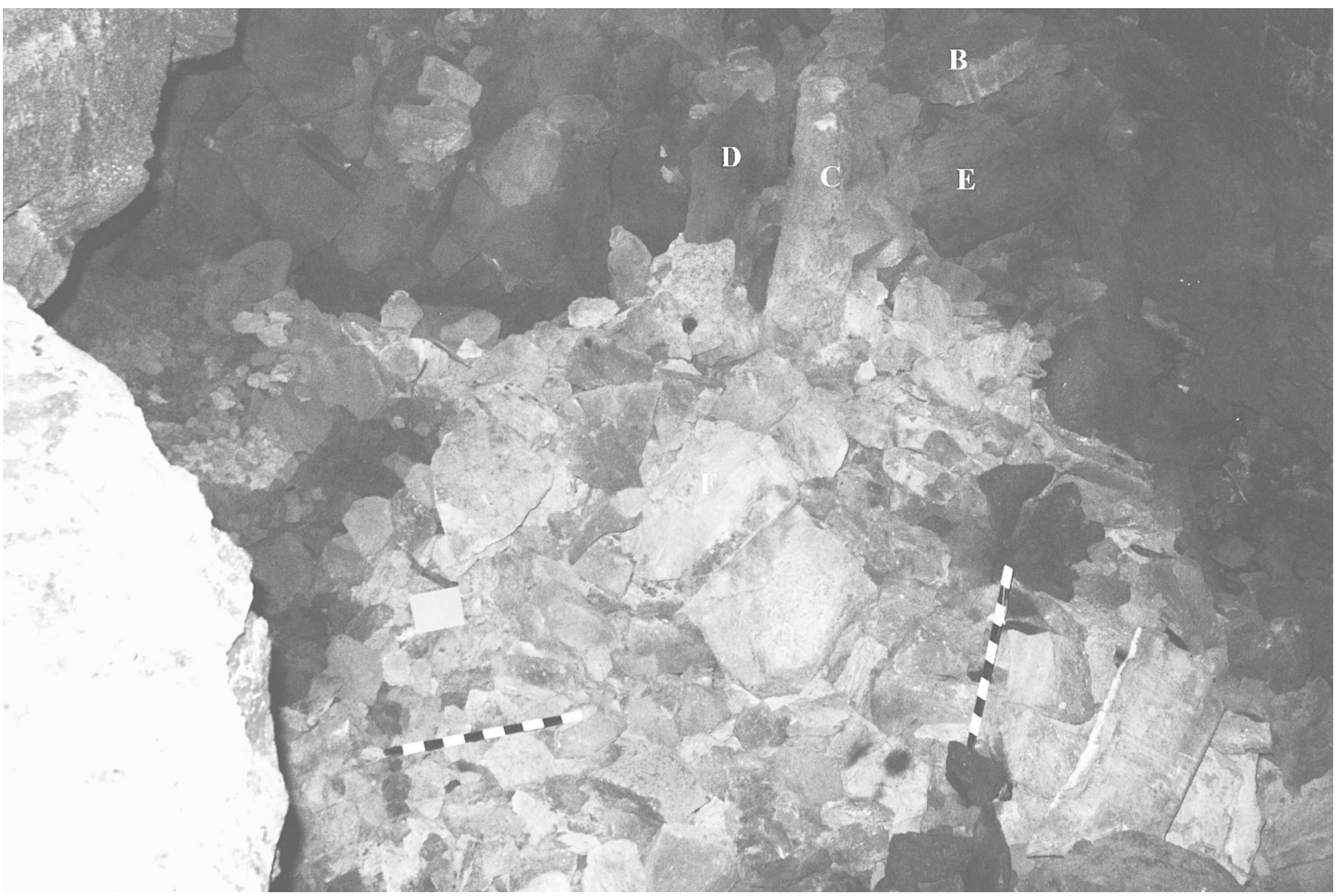

Figure 11. Merrill Cave Ice deposit, September 2005. The large ice pool has been entirely melted. The only visible basalt blocks still in place are B, C, D, E and F. The remaining blocks have fallen into the jumble of blocks on the floor of the lower section of the cave or shifted as a result of ice melting out of cavities between blocks. Note meter sticks and color board located on the breakdown floor of the former perennial ice deposit for scale.

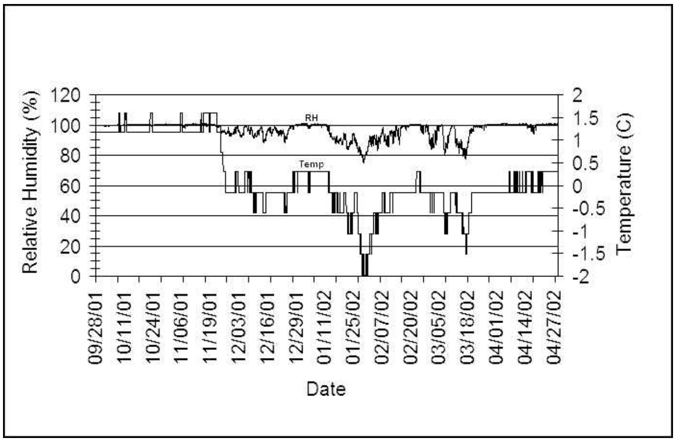

Figure 12. The relative humidity conditions on the surface of the ice pond are more variable with a lower average relative humidity (74.7% to 100.9%, average 96.7%) and temperatures slightly higher (−2 °C to 2 °C) because of exposure to the environmental influences in the lower level of the cave.

presence of visitors in the cave has had direct impacts on the ice deposit. The influences of visitation on the ice deposit include discarded trash, direct manipulation of the ice deposit, as well as potential influences of visitation on lower level cave temperatures by large numbers of visitors. Items discarded by visitors that included coins, 1970s era flash bulbs, glass bottles, tin cans, charred wood, etc. were found in different layers of the ice. Remnant catwalk platform materials were also found at lower levels in the ice deposit (Sowers and Devereaux, 2000). The results of deliberate attempts by cave visitors to enlarge the edges of the existing cavity in the ice with large rocks, and by

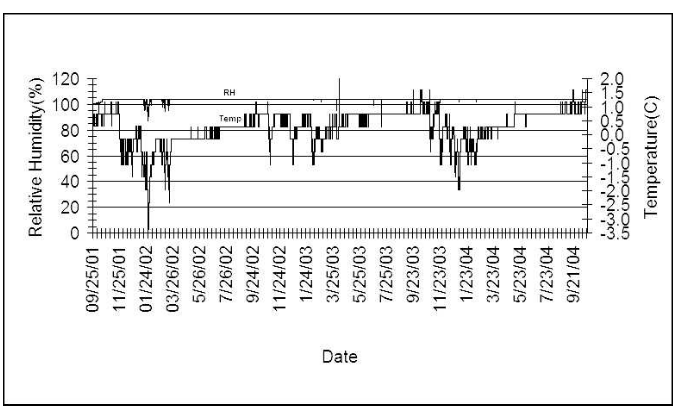

Figure 13. The recorded conditions inside the ice cavity from September 2001 through April 2002 show higher average and more stable relative humidity (86.9% to 103.7%, average 103%) and lower temperatures (−3 °C to 1 °C) for longer periods of time. This graph records a relative humidity that may be influenced by high evaporation rates of ice from inside the ice cavity.

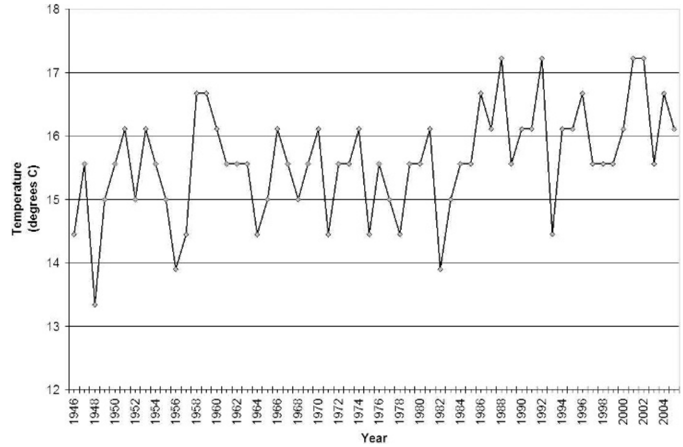

Figure 14. Average annual high temperatures (1946–2005) from the National Weather Service weather monitoring station at Indian Wells Headquarters reveal increasing ambient surface temperatures in the region of Lava Beds National Monument. This may directly affect the interior cave temperatures via interface with surface conditions through lava tube breakdown material.

physically kicking the edges to break off large chunks of ice, were observed by the author. These activities contributed to the premature enlargement of the cavity observed between 1998 and 2002. Visitor-level monitoring was reinitiated in 2004 after the cave was reopened.

Western Juniper Vegetation Community

The presence of western juniper (*Juniperus occidentalis*) is also worth mentioning in the context of this topic because of an indirect relationship in the surrounding terrestrial ecosystem above the cave. The expansion of western juniper in the region during the past 130 years has been cause for concern because of its impacts on plant communities and related components of affected ecosys-

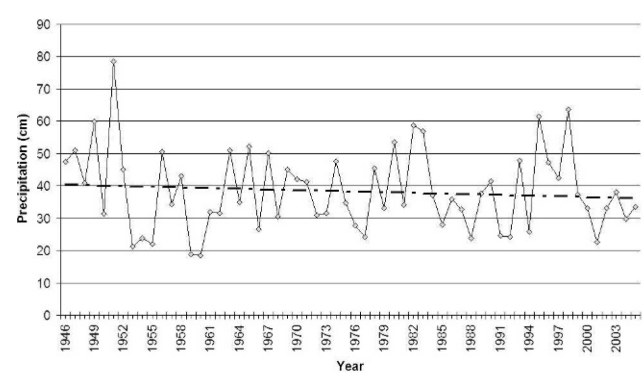

Figure 15. Average annual precipitation patterns (1946–2005) from the National Weather Service weather monitoring station.

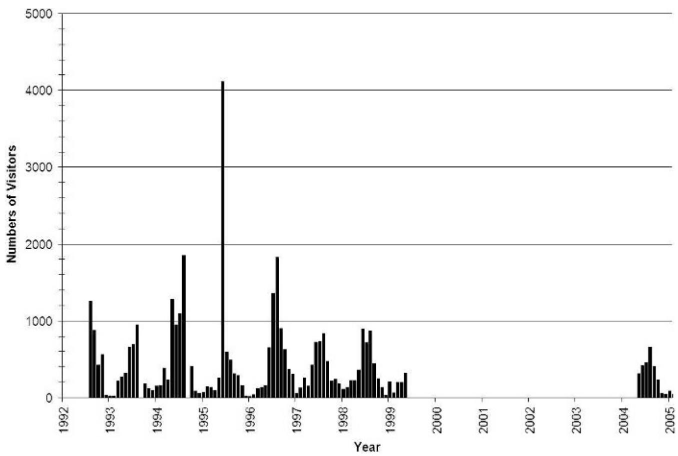

Figure 16. Visitation levels in Merrill Cave were recorded with a seismic trail sensor placed along the entrance/exit trail inside the cave.

tems (Miller et al., 2005). The abundance of western juniper in the high desert ecosystem on the surface above the cave may have an indirect effect on the hydrology of the cave environment. It is possible for a single mature western juniper to uptake approximately 35+ gallons of water per day during the summer months with extensive tap roots (personal communication, Richard F. Miller, Range Ecologist, Eastern Oregon Agricultural Research Center, Oregon State University, Corvalis, Oregon). This may influence the presence of water in the cave environment because it may relate directly to the number of mature junipers present and their proximity to Merrill Cave. The potential influence of the juniper community on the cave has not been investigated.

Conclusions

The current decline in the ice level in Merrill Cave is drastic and expected to continue until all the ice in the lower level of the cave is gone. Several explanations may independently, or in conjunction with one another, explain the cause of ice loss. Airflow from another section of the lava tube may have also contributed to forming the cavity in the ice deposit of the cave, which has subsequently expanded and consumed the entire deposit of ice. The loss of ice from evaporation indicates a change of air flow and a fluctuation in cave temperature.

Another explanation may be an increase in temperatures at a lower level of the master tube of which Merrill Cave is a part. The ice in this passage may have melted, and accelerated the melting of ice at the bottom of the ice pond. Thus, the ice cavity may have been the result of an opening of a smaller passage that had been filled with ice.

The ice may have possibly melted due to warmer temperatures outside the cave that exposed the base of the main ice deposit in the lower level of the cave to warmer air flow. Whatever the cause, the loss of ice by evaporation has consumed the majority of the ice present in the perennial ice deposits and feeder ice flows.

Future management of this cave will include environmental and ice-level monitoring of the lower level site that the main ice deposit once filled and new signed interpretation of the phenomenon at work for visitors to the cave. The presence of western junipers on the surface and the effect of this species on the hydrologic cycle of the cave require investigation. Future climate conditions and geological activity will determine the processes influencing this cave, which may, eventually, include the return of ice to its accessible lower level.

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BARKA DEPRESSION, A DENUDED SHAFT IN THE AREA OF SNEŽNIK MOUNTAIN, SOUTHWEST SLOVENIA

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Abstract: On the southern slope of Dedna gora, Slovenia, at an elevation of 1147 m, an interesting large closed depression referred to as Barka (Barge) is developed. It is about 40 m long, 25 m wide and 20 m deep, with smooth, almost polished precipitous walls. It is developed in Upper Cretaceous limestones and affected by several faults and fissure zones. The feature lies within a large karren field (about 10^4 m^2) with many closed depressions of various dimensions. In the winter time, snow accumulates in the bottoms giving the appearance of snow-kettles, such as those found in the Alps. The size and especially the shape of the walls suggests that these features are the remains of shafts. After their primary genesis as the inner vadose shafts of one or more caves, their upper parts would have been denuded. Walls and bottoms were subsequently remodeled by snow and ice action during the last glaciations, and this continues today as winter snow accumulates at their bottoms. This is indicated by silt fragments (gelifraction) and frost rubble accumulated in portions of the depression, and the development of sorted and nonsorted polygons. Shafts that have been exposed at the surface are a potentially important morphological element of karst topography. They can represent a significant portion of closed depressions of different sizes, including many snow-kettles.

Introduction

The aim of this paper is to clarify the genesis of a large, unusual closed depression in the karst massif of Snežnik-Javorniki in the area of Dedna gora, Slovenia. The area is situated in the southwest of Slovenia, between the town of Postojna and the Croatian border. The massif is bounded on the eastern side by the Idrija fault, along which the well-known karst Cerknica and Loško poljes have developed. To the northwest, it is delimited by Eocene flysch of the Pivka basin, and to the southwest by the Ilirska Bistrica basin (Fig. 1). The name of the depression, Barka, derives from its shape, as it resembles a barge hull (Fig. 2) at an elevation of 1147 m. Dedna gora, 1293 m above sea level, is the summit of the central part of the massif, lying between Javorniki Mountain on the north and Snežnik Mountain to the south. The highest peak of the area is Mt. Snežnik at 1796 m.

The massif of Snežnik - Javornik is a high karst plateau belonging to the High Dinaric karst physiographic province according to Habič (1969). The massif is dissected by large closed depressions and conical summits, formed in Jurassic and Cretaceous limestone and dolomites and their breccias. In caves whose entrances lie higher than 900 m above sea level, ice is present during the whole year. The Snežnik region was under ice during the last glaciation and boundary-line permanent snow was at the elevation of 1250 m (Šifrer, 1959). This is the reason why glacial and periglacial sediments are found in the area. Karstification, glacial, periglacial, and fluvio-glacial processes were significant geomorphic agents in the area in the past. In the present day, karstification is the main process. Various dolines and closed depressions of larger dimensions are present, as well as smaller forms such as karren and micro-karren.

Geologic Setting

The Javorniki and Snežnik area is within the Outer Dinarids geologic sub-province (Placer, 1981). From a tectonic point of view (Placer, 1981), the studied area is on the Snežnik thrust sheet (Javorniki and Snežnik mountains), which is overthrusted on another relatively autochthonous thrust sheet with a displacement of about 7 km. An important aspect of this overthrusting is that about 1000 m of carbonate rocks (limestone and dolomite of Jurassic and Cretaceous age) are placed over impermeable Eocene flysch sediments.

In the context of the regional tectonic development of the area, the Snežnik- Javorniki karst massif is a part of the Alpine-Mediterranean Orogenic Belt, formed by the convergence of the Africa and Europe Plates. The spatial and temporal histories are rather complicated. The main period of thrusting and folding of the area is post Eocene, mostly younger then 30 Ma, being the result of post-collision processes between the Africa and Europe Plates. At 6 Ma the latest tectonic phase in the region started with counter-clockwise rotation of the Adria Microplate. The rotation caused reactivation of Dinaric faults, which had previously formed as dextral strike-slip faults related to the aforementioned thrusting (Vrabec and Fodor, 2006). The general WNW-ESE trending compression in the area is due

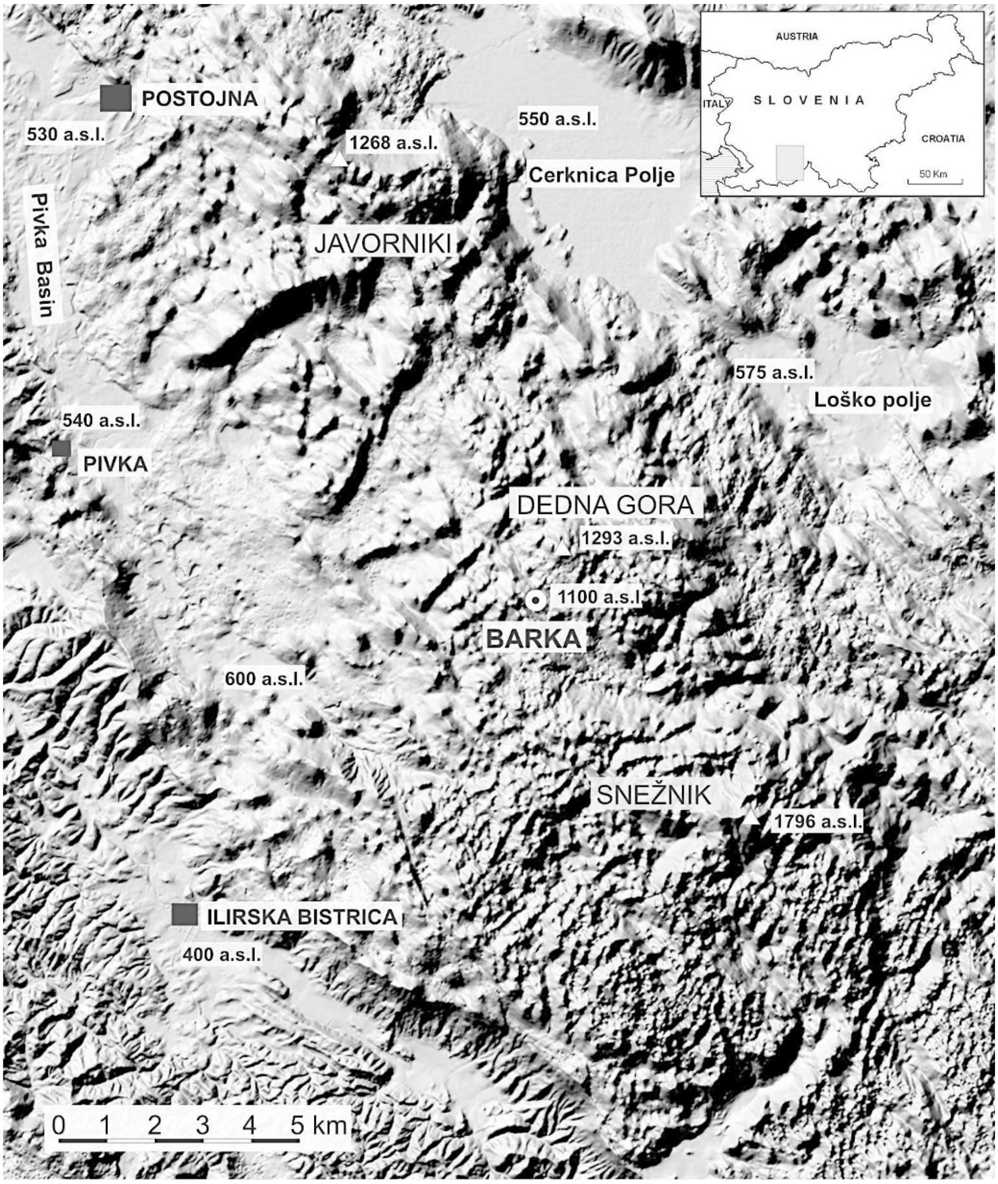

Figure 1. Shaded digital elevation rendering of the Barka depression area.

to the counter-clockwise rotation of the Adriatic Microplate. This motion is still active, and it is the main factor in regional relief formation. The main tectonic patterns of the area are fault zones of Dinaric (NW-SE) and Cross-Dinaric (NE-SW) directions, fissures in the S-N and NE-SW directions, and deformations of the carbonate rocks due to overthrust structures.

The Snežnik-Javorniki massif consists of carbonate rocks of Jurassic and Cretaceous age (Buser et al., 1967; Šikić et al., 1972). Javorniki Mountain (the northern part of the massif) consists mainly of Lower Cretaceous limestones with inliers of granular bituminous dolomites, Upper Cretaceous limestones with zoogeneous breccias (Turonian), and Senonian limestones with rudists. Snežnik Mountain (the southern part of the massif) consists mainly of Jurassic and Cretaceous limestones and dolomites.

In the Quaternary, Snežnik Mountain was glaciated at elevations above 1250 m, and the glaciated area was separated from the Alps (Šifrer, 1959). From the ice cap on Mt. Snežnik, small glaciers moved in different directions towards closed karst depressions in which they were stopped. This is inferred from terminal and lateral moraines present in the area (Zupan Hajna, 2007). Glaciation in the Snežnik area was previously noticed by Pleničar (1957) and was described in detail by Šifrer (1959). Habič (1978) wrote about remodeling of karst depressions by ice in the area of karst plateaus in Slovenia; he also studied glaciation at Risnik and found some glacial sediments south of Mašun. Only Šifrer (1959) systematically studied the Quaternary glaciations in the area of Snežnik and moraine deposits. He did not distinguish the sediments by age, but only the extent of

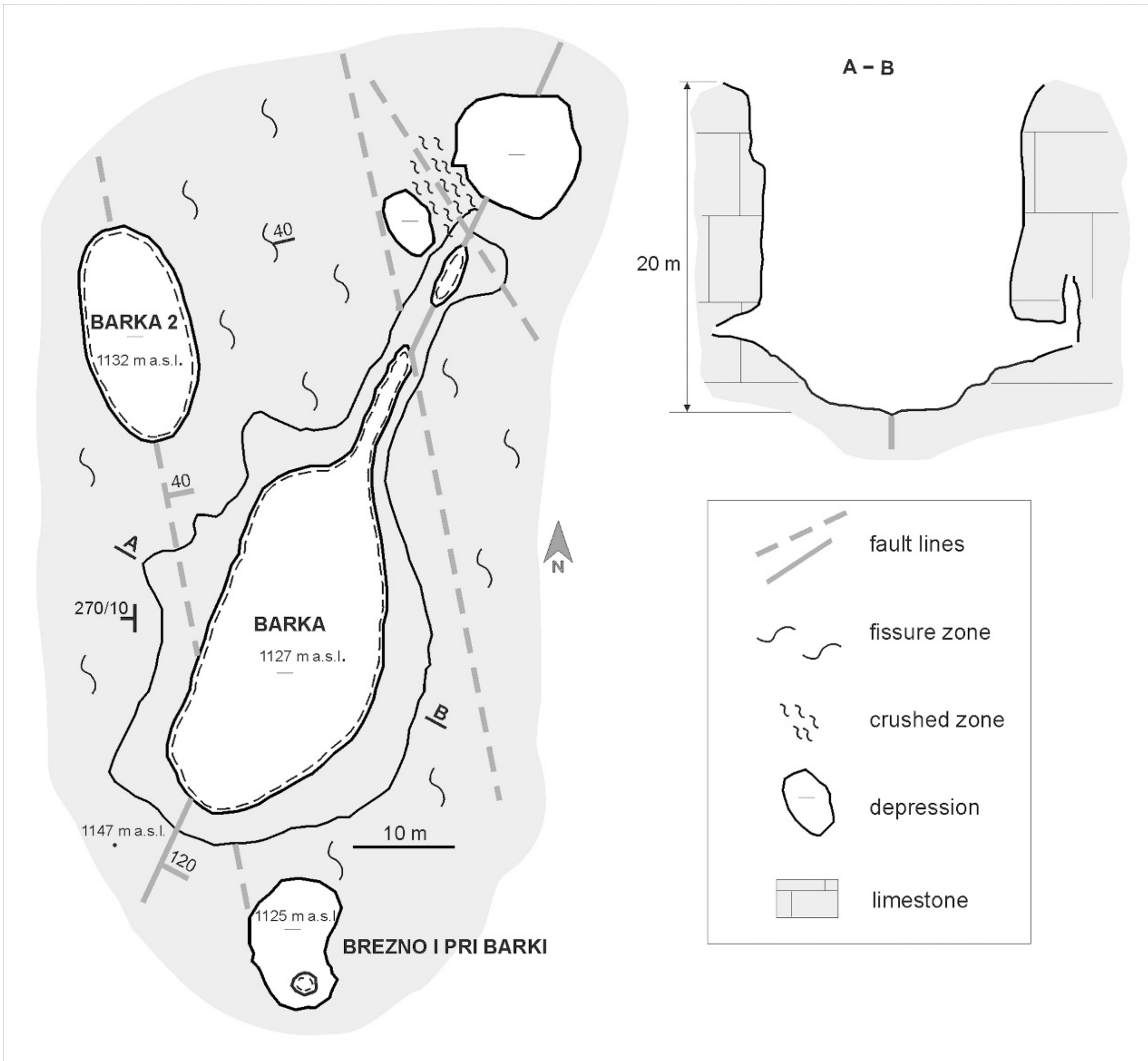

Figure 2. Geologic map of the Barka area. Upper Cretaceous limestone ($K_2^{2,3}$) is fractured by tectonic zones in different directions. Barka is formed along a fault line in which continuation as a small cave (with window in ceiling) is located in another depression. In the fissure, which crosses Barka, Barka 2 and the shaft Brezno I pri Barki are developed.

glaciation and directions of glacier movements. According to Šifrer (1959), during the glacial maximum the ice covered large karst depressions (named draga) in the area; their bottoms are now located at about 1100 m above sea level. Some of these moraines are cemented and some of them are not. From this we can conclude that probably they are different in age. The surrounding area of Dedna gora and the Barka depression was not covered by ice, but perhaps Barka was filled by snow or ice during peaks of the glaciations.

Climate and Vegetation of the Area

A mountainous climate is typical of the area. Precipitation is rather high, with an average of 2928 mm in the southern slopes of Snežnik and, according to an estimation (Ogorelec and Mastnak, 1999), about 4219 mm at the summit. Thus, Snežnik Mt. is one of the wettest regions in Slovenia. Precipitation is either rain or snow and snow cover lasts for several months. Temperature depends on altitude; the bottoms of deep depressions are colder due to temperature inversion, a fact easily observable in the vegetation distribution. At the meteorological station south of Snežnik Mountain (Gomance, at about 1100 m a.s.l.), the average annual temperature is 6.7 °C, the average temperature in July is 15.5 °C, and the average temperature in January is −3.5 °C. In a year there are on average 127 days with temperatures below 0 °C. Forest covers more than 90% of the plateau. Dinaric *Abies–Fagetum* forest between 700 and 1200 m prevails.

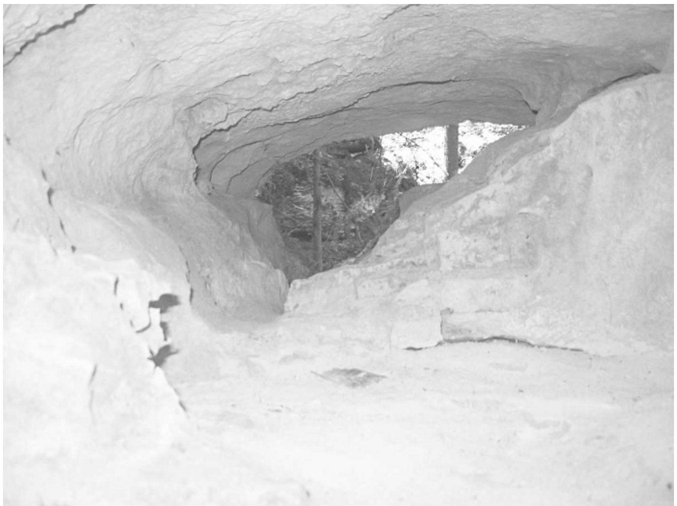

Figure 3. Open channel along one of the bedding planes in the limestone between the Barka depression and Barka 2.

Karst and Hydrology of the Area

The area of the Snežnik-Javorniki karst massif is fed by diffuse infiltration of precipitation water over the whole surface. Rainwater immediately disappears underground into karstified land and feeds a vast aquifer. At the surface there are only short streams originating from local perched

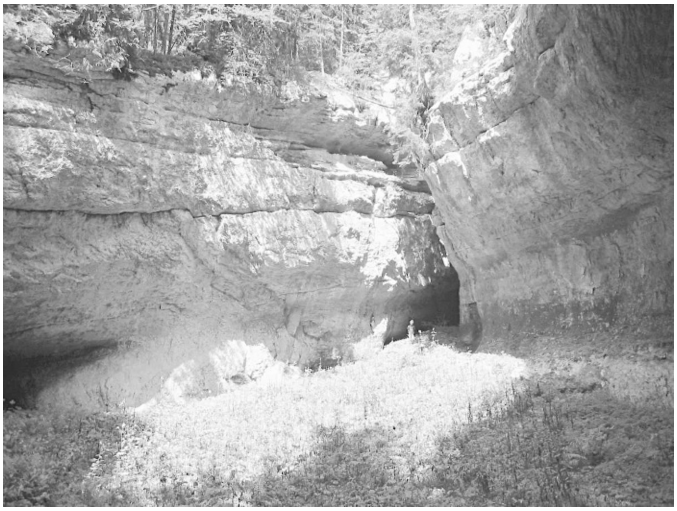

Figure 5. On the walls of the Barka depression there are distinctive bedding planes and on the northwest side a small cave is developed along the main fault plane.

springs. The large springs around the massif appear at about 600 m a.s.l., at the contact with impermeable flysch rocks, or at the borders of karst poljes (Cerknica polje, Loško polje, etc.). The vadose zone is about 1000 m thick, although it varies according to precipitation, relief, and structural elements. Karst bifurcation in different direc-

Figure 4. The shape of the Barka depression resembles a barge hull. Its bottom is covered with snow, April 2005.

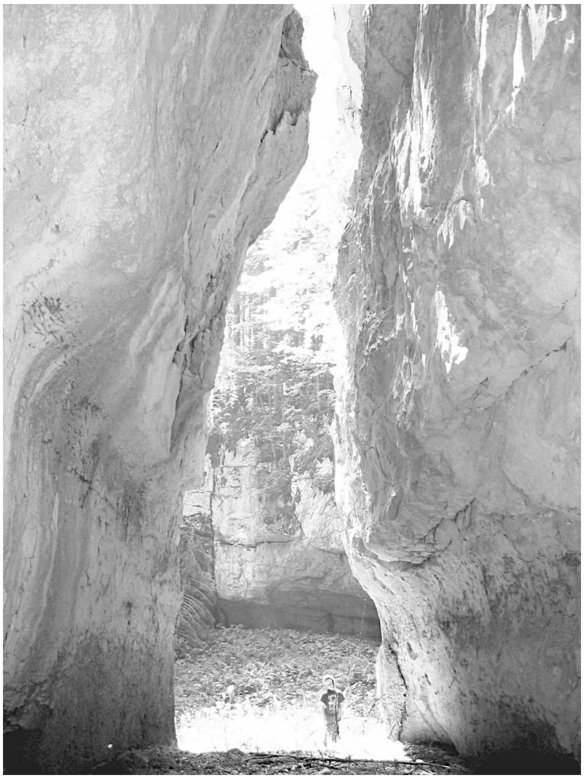

Figure 6. Short cave in the continuation of the Barka depression at its northwest side.

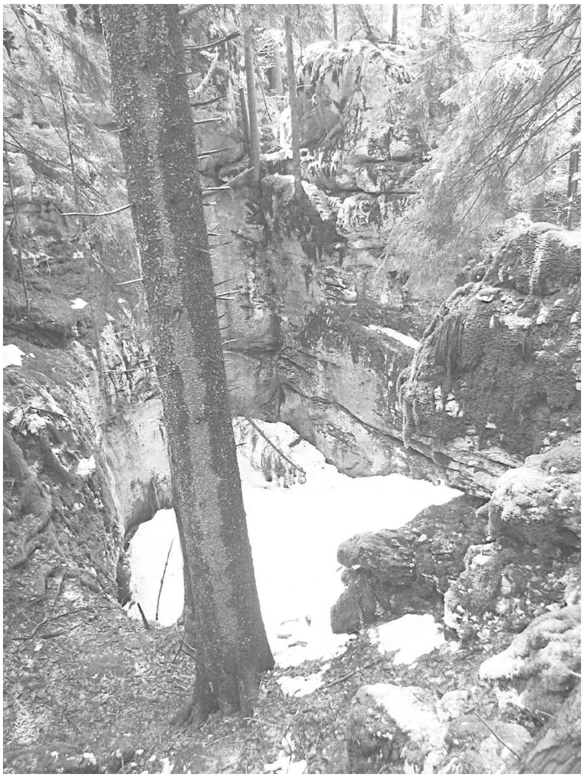

Figure 7. Closed depression in the continuation of the same fault line as the Barka depression, and a short cave.

tions is typical of the area and was proved by several water tracing tests (Habič, 1989). From the Pivka basin, water mostly flows towards the Black Sea watershed, or else towards the Adriatic Sea.

Vast plateaus, deep closed depressions, and clusters of more or less conical summits (Habič, 1981, 1986; Šušteršič, 1975) are typical of the Javorniki - Snežnik massif. The surface displays all the typical karst features from karren, solution flutes, dolines, to huge depressions, so-called Draga, formed amidst cone shaped peaks. On the southern Snežnik slopes, there are deep and narrow depressions, named Ždrocle, which are more like remains of vadose shafts than solutional dolines (Zupan Hajna, 1997). In big karst depressions (drage) in the Snežnik area, moraines are present, representing the combined actions of small glaciers and concurrent karstification.

Many caves were discovered and described 30 years ago during the Speleological Map of Slovenia project by the Karst Research Institute (Šušteršič, 1975). Today 560 caves are registered in the area (Cave Register of Karst Research Institute ZRC SAZU and Speleological Association of Slovenia). These are mostly deep shafts (up to 100 m or more) due to vadose drainage from the karst surface towards the regional base water level. In the Register, the deepest shaft is Brezno Bogomira Brinška on the east-southern part of Snežnik Mountain, which is 506 m deep. There are almost no horizontal caves in the area.

Figure 8. Along the bottom of the Barka depression a shelter opens in the wall. The floor of the shelter is covered by rubble and silt.

Study Area

The study area, Dedna gora and surroundings, is located between Javorniki Mountain on the north and Snežnik Mountain on the south (Fig. 1). The Barka depression is situated southwest of the top of Dedna gora

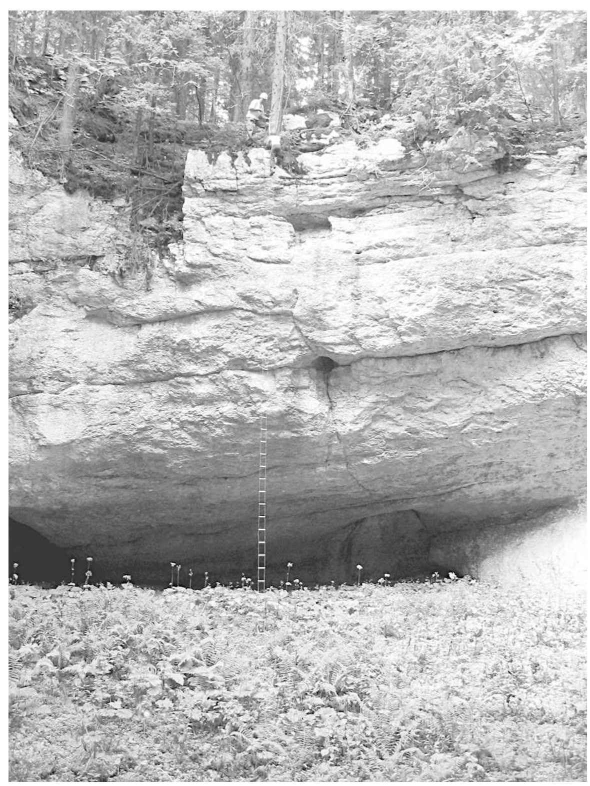

Figure 9. Detail of a shelter along one of the bedding planes in the Barka depression.

Figure 10. Patterned ground on the bottom of a shelter below the Barka depression walls: sorted (a) and non-sorted (b) polygons are developed.

Figure 11. Within an area of 100 × 100 m, many smaller depressions are found. Barka 2, with vertical walls and snow at its bottom is one of them (April 2005).

at the elevation of 1147 m a.s.l. (45°39′7.9″N, 14°22′57.6″E). During fieldwork for the Speleological Map (Šušteršič, 1975) Barka was included in the Cave Register. For the purpose of the present research, I have done a detailed survey of the Barka depression and the surrounding area, as well as basic geological mapping.

In the area nearby, the Upper Cretaceous limestones are densely fractured and faulted (Fig. 2). The fault zones generally run in the directions NW-SE, NE-SW and E-W, while the fissured zone displays N-S orientation. South of the Barka depression the dark limestone is thin bedded and tectonically fractured. Closer to the depression the limestone is as thick bedded, with white calcite veins. The limestone layers are almost horizontal, dipping slightly south. Along fissures deep karren are developed. The whole area, about 10^4 m^2 in the vicinity of Barka, is a huge karren-field with larger or smaller depressions in between the karren, with the appearance of big snow-kettles. Within open bedding planes in the vicinity, there is copious silt due to gelifraction. The clay is moist even in summer. In some of the bedding-planes, there are traces of water flow, as water remains after snow thawing at different levels and flows through opened bedding-planes and fissures in the limestone (Fig. 3).

Barka is a closed depression about 40 m long, 25 m wide and 20 m deep, with precipitous walls. The walls are smooth, but the bedding planes of the limestone can be clearly seen. Barka's shape resembles a barge hull (Fig. 4), with a volume of about 1500 m^3. The bottom of Barka is covered by silt, sand, and rubble, inclined towards the center where a smaller sinkhole exists. While in summer the bottom is overgrown by coltsfoot, winter snow remains long into springtime. The present form of Barka results from the remodeling of its walls, which were, and still are, affected by ice, snow, and frost. The shape and smooth surface of walls indicate a large quantity of snow that probably remained in its bottom in the past.

The longer Barka axis is oriented along a subvertical fault oriented NE-SW (Fig. 2). The fault continues in a short cave at the northern side of the depression (Fig. 5). The cave (Fig. 6) has a small window in the ceiling and ends after a few meters. Along the same fault, further northeast from the end of the cave, there are two smaller depressions. Only some of their walls are vertical and their steep-sided slopes are covered by boulders (Fig. 7).

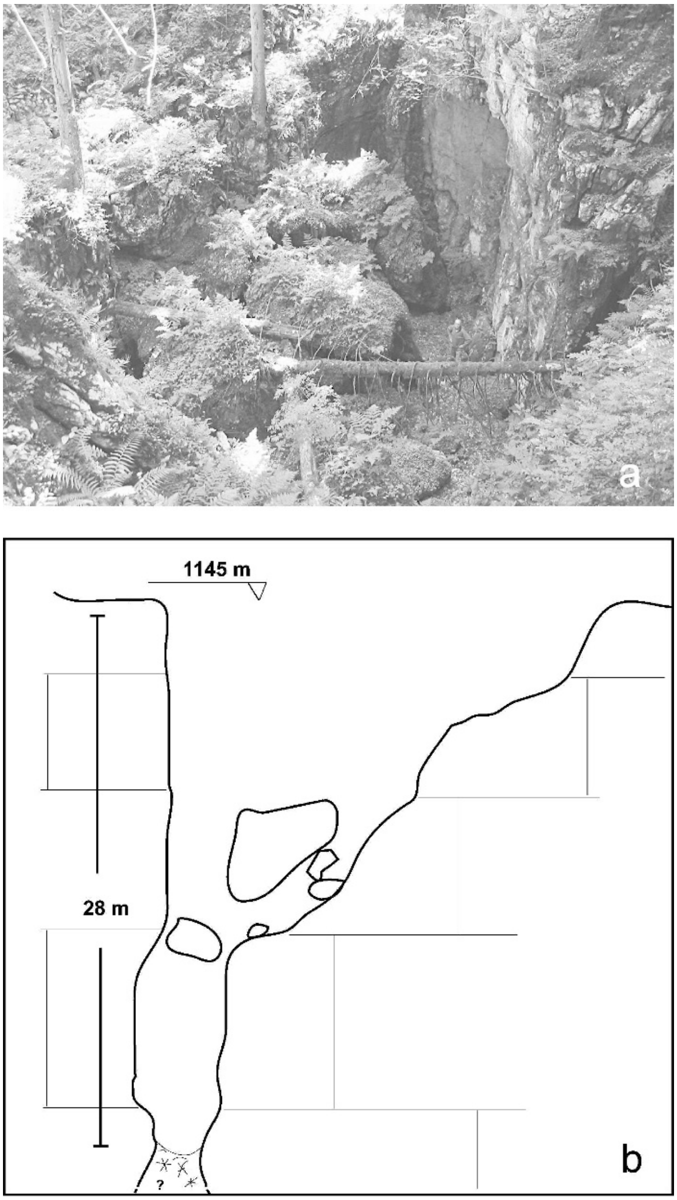

Figure 12. Entrance to the cave Brezno 1 pri Barki is below the precipitous wall of a smaller depression covered by collapse blocks (a, b).

Approximately four meters above Barka's bottom, a ledge opens in its rim (Fig. 8) along one of the bedding planes (Fig. 9). The ledge ends as a shelf below an overhanging wall. On the shelf floor, silt and rock debris are collected as a result of gelifraction and freezing. The material on the shelf floor is exposed to freezing during the winter (frost action). Repeated freezing and thawing of the ground causes a movement of its coarser elements towards the freezing surface. Sorted and non-sorted polygons are formed because of that process. The polygons in some places are fully developed and well sorted (Fig. 10), which is very rare in these latitudes, even higher in the Alps. A few polygons have been described before from cave entrances on the Kras plateau (Mihevc, 2001).

On the western side of Barka, in a fissured zone, another closed depression is situated (Fig. 11). Barka 2 is smaller in dimensions, 26 × 10 m, and about 15 m deep, with a similar shape of walls and bottom as Barka. Also, the ledge is present around the whole depression, upon which silt material is accumulated.

On the eastern side of Barka, in the same fissure as Barka 2, the shaft Brezno I pri Barki is situated (Fig. 2). The entrance to the shaft opens in the bottom of a closed depression where the slopes are covered by breakdown rubble and big blocks of limestone (Fig. 12). The depression where the entrance to the shaft Brezno I is situated is only ten meters from the Barka rim. Shaft Brezno I pri Barki is 28 m deep. In the entrance, ice remains for the whole year, in some years obstructing the entrance. In the shaft there are remains of old wooden ladders used to extract ice.

Discussion and Conclusion

During the last glaciation, the snow line was not much higher than the location of Barka, between 1250–1300 m (Šifrer, 1959). At that time the region was not covered by forest, and thus Barka could have been filled and covered by snow, which probably thawed in warmer periods, with water flowing between snow and walls. Even now, the air at the bottom of the depression is cooler and snow remains for quite a long time.

The genesis of Barka can be explained by several hypotheses. One possible mode of origin is the development of a vast karren-field on suitably fissured sub-horizontal limestone with interlying closed depressions, snow-kettles shaped by snow. Such a case would be the classic development of snow-kettles in high mountainous karst (Kunaver, 1983; Gams, 2003). However, closed depressions in the vicinity, and in particular Barka itself, are much too large to be snow-kettles, and their walls are too even and smooth. Therefore, a more probable explanation would be that these closed depressions were caves in the past, most probably inner shafts such as those in the Alps or High Dinaric karst plateaus such as Trnovski gozd (shafts in Velika ledena jama v Paradani described by Mihevc (1995)). These shafts were then uncovered by surface denudation and exposure to superficial conditions, as is seen in innumerable examples from Classical karst (Mihevc, 1996; Mihevc, Zupan Hajna, 1996; Mihevc, 1998a, 1998b, 1999a, 1999b, 1999c; Šušteršič, 1999; Mihevc et al., 2002; Knez and Slabe, 2002; Mihevc, 2006, 2007).

Mihevc (2001) described such cases with examples from Divaški karst, where denudation of the karst surface exposed caves and their contents to the surface. That author stressed the importance of inherited forms, inside caves in the past and on the surface at present. According to Mihevc (1996) the denudation rate of the karst surface

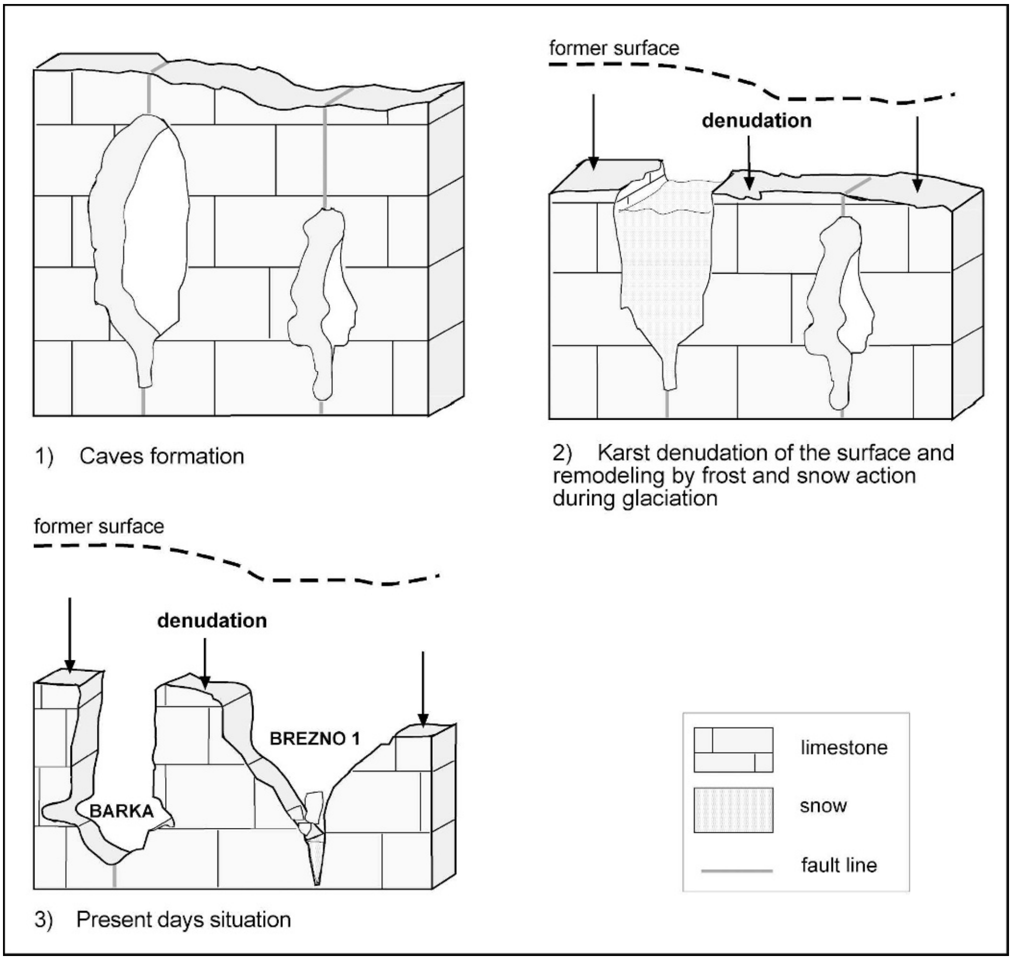

Figure 13. Schematic model of the transformation of earlier caves into kettle-shaped depression by karst denudation and frost/snow action.

on the Kras plateau and the Reka river watershed is about 50 m per Ma. Denudation rates can be lower or higher, depending on the amount of precipitation, etc. (Gams, 2003). Audra et al. (2002) describe in Austria the denudation of carbonate rocks above old caves, their exposure to weathering, and their remodeling into kettle-shaped dolines, acting as snow-pits as a result of periglacial activity. Different types of denuded shafts have been studied by Klimchouk et al. (2006); they describe the exposure of shafts in vertical walls as mainly due to intense gravitational processes induced by removal of the ice supporting the cliffs.

The shape and location of Barka depression suggest that this is an inherited feature of a former shaft, transformed during glaciation to a kettle-shaped depression, and still influenced by freezing effects during winter (Fig. 13). It is also likely that all smaller depressions in the vicinity are remaining clusters of smaller shafts with denuded ceilings. In the present day, all these closed depressions act as traps for snow. Snow can remain in them more than six months per year. Considering that denudation of the karst surface is continuous and constantly exposes underground features to the surface, this is the most probable explanation of the origin of Barka.

I conclude that exposure of shafts due to denudation is a significant process. Denuded shafts can be an important morphological element of karst relief, especially expressed as closed depressions of different sizes, including many snow-kettles in high mountains.

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A REDESCRIPTION OF *CERATOPHYSELLA LUCIFUGA* (PACKARD) (COLLEMBOLA, HYPOGASTRURIDAE) FROM NORTH AMERICAN CAVES

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Abstract: The problematic species *Ceratophysella lucifuga* (Packard) is redescribed based on topotypes from Wyandotte Cave and specimens from two other caves of the south-central Indiana karst area. This species is characterized by lack of body pigmentation, slightly reduced ocelli, absence of an eversible sac between antennal segments III–IV, presence of long lateral sensilla in antennal III-organ, postantennal organ with somewhat subdivided posterior lobes, well developed furca and the absence of setae a'_2 on abdominal tergum V. *C. lucifuga* is similar to other cavernicolous species of the ceratophysellan lineage grouped in genera *Ceratophysella* Börner and *Typhlogastrura* Bonet, especially *C. proserpinae* (Yosii) and *C. troglodites* (Yosii) from Japan, *C. pecki* Christiansen and Bellinger from USA and *C. kapoviensis* Babenko from Russia.

Introduction

In spite of long-term studies, our knowledge of the Nearctic *Ceratophysella* Börner, 1932 is still far from the expected state. The total number of species recorded from the USA and Canada is only 26 (Christiansen and Bellinger, 1998; Skarżyński, 2006), while 66 have been reported from the Palaearctic region (Thibaud et al., 2004; Skarżyński, 2005; Skarżyński and Smolis, 2006). Moreover, the taxonomic status of some Nearctic species remains unclear. Additional faunistic and taxonomic studies are needed to estimate the real biodiversity of North American springtails. In material obtained from Dr. Kenneth Christiansen, several specimens were present of the problematic species *Ceratophysella lucifuga* (Packard, 1888) from the type locality, Wyandotte Cave in southern Indiana. A redescription of this species is presented below.

Species Redescription

Ceratophysella lucifuga (Packard, 1888) (Fig. 1 A–K)
Lipura? *lucifuga* Packard, 1888: p. 65
Lipura? *Achorutes*? *lucifuga* Packard, 1888: 88
Hypogastrura lucifuga: Bonet (1930: 123)
Hypogastrura armata lucifuga: Bonet (1934: 362)
Hypogastrura (Ceratophysella) lucifuga: Christiansen and Bellinger (1980: 161)

Material Examined

Wyandotte Cave, ca. 5 km NE Leavenworth, Crawford Co., Indiana, from surface of water, four females, one male on slides, August 27, 1928, leg. R. Jeannel (2404); same locality, seven females, four males, four juveniles, June 17, 1934, leg. A. Emerson (384); Ed's Hole, ca. 3.2 km N DePauw, Harrison Co., Indiana, leaf litter on the floor of the entrance, two females, May 29, 1996, leg. J. Lewis (7976); Little Mouth Cave, ca. 3.2 km S Laconia, Harrison Co., Indiana, one male, November 25, 1992, leg. J. Lewis (7616) (all preserved at the collection of Grinnell College, Iowa).

Description

Body length 0.9–2.2 mm. Body color white, eye patches dark, anal spines yellowish. Granulation rather uniform, 9–14 granules between setae p_1 on abdominal tergum V (Fig. 1B).

Dorsal chaetotaxy of thorax and abdomen as in Figures 1A–1B, chaetotaxy of head typical of the genus. Dorsal setae well differentiated. Macrochetae long and serrated, usually slightly curved and blunt-tipped on head, thorax and first abdominal segments and distinctly curved and pointed on last abdominal segments. Body sensilla (s) fine and smooth. Thoracic tergum II with p_2 shifted forward, a_3 longer than a_2, m_3 absent and m_6 present. Setae a'_2 on abdominal terga I–III usually present, on abdominal tergum V always absent. Abdominal tergum IV with p_1 and p_2 microchaetae and macrochaetae respectively, setae p_3 present. The three axial setae (a_1, m_1, p_1) on abdominal tergum IV diverging. Subcoxae I, II, III with 1, 3, 3 setae, respectively. Microsensillum (ms) on thoracic tergum II present.

Antennal segment IV with trilobed apical vesicle (av), subapical organite (or), microsensillum (ms), seven cylindrical sensilla, about 15 thin only slightly modified sensilla in the ventral file (Figs 1C–D). Antennal III-organ with two long (20–22 µm, lateral) and two short (internal) curved sensilla. Microsensillum on antennal segment III present. Eversible sac between antennal segments III–IV absent. Antennal segment I with 7 setae. Ocelli 8 + 8 or 8 + 7 (F + G fused) (Figs 1H–K). Arrangement of ocelli labile (Fig. 1I). Diameter of eyes usually reduced to 9–12 µm and incidentally to 5–6 µm (Fig. 1H). Postantennal organ 2–3

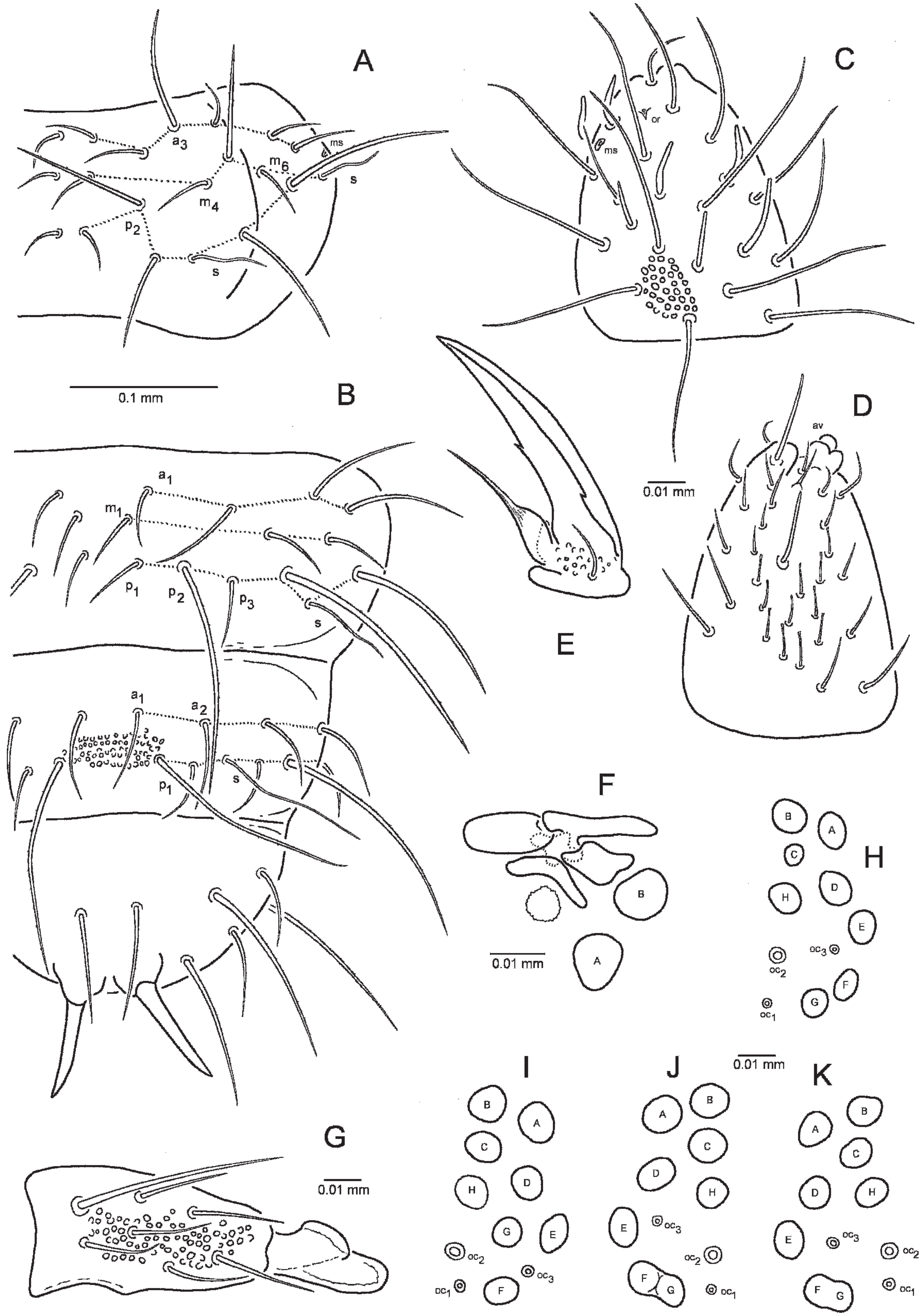

Figure 1. ***Ceratophysella lucifuga*: (A) chaetotaxy of thoracic tergum II; (B) chaetotaxy of abdominal terga IV–VI; (C) dorsal side of antennal segment IV; (D) ventral side of antennal segment IV; (E) claw III; (F) postantennal organ and neighbor ocelli; (G) dens and mucro; (H–K) variants of eye arrangement: (H) ocelli A, B, D–G normal, ocellus C minute; (I) ocelli A–F in typical positions, ocellus G dislocated; (J) ocelli A–E normal, ocelli F and G incompletely fused; (K) ocelli A–E normal, ocelli F and G completely fused.**

Table 1. Morphological differences between *C. lucifuga*, *C. kapoviensis*, *C. pecki*, *C. proserpinae*, and *C. troglodites* (after Yosii, 1956, 1960; Christiansen and Bellinger, 1980; Babenko et al., 1994).

Characters	*kapoviensis*	*lucifuga*	*pecki*	*proserpinae*	*troglodites*
Body colour	white with dark spots	white	white with dark spots	white with dark spots	white
Number of ocelli	8 + 8, 8 + 7	8 + 8, 8 + 7(F + G)	8 + 8	8 + 8, 8 + 7(H absent)	8 + 8
Apical vesicle on antennal segment IV	simple	trilobed	simple	simple	simple
Eversible sac between antennal segments III–IV	+	−	−	+	−
Number of lobes in postantennal organ	4–5	4	4	4	4
Number of setae on dens	5–6	7	7	6	7
Estimative ratio: empodial filament/ inner edge of claws	0.6	0.6	0.9–1.1	?	0.5
Setae a'_2 on abdominal terga I–III	−	+/−	+	+/−	+
Setae p_3 on abdominal tergum IV	−	+	+	+	+
Setae a'_2 on abdominal tergum V	−	−	+	−	+
Setae p_2 and p_4 on abdominal tergum V	−	+	+	+	+
Body sensilla longer than macrochaetae	−	−	−	+	−

times as long as nearest eyes, with four lobes of which the anterior pair is distinctly larger than the posterior. Posterior lobes often incompletely subdivided. Accessory boss present (Fig. 1F). Labrum with 5, 5, 4 setae and 4 prelabrals. Labium of the *succinea* type (papilla C absent, see Fjellberg, 1999). Head of maxilla of the *denticulata* type (Fjellberg, 1984). Outer lobe with 1 sublobal hair.

Tibiotarsi I, II, III with 19, 19, 18 setae, respectively; clavate setae absent. Claws with inner tooth and two pairs of lateral teeth. Empodial appendage with broad basal lamella and the apical filament reaching slightly beyond inner tooth (Fig. 1E). Ventral tube with 4 + 4 setae. Furca well developed, but with delicate cuticular skeleton (see Skarżyński, 2000, Fig. 10). Dens with seven unmodified setae, about twice as long as mucro. Mucro boat-like, delicate (Fig. 1G). Retinaculum with 4 + 4 teeth. Anal spines thin and slightly curved, situated on high basal papillae (Fig. 1B). Anal spines 1.0–1.3 as long as inner edge of last claw.

Remarks

C. lucifuga was briefly described by Packard (1888). The redescriptions of Bonet (1934) and Christiansen and Bellinger (1980) increased our knowledge, but the taxonomic status of this species remained unclear. Due to little morphological differentiation, *C. lucifuga* was considered by Christiansen and Bellinger (1980) to be a local variant of the *denticulata* complex. Examination of topotypes revealed new characters and allowed refinement of its systematic position.

The following morphological characters, which may be regarded as cave adaptations, appear most characteristic: lack of body pigmentation, slightly reduced ocelli, absence of eversible sac between antennal segments III–IV, presence of long lateral sensilla in antennal III-organ and postantennal organ with somewhat subdivided posterior lobes. These regressive and progressive features, the well developed furca and well differentiated chaetotaxy of A type (Thibaud et al., 2004) make *C. lucifuga* similar to other cavernicolous species of the ceratophysellan line among *Ceratophysella* (*denticulata* group) and *Typhlogastrura* Bonet, 1930 (see Thibaud, 1980; Christiansen and Bellinger, 1998; Thibaud et al., 2004; Christiansen and Wang, 2006). Considering the small amount of troglomorphy (Christiansen, 1985), *C. lucifuga* is comparable with weakly pigmented *Ceratophysella proserpinae* (Yosii, 1956) (Japan), *C. kapoviensis* Babenko, 1994 (Russia, Bashkiria), *C. troglodites* (Yosii, 1956) (Japan) and *C. pecki* Christiansen and Bellinger, 1980 (USA). The first two species have slightly reduced eyes and dental chaetotaxy, while the latter two have the full number of dental setae and ocelli (Table 1). One may say that *C. proserpinae* and *C. kapoviensis* have evolved as *Schaefferia* (Absolon, 1900) and *C. lucifuga*, *C. troglodites* and *C. pecki* as *Typhlogastrura*.

C. lucifuga is a species of limited distribution. It is known from three caves that occur in the unglaciated south-central Indiana karst belt. Ed's Hole and Wyandotte Cave are both in the Crawford Upland, while Little Mouth Cave is in the adjacent Mitchell Plain. Little Mouth Cave lies about 35 km SE and Ed's Hole Cave is about 19 km NNE of Wyandotte Cave (Lewis, 1998).

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A CONCEPTUAL MODEL OF THE FLOW AND DISTRIBUTION OF ORGANIC CARBON IN CAVES

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Abstract: We present a conceptual model for the movement of organic carbon in karst. We argue that the drainage basin is the most appropriate unit for analyzing energy flux in karst. There are two main inputs in karst basins: 1) localized flow of particulate organic carbon (POC) and dissolved organic carbon (DOC) through sinks and shafts and 2) diffuse flow of POC and DOC from soils and epikarst. After entry, this organic matter is processed and transported before eventual loss through respiration or export from the basin. To begin parameterizing our conceptual model, we estimated carbon fluxes for the first two inputs for two karst basins (Organ Cave in West Virginia and Postojna-Planina Cave System (PPCS) in Slovenia) that have sinking streams and many active epikarst drips. We made a series of measurements of organic carbon, especially DOC in epikarst drip water, cave streams, surface streams sinking into the cave, and at resurgences, which we combined with other published data. In both caves, most of the organic carbon entering through the epikarst was DOC, at concentrations averaging around 1 mg C L^{-1}. In both basins, sinking streams accounted for the large majority of DOC input. It is likely that considerable processing of organic carbon occurs within both caves, but more detailed measurements of organic carbon flux at both the basin and stream scale are needed.

INTRODUCTION

It has long been recognized that caves and other subterranean habitats are likely to be food-limited because of the absence of photosynthesis. There is a great deal of indirect evidence such as reduced metabolic rate, larger but fewer eggs, and increased longevity of subterranean animals (see Hűppop, 2000 for a review) that is consistent with the hypothesis of resource limitation. However, there has been remarkably little direct measurement of the input to, and subsequent use of, energy in caves. Indeed, with the exception of a study by Simon and Benfield (2002) in Organ Cave, West Virginia, no one has experimentally tested whether cave streams are carbon or nutrient (nitrogen or phosphorus) limited. In fact, some authors, dating back to Racovitza (1907), have questioned whether caves are food-limited at all.

The lack of emphasis by speleobiologists on the flux of food, especially organic carbon, is all the more remarkable because the discipline of ecology was revolutionized in the 1950s and 1960s by the introduction of ecosystem concepts. Perhaps the most important advance of ecosystem ecology was re-parameterization. Instead of a focus on numbers of individuals, numbers of species, and the like, systems ecology focused on standing stocks and fluxes of matter and energy (especially carbon, phosphorus, nitrogen). Ecosystem ecologists also changed the scale of measurement in ecology. At least in the early days of ecosystems ecology, the spatial scale of analysis tended to be larger than that employed by most population biologists, and took into account multiple features of landscapes such as uplands, riparian areas and streams. For example, the idea of a watershed as a unit of study (Bormann and Likens, 1967), for which input/output budgets could be developed, particularly revolutionized ecosystem ecology. It is ironic that given the nearly complete absence of ecosystem thinking from speleobiology (but see below) that the classic study of energy flux in an ecosystem was that of a karst spring in Florida—Silver Spring (Odum, 1957).

There have been two significant steps forward in ecosystem thinking about cave environments. Historically, the first was the extensive work of Rouch and his colleagues on the Baget Basin, a small karst drainage in France. In a series of more than 20 papers (summarized in Rouch, 1986) he used the ecosystem approach of measuring inputs and outputs of the Baget Basin, but rather than use ecosystem parameters such as carbon and calories, he used numbers of animals. Thus, he used elements of both ecosystem and population ecology. He also made an important conceptual advance of using an entire drainage basin rather than only the cave (Rouch, 1977) as an appropriate unit of analysis in karst. Gibert (1986), in what is the first true ecosystem study in karst, used Rouch's framework and quantified the flux of organic carbon from springs draining the epikarst and the saturated zones of the Dorvan-Cleyzieu basin in France. Among Gibert's most important findings were that dissolved organic carbon (DOC) represented a larger flux than particulate organic

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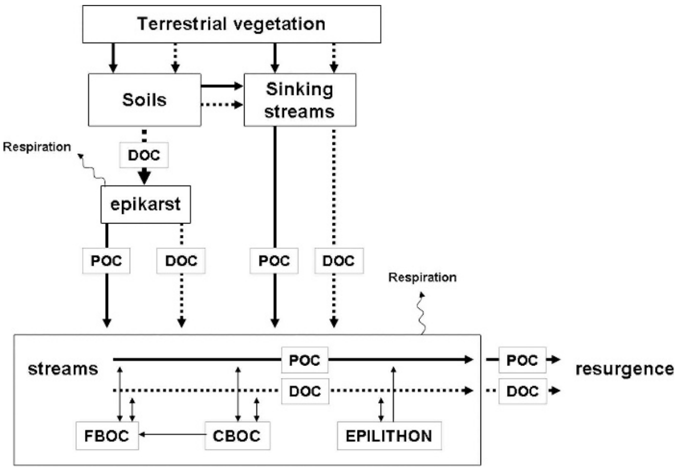

Figure 1. A conceptual model of energy flow and distribution (as organic carbon) in a karst basin. Standing stocks are particulate (POC) and dissolved (DOC) organic carbon in the water column and fine (FBOC) and coarse (CBOC) benthic organic carbon and microbial films on rocks (epilithon). Solid and dashed arrows represent fluxes. Within the cave stream double headed arrows connecting DOC to BOC and epilithon represent leaching and microbial uptake. Double headed arrows connecting POC and BOC represent deposition and suspension. The arrow connecting CBOC and FBOC represents breakdown.

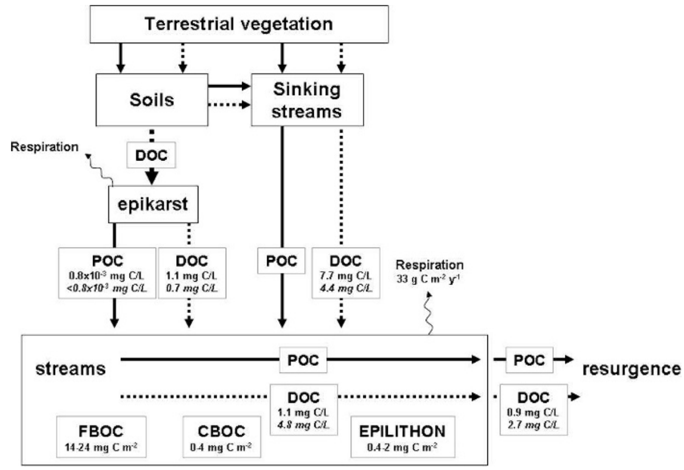

Figure 2. Schematic diagram of organic carbon flux in Organ Cave and the Postojna Planina Cave System (PPCS). Values in italics are PPCS data. Data are standing stocks of C except for respiration flux. POC, DOC, FBOC and CBOC are particulate, dissolved, fine benthic, and coarse benthic organic carbon, respectively. Values for FBOC, CBOC and microbial film are taken from Simon et al. (2003). Whole-stream respiration rate is from Simon and Benfield (2002).

carbon (POC), that those fluxes were temporally variable, and that microbes were likely to be key players in mediating energy transfer between organic carbon and animals in karst. Second, Simon and colleagues applied the methods and paradigms of surface stream ecology to the study of organic carbon cave streams. Among their findings were that most coarse particulate organic matter (CPOM) moved relatively short distances (tens of meters) before it was broken down or consumed (Simon and Benfield, 2001), that cave streams were more likely carbon rather than nutrient limited (Simon and Benfield, 2002), and that microbial films fueled by DOC are an important food in cave streams (Simon et al., 2003).

Our goals in this paper are to: 1) elaborate a conceptual model of energy flow through karst; 2) begin to parameterize this model with existing data from the literature and new data collected from European and North American karst systems; and 3) use these data to compare the various inputs of energy in karst systems and the processing of that energy as it moves through karst.

A Conceptual Model of Energy Flux in Karst

The most appropriate scale for an ecosystem approach to studying energy flow in karst is one that includes the relevant energy sources to caves and one for which input-output budgeting may be used. The karst basin used by Rouch satisfies both requirements. Energy inputs to karst basins can include internal production and the import of DOC and POC derived ultimately from surface vegetation. While some karst basins may have substantial internal energy production by chemoautotrophs (e.g., Sarbu et al., 1996), in most karst basins, internal production is effectively zero. Input of DOC and POC may arrive via two different pathways (Fig. 1). Localized openings such as sinking streams and shafts permit entry of DOC or POC, such as leaves, wood, and fine detritus from streams and soils. Water percolating through soils and the epikarst, the zone of contact between soils and bedrock lying above caves, carries with it DOC, but POC is effectively filtered by soils (Gibert, 1986). POC may arrive from the epikarst in the form of animals dripping into caves through the epikarst. While localized input of organic carbon is the most easily observed and likely to be large, there is considerable reason to think that diffuse input from the epikarst is also important. For example, Pipan (2005) has shown that there is a rain of POC in the form of copepods in epikarst drips, and Simon et al. (2003) found that microbial films fueled by DOC from soils were a primary food for animals in cave streams.

For terrestrial habitats in caves there is another source of carbon, movement of organic matter into the cave through entrances, especially from animals that regularly enter and exit the cave (e.g., bats and crickets). In some circumstances, bat guano may enter the cave stream (Graening and Brown, 2003), and we consider this part of the localized transfer of organic carbon. Deep ground water may be another source of DOC, but considering the long residence time and distance from organic matter sources, deep ground-water inputs likely contribute little organic carbon within karst basins.

After input into the karst basin, POC and DOC are used or processed to different forms before eventually being exported through resurgences (Fig. 1). The major standing stocks of organic carbon within the basin include DOC and POC (or, seston) in the epikarst, epikarst drips, sinking streams, and cave streams, and POC (either fine (FPOC), <1 mm, or coarse (CPOC) >1 mm) and microbial films on rocks (epilithon) in epikarst and cave streams. The major fluxes of organic carbon include transport of DOC and POC in drips and streams (sinking and within caves), suspension and deposition of CPOC and FPOC in streams, breakdown of CPOC to FPOC, leaching of DOC from POC and epilithon, uptake of DOC by epilithon and microbes associated with benthic POC, losses from respiration along the flowpath of water through the basin, and export from springs (Fig. 1). While ideally the standing stocks and fluxes within the epikarst should be included within the karst basin, operationally this is virtually impossible given the inaccessibility of the epikarst. Therefore, only the fluxes out of the epikarst are likely to be directly measurable.

Within karst basins, standing stocks and fluxes of organic carbon are likely to be both spatially and temporally variable. This variation is likely to be important, but given the paucity of data, our focus is primarily on the conceptual model and includes only an initial parameterization of standing stocks and fluxes of energy. In particular, we do not address temporal variation in standing stocks or fluxes of carbon and only touch upon spatial variation among epikarst drips. These issues we leave for future, detailed analysis.

Methods and Materials

We parameterized models of two cave systems: Organ Cave in West Virginia and Postojna-Planina Cave System (PPCS) in Slovenia. We used published estimates for some standing stocks and fluxes for Organ Cave (Simon and Benfield, 2002; Simon et al., 2003). We also collected new data about inputs of organic carbon through epikarst drips and sinking streams, as well as DOC in cave streams and the resurgences, of both systems.

Organ Cave is a large, mostly horizontal cave with over 60 km of surveyed passage located in Greenbrier County, West Virginia (Stevens, 1988). Organ Cave drains an 8.2 km^2 basin, 70 percent of which is underlain by Mississippian limestone and the rest by Mississippian sandstone and shale. A series of small cave streams eventually coalesce in a single stream that emerges at a spring on the edge of Second Creek, itself a tributary of the Greenbrier River, the base stream of the region. Small streams, some of them seasonal, that originate in a non-carbonate part of the basin, sink at or near some of the nine entrances to the cave system. Most of the land in the basin is agricultural, especially pastures. Organic carbon samples were taken at one stream that sinks into the cave near the Organ Cave main (commercial) entrance, three small streams in the cave, Lipps, Sively No. 2, and Sively No. 3 (all place names can be found in Stevens (1988)), 13 epikarst drips (see Pipan and Culver [2005] for locations) draining into the three streams, and the resurgence of the system.

The Postojna-Planina Cave System (PPCS), with approximately 23 km of surveyed passage (17 in Postojna and six in Planina connected by 2 km of flooded passage), is arguably the most extensively studied cave in the world (e.g., Pipan and Brancelj, 2004; Sket, 2004). There are two main streams in PPCS which join and exit at Planina Cave entrance. One stream is formed by the Pivka River, a moderate-sized river draining approximately 230 km^2 of carbonate and flysch which sinks near the Postojna Cave entrance. The other stream (Rak) is a somewhat smaller stream draining approximately 27 km^2 of carbonate and flysch. The land over PPCS, which is developed in Upper Cretaceous carbonate rocks, is forested, and the Pivka River drains land with a variety of uses, including forest and agriculture, as well as several small towns. The area over the cave system itself is approximately 20 km^2. Samples were taken at 28 drips in Postojna Cave (see Pipan (2005) for locations), five drips in Planina Cave (Pipan, unpublished), the two cave streams, the Pivka River where it enters the cave, and one resurgence, the Unica River.

An important difference between the two sites is the extent to which the cave fills the drainage. The ratio of cave passage length to basin size is 7.3 km^{-1} in the Organ Cave basin and 0.089 km^{-1} for the PPCS basin. The difference is largely the result of differences in drainage area and cave morphology (Palmer, 1991).

For the epikarst estimates, we collected water samples from epikarst drips and cave streams between April 2006 and November 2006. For drips, water was collected in acid-washed 50 mL HDPE sample bottles over the course of at most one hour, depending on drip rate, which ranged between 75 and 1500 mL h^{-1}. This minimizes losses of DOC in the sample (see Emblanch et al., 2005). Water was then placed in a 60cc syringe and passed through a 0.45 μm glass fiber filter (Gelman GF/F) into a second bottle and preserved to pH $<$ 2 with a drop of concentrated HCl. Water from streams was collected directly in a syringe and then filtered and preserved as above. The samples were analyzed for DOC concentration using the persulfate digestion method (APHA 1999) on an OI Analytical Total Organic Carbon Analyzer Model 1010.

We estimated the standing stock of POC, as copepods and other organisms, from the portions of the epikarst to cave streams by using data on numbers of individuals caught in 60 μm nets given in Pipan (2005) and Pipan et al.

Table 1. Estimates of dissolved organic carbon from Organ Cave and PPCS.

	Organ Cave			Postojna-Planina Cave System		
Cave Inflows	n	Mean, mg C L^{-1}	S.E.	n	Mean, mg C L^{-1}	S.E.
Sinking streams	3	7.67	1.03	2	4.36	0.46
Epikarst drips	20	1.10	0.15	99	0.70	0.04
Cave streams	6	1.08	0.32	3	4.75	1.57
Resurgence	3	0.90	0.17	2	2.67	0.80

(2006). We converted the numbers of animals entering to organic carbon by measuring the ash-free dry mass of 100 copepods obtained from Carolina Biological Supply.

Results

For Organ Cave, DOC concentration in sinking streams was seven times higher (7.67 mg C L^{-1}) than in epikarst drips (1.10 mg L^{-1}, Table 1), a statistically significant difference ($t = 6.32$, $df = 2$, $p < 0.02$). Individual drips showed considerable variation ($CV = 0.62$), but we do not yet have enough spatial or temporal data to make any statements about pattern. On average, epikarst drips and the cave streams had similar concentrations of DOC (Table 1, $t = 0.039$, $df = 7$, $p = 0.48$). Interestingly, the concentration of DOC was lower in the Lipps stream (0.73 mg L^{-1}) which is entirely epikarst fed (Simon and Benfield, 2001), than in the other streams (1.25 mg L^{-1}), but the difference was not statistically significant. In a paired sample taken in May 2006, the DOC concentration in Lipps stream, which was fed by epikarst water, was five times lower (0.19 mg L^{-1}) than in a drip feeding it (1.01 mg L^{-1}). In August 2006, the concentration of DOC in Lipps streams (1.26 mg L^{-1}) was about 75 percent that of two drips (1.72 mg L^{-1} and 2.48 mg L^{-1}) that fed the stream. If our drip samples were representative of all the epikarst water feeding the stream, then it appears that there is considerable processing of DOC along the epikarst-stream flowpath. DOC concentration in the resurgence of Organ Cave was similar to that in the epikarst drips and cave streams (Table 1).

In PPCS, DOC concentration in the sinking streams was also higher (4 times) than that in the epikarst drips (Table 1, $t = 7.87$, $df = 1$, $p = 0.04$). The DOC concentration in sinking streams of PPCS was 43 percent lower than that at Organ Cave ($t = 2.93$, $df = 2$, $p = 0.03$). For epikarst drips in PPCS, DOC concentration was slightly ($t = 2.57$, $df = 21$, $p < 0.01$) lower than in Organ Cave and the variation among drips was slightly less in PPCS ($CV = 0.53$). Unlike in Organ Cave, DOC concentration in the cave streams of PPCS was high and similar to that in the sinking streams (Table 1). At the resurgence of PPCS, DOC concentration was intermediate between the streams and epikarst drips. Compared to the resurgence of Organ Cave, the resurgence of PPCS had significantly higher DOC ($t = 6.32$, $df = 2$, $p = 0.02$).

Finally, we estimated the standing stock of POC, as copepods, in epikarst drips. The average ash-free dry mass (AFDM) of a copepod, 1.6×10^{-3} mg per individual, was converted to carbon (0.72×10^{-3} mg C per individual) assuming AFDM was 45 percent C (Sinsabaugh, 1997). In Organ Cave, Pipan et al. (2006) estimated copepod density to be 0.0041 copepods/L, equating to 2.95×10^{-6} mg POC L^{-1} in epikarst drips. This value is about 6 orders of magnitude lower than the average standing stock, 1.10 mg DOC L^{-1} in epikarst drips (Table 1).

Discussion

From an ecosystem perspective, cave streams are very similar to a rather unproductive surface stream (Simon and Benfield, 2001, 2002). Indeed, the concentration of DOC in streams of Organ Cave and PPCS are at the low end of the range (0.1 to 36.6 mg L^{-1}) reported for surface streams (Muholland, 1997). The standing stocks of particulate organic matter in Organ Cave streams are also quite low (Simon and Benfield, 2002). It is important to note that most data available for examining energy distribution in karst are standing stocks, not fluxes (Fig. 2). We know of only three estimates of energy flux in karst systems. Gibert (1986) quantified the annual flux of organic carbon from springs draining portions of the Dorvan-Cleyzieu basin; Graening and Brown (2003) estimated flux of organic matter into and out of a reach of a cave stream; and Simon and Benfield (2002) measured whole-stream respiration in a stream in Organ Cave. This places considerable restrictions on our ability to generalize, but we can use the data we have to speculate on how karst systems process energy and what further data are needed.

At both the aquifer (Gibert, 1986) and stream reach (Graening and Brown, 2003) scales, DOC is the largest input of organic carbon in karst. The concentration of DOC was much higher in sinking streams than in epikarst in both basins we examined. The relative importance of those two sources in a karst basin depends, in part, on the magnitude of those flows (i.e. the concentration times the volume of water entering from each source). We do not know the total amount of water entering the basins through epikarst drips and sinking streams, but we can use drainage area as a surrogate. It is difficult, if not impossible, to estimate the average drainage area of a drip, especially since water entering from the surface is stored in the epikarst (Williams, 1983) and some, perhaps even most, of the water stored in epikarst enters the water table without ever being intercepted by a cave passage. Nevertheless, if we conservatively assume that all the epikarst water ultimately arrives in cave streams, we can use the proportions of the basins draining to sinking streams and assume the remainder drains through the epikarst. In the Organ Cave basin, sinking streams drain 30 percent of the basin at a DOC concentration of 7.67 mg L^{-1} (Table 1), while the epikarst drains 70 percent of the basin with a DOC concentration of 1.10 mg L^{-1} (Table 1). Even if all this epikarst water ends up in the cave, which seems highly unlikely, the expected contribution of DOC from sinking streams is about three times higher than that supplied by the epikarst. The figures for PPCS are even more striking. Sinking streams drain a much larger proportion of the basin (93%) and, when combined with DOC concentrations, sinking streams account for 99 percent of the DOC entering the subsurface.

However, the relative amount of DOC entering from epikarst and sinking streams will not be the sole determinant of the importance of those two carbon sources. First, DOC is a complex mix of organic molecules that differ in quality as energy sources and DOC composition likely differs between epikarst and sinking streams considering their differing origins. Second, the spatial distribution of percolating water is more widespread than that arriving in streams. Not all caves have sinking streams and many streams and pools in caves can be fed exclusively by percolating water. In these circumstances, the only source of organic carbon to much of the aquatic habitat in caves would be percolating water. Of course, there may also be cave passages deep underground with few or no drips, and it is likely that DOC decreases with depth, as it does in alluvial aquifers (Pabich et al., 2001, Datry et al., 2005). Third, the residence time of water arriving through epikarst drips and sinking streams is likely to be quite different. Most drip-fed streams are small, allowing greater time for organic matter uptake and processing than in fast-flowing, large channels fed by sinking streams. Ultimately, the relative importance of epikarst and sinking streams as organic carbon sources will depend on the relative magnitude of carbon flux arriving from each flow path, the composition of organic carbon arriving from each source, the residence time of water arriving via each flowpath, and the spatial extent of habitat fed by each source. These factors will need to be integrated into models of energy flux in karst and they may be quite variable among karst systems depending on the geological structure of the basins and distribution and composition of vegetation and soils on the surface.

How much biological processing of organic matter entering karst occurs is unclear. Processing of POC at the stream reach scale can be quite efficient in caves. For example, in Organ Cave most coarse organic matter (leaves and sticks) is transported only a few hundred meters into the cave before it is retained and broken down into smaller particles or consumed by animals and microbes (Simon and Benfield, 2001). In addition, rates of organic carbon turnover, estimated from organic carbon standing stocks and rates of metabolism, in Organ Cave streams are high compared to surface streams (Simon and Benfield, 2002). Processing of organic carbon at the basin scale is unknown. On one hand, in both Organ Cave and PPCS, DOC concentration at the resurgences was lower than that arriving through surface streams and in the streams within the caves, suggesting DOC was consumed in the aquifer. On the other hand, DOC concentration in the epikarst drips was similar to or lower than that at the resurgence, a trend also found in the Dorvan-Cleyzieu basin (Gibert, 1986; Simon et al., 2001). This highlights the need for careful measures of carbon flux, rather than only standing stocks, into and out of karst basins to generate mass balances that can be used to measure organic carbon processing at the basin scale. This may be difficult considering it may not be possible to access all portions of a basin. For example, Gibert (1986) measured the annual fluxes of DOC and POC from a spring draining a portion of the epikarst and another spring draining the base of the Dorvan-Cleyzieu basin, but these springs represented only a portion of the water moving through the basin, making it impossible to calculate whole-basin processing of organic carbon. Linking data regarding carbon fluxes in portions of basins to hydrological models of the whole basin may provide a means of scaling up carbon studies to the whole-basin level.

Conclusions

We believe an ecosystem perspective applied to karst holds the potential to greatly increase our understanding of the ecology and evolution of karst systems. The greatest challenges, and most promising data, will arrive from a careful accounting of inputs and outputs to a karst basin and measures of standing stocks and fluxes (transport and respiration) within basins. Ultimately, this will need to include an analysis of the quality and spatial and temporal distribution of organic matter inputs and outputs in karst. In comparing Organ Cave and PPCS, some similarities (e.g., lower DOC concentration in epikarst than sinking streams) emerged, but there were also differences (e.g., concentration of DOC in cave streams relative to other locations in the basin). This suggests that there will be some common features of organic carbon flux in karst, but not all basins will function the same. A careful integration of basin structure and hydrology should enhance our understanding of how different basins function.

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J. Molinari, E. Aldana, and J.M. Nassar – *Panstrongylus geniculatus* (Heteroptera: Reduviidae: Triatominae): natural infection with *Trypanosoma cruzi* under cavernicolous conditions in Paraguaná Peninsula, Venezuela. *Journal of Cave and Karst Studies,* v. 69, no. 2, p. 285–287.

PANSTRONGYLUS GENICULATUS (HETEROPTERA: REDUVIIDAE: TRIATOMINAE): NATURAL INFECTION WITH *TRYPANOSOMA CRUZI* UNDER CAVERNICOLOUS CONDITIONS IN PARAGUANÁ PENINSULA, VENEZUELA

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Abstract: The flagellate protozoan, *Trypanosoma cruzi*, causes Chagas disease, a zoonosis affecting millions of humans in the Americas. The triatomine insect, *Panstrongylus geniculatus*, a well known vector of this disease, inhabits and is infected with *T. cruzi* in Cueva del Guano, a limestone cave in Paraguaná Peninsula, Venezuela. *P. geniculatus* probably feeds on the blood of four rare or endangered bat species roosting in this cave, infecting them with *T. cruzi*. It is recommended that (1) any epidemiological activity at this cave be designed to minimize bat mortality, and (2) speleologists visiting tropical caves avoid contact with triatomine insects and their feces.

Introduction

Cueva del Guano is an underground limestone cave located in a flat thorn-scrub region, in Paraguaná Peninsula, Venezuela, at elevation 120 m. The cave has approximately 70 m of galleries, and has a 1 × 1 m entrance that opens on a 24 × 20 m antechamber, which in turn communicates with the exterior through an ample (15 × 6 m), 10 m deep, sink (SVE, 1972; Matson, 1974; Molinari et al., 2005). Inside the cave, atmospheric temperature is 31–36°C, and humidity is 88–96% (Matson, 1974; Bonaccorso et al., 1992). The crown of a large tree (*Ficus* sp.) rooted at the bottom of the antechamber occludes most of its sink. Therefore, the environment of the antechamber is dark, warm, and humid, though to a lesser degree than that of the cave proper.

Materials and Methods

On the nights of December 8–10, 2004, a team of four persons, including two authors and a British Broadcasting Corporation (BBC) filming crew, spent approximately 20 hours in the antechamber of Cueva del Guano observing centipedes and bats. On several occasions during this activity, the team observed groups of flying triatomine insects (Heteroptera: Reduviidae: Triatominae) being attracted to the light of headlamps. These insects appeared to belong to a single taxon identifiable (Lent and Wygodzinsky, 1979) as *Panstrongylus geniculatus* (voucher material collected), a species known for being easily attracted by artificial light (Lent and Wygodzinsky, 1979; Miles et al., 1981; Omah-Maharaj, 1992; Pieri et al., 2001). In addition, on the morning of December 10th, we captured one nymph, also identifiable as *P. geniculatus*, found resting on a wall of the antechamber. Because this nymph arrived alive at the laboratory, it was tested for infection with *Trypanosoma cruzi*, the protozoan causing Chagas disease, a zoonosis also affecting an estimated 16–18 million people in the Americas from Mexico to Argentina (Lent and Wygodzinsky, 1979; Prata, 2001). The test consisted of a microscopic examination of mixtures of its feces and hemocoel with isotonic saline solution. Abundant trypomastigotes (the infective stage of *T. cruzi*) were observed in the fecal mixture, and no trypomastigotes in the hemocoel mixture, a combination of findings indicating that the nymph was infected with *T. cruzi*, but not with *T. rangeli* (Cuba, 1998; Guhl and Vallejo, 2003). It must be noted that *P. geniculatus* is a major sylvatic vector for *T. cruzi* that has never been found naturally infected with *T. rangeli* or other *Trypanosoma* species (Lent and Wygodzinsky, 1979; Povoa et al., 1984; Omah-Maharaj, 1992; Guhl and Vallejo, 2003; Feliciangeli et al., 2004).

Results

P. geniculatus typically inhabits animal burrows, especially those excavated by armadillos (Lent and Wygodzinsky, 1979; Miles et al., 1981; Omah-Maharaj, 1992). Peridomestic colonies of the species have been found in Brazil (Valente et al., 1998; Valente 1999), and domestic colonies in Colombia and Venezuela (Angulo et al., 1999; Reyes-Lugo and Rodríguez-Acosta, 2000; Feliciangeli et al., 2004). Because triatomine nymphs are not capable of flight, and therefore have a low mobility, the finding of one *T. cruzi*-infected nymph (in addition to numerous adults) of *P. geniculatus* in the interior of the antechamber of Cueva del Guano proves that the species can be cavernicolous, and that it can act as a vector for Chagas disease in or around caves. To the authors' knowledge,

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only Omah-Maharaj (1992), who collected *T. cruzi*-infected nymphs in two caves (Caura, Tamana) in Trinidad, inhabited by seven bat species (*Anoura geoffroyi*, *Carollia pespicillata*, *Mormoops megalophylla*, *Natalus tumidirostris*, *Phyllostomus hastatus*, *Pteronotus davyi*, *P. parnellii* (Goodwin and Greenhall, 1961)), has reported similar findings for *P. geniculatus*. In addition, for *Triatoma pallidipennis*, another triatomine species, *T. cruzi*-infected nymphs have been found in bat-inhabited caves in Ticumán, Mexico (Villegas-García et al., 2001). Bats from the same locality, including cavernicolous (*Artibeus jamaicensis*, *Choeronycteris mexicana*, *Glossophaga soricina*, *P. parnellii*) and tree-dwelling (*Sturnira lilium*) species, were found to have high rates of infection with *T. cruzi* (Villegas-García et al., 2001).

Discussion

The finding of *T. cruzi*-infected triatomine nymphs in bat-inhabited caves (Omah-Maharaj, 1992; Villegas-García et al., 2001; this study), the known role of bats as reservoir hosts of *T. cruzi* (Barretto, 1985; Villegas-García et al., 2001), and the fact that Cueva del Guano is inhabited by 45,000–50,000 bats of five species (*Leptonycteris curasoae*, *M. megalophylla*, *N. tumidirostris*, *P. davyi*, *P. parnellii* (Matson, 1974; Molinari et al., 2005)), indicate that cavernicolous bats are likely to be a part of the sylvatic cycle of *T. cruzi* in Paraguaná Peninsula. However, it should be emphasized that bats are by no means the only possible source of blood for *P. geniculatus* in or around Cueva del Guano. Armadillos (*Dasypus novemcinctus*) and skunks (*Conepatus semistriatus*) inhabit small limestone cavities that abound in the area. A large rat (probably *Proechimys* sp.) and a marsupial (*Marmosa* sp.) have been observed by the research team on the branches of the large *Ficus* rooted in the antechamber, and a domestic goat and her calf sleeping under the crown of this tree. Some of these mammals (*Marmosa* sp., goat) have been observed inside the antechamber.

Conclusions

To conclude, it should be noted that Cueva del Guano is the refuge of four rare or endangered bat species, namely *P. parnellii paraguanensis* (probably deserving full specific status and known to exist in only three caves in the Peninsula (Gutiérrez and Molinari, in press)), *M. megalophylla* and *N. tumidirostris* (known in Venezuela from only a few caves (Linares, 1998)), and *L. curasoae* (a migratory species essential for the pollination of cacti and other plants of Venezuelan arid zones (Nassar et al., 2003)). Although protective measures are being taken, vandalism is reducing the populations of these species. Therefore, it is recommended that any epidemiological activity at Cueva del Guano be designed to minimize the disturbance and mortality of bats. It is also recommended that speleologists exploring tropical caves to learn to recognize triatomine insects, and avoid contact with them or with their feces.

Acknowledgements

BBC personnel, especially Tim Green and Saúl Gutiérrez, provided help during our stay in Paraguaná. We benefited from the protozoological expertise of Juan Luis Concepción to find and identify trypomastigotes.

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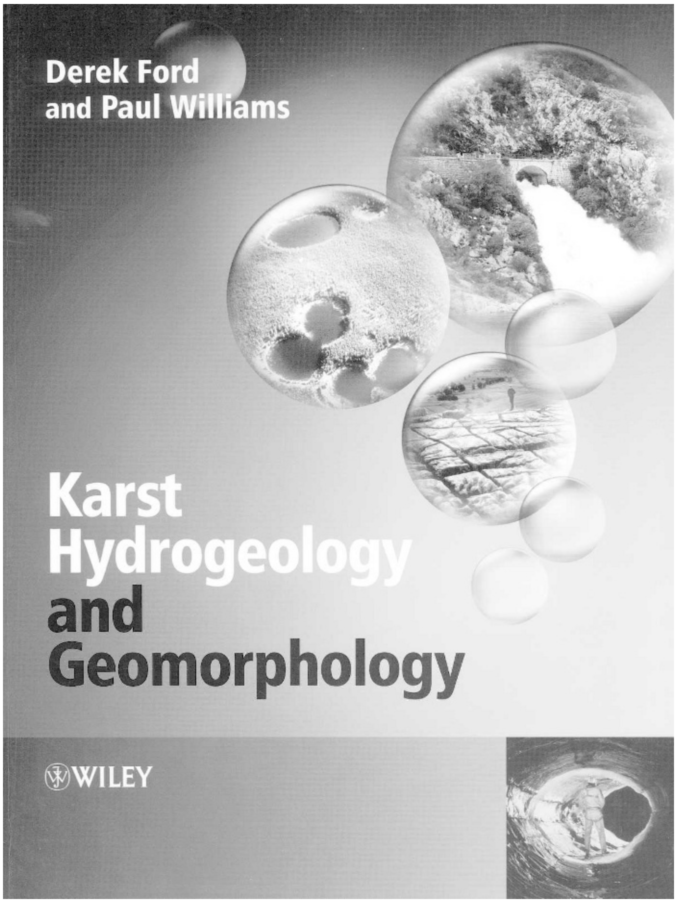
BOOK REVIEW



Karst Hydrogeology and Geomorphology

Derek Ford and Paul Williams, 2007. Chichester, U.K., John Wiley and Sons, Ltd., 562 p., 7.5 × 9.7 inches. ISBN 978-0-470-84996-5, hardbound, $165; 978-0-470-84997-2, softbound, $65.

This book is essentially the second edition of the authors' 1989 book, *Karst geomorphology and hydrology*. The change in title reflects a slight change of emphasis in the book and also highlights the increasingly important role of karst principles in addressing water-supply issues. The authors complement each other perfectly. They share similar backgrounds in classical British geomorphology. Ford specializes in cave processes, with emphasis on high-latitude and alpine karst. Williams is concerned mainly with karst surfaces and drainage patterns, with special attention to tropical karst. However, each has such a broad command of the subject that they are able to cover the entire field in an all-inclusive way.

The first edition had set such a high standard that writing a second edition posed a considerable challenge. It is impossible to keep up with the torrent of karst literature, even in one's own language, let alone on a global scale. A glance at the massive references section will show how well the authors have met this challenge. In addition, the revised book had tight space limits. To achieve the seemingly impossible, the page format has been slightly enlarged and the font size reduced, so that the original 601 pages, plus new material, have been compressed into 562 pages. Coverage of some topics has been reduced from the first edition, but with little loss of substance. The new book compresses two lifetimes of karst knowledge into a very compact package. It is not for casual reading, but it is clearly written and well organized.

Chapter topics are identical to those in the first edition, except that a 12th chapter has been added on human impacts and environmental rehabilitation. Chapter coverage is as follows: (1) Introduction to karst: definitions, scope, global distribution, evolution of ideas. (2) Karst rocks: rock types, origin of rocks, and structure. (3) Dissolution processes: a rigorous approach that resembles a chapter from a geochemistry book. (4) Karst denudation. (5) Karst hydrogeology: nature of karst ground water and flow dynamics. (6) Karst drainage systems: hydrographs, well tests, computer modeling of aquifers. (7) Speleogenesis: a very systematic approach, with expanded coverage of computer modeling. (8) Cave interior deposits: sediments, minerals; at least half the chapter deals with age dating and paleoclimatology. (9) Karst landform development. (10) Climatic influences on karst. The final chapter of the first edition has been split into two, with expanded coverage of both topics: (11) Karst water resources management and (12) Human impacts and environmental rehabilitation.

The new edition retains the look and feel of the first, and it is only by delving into specific topics that the substantial changes become clear. A great majority of the material is based on the authors' personal experience, as it should be, and their personal enthusiasm shows through. Because of space limitations, certain topics such as paleokarst receive less coverage than one might wish. But the many references give access to extensive literature on all topics discussed in the book. The flow of ideas is smoother, the graphics are enhanced, and there is more emphasis on practical application. A few errors have been corrected, but inevitably a few others have crept in. Anyone bothered by this has clearly never tried to proof-read a lengthy technical book.

A comparison with other recent karst books is appropriate. W.B. White's *Karst Geomorphology and Hydrology* (Oxford Press, 1988) covers only the basic topics but in a more analytical way, with emphasis on functional relationships; its examples are mainly from the USA. W. Dreybrodt's *Processes in Karst Systems* (Springer, 1988) concentrates on the physical chemistry and hydraulics of karst aquifers and provides a basis for the extensive digital karst modeling that he and his colleagues have done since. The volume *Speleogenesis – Evolution of Karst Aquifers*, edited by A. Klimchouk and others (NSS, 2000) concentrates mainly on the development of solution conduits and caves; it is well organized, but, like most multi-author works, its coverage is uneven in style and detail. Two recent encyclopedias on caves, edited by J. Gunn (2004) and D. Culver and W. White (2005) for Fitzroy-Dearborn and Academic Press respectively, contain an enormous amount of material extending well beyond the physical aspects of the subject, but (as in any encyclopedia) presented in disconnected pieces. The several volumes on karst hydrology and related topics written over the past few decades by P. Milanović (Lewis Press) are tightly focused on practical aspects of water supply and engineering in karst, with little theoretical or conceptual basis.

Anyone with a serious interest in karst will find the new volume by Ford and Williams to be useful. Should those who own the first edition also buy the second? For anyone so deeply involved as to ask this question, the answer is yes. The greatest benefit of all may be for those in fields other than karst, who need a knowledge of the subject for application to their own professions. Ground-water hydrologists come to mind, and that is a substantial reason for the change in emphasis in the book's title and contents. The soft-cover edition is robust enough to handle extensive use. Except for libraries and book collectors, an additional $100 seems a steep price for a hard cover.

This new edition strengthens the book's position as the essential reference in the field. Karst geoscientists will not dare to stray beyond arm's reach of this volume. It is certain to remain the professional standard for many decades.

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Adits, Caves, Karizi-Qanats, and Tunnels in Afghanistan: An Annotated Bibliography
by R. Lee Hadden

Topographic Engineering Center
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November 2005

Adits, Caves, Karizi-Qanats, and Tunnels in Afghanistan: An Annotated Bibliography

R. Lee Hadden, 2005. Topographic Engineering Center, U.S. Army Corps of Engineers, 80 p. Free PDF download at http://stinet.dtic.mil/cgi-bin/GetTRDoc?AD=ADA444101&Location=U2&doc=GetTRDoc.pdf.

Shortly after 9/11 the United States invaded Afghanistan with the intention of dislodging the Taliban government and Al-Qaeda. In particular, the leader of the Taliban, Mullah Mohammed Omar, and the leader of Al-Qaeda, Osama bin Laden, were desired targets. However, after the invasion, these two individuals and other high-value targets reportedly escaped into the Tora Bora caves and/or tunnels in the White Mountains near the Khyber Pass.

U.S. and coalition forces found themselves unfamiliar with the Tora Bora Mountains and sent out a request for cave and karst experts to provide any information available on the caves of Afghanistan and methods for detecting caves. Although I have no knowledge of what information was forwarded on to the U.S. Army, I suspect that the information received was less than hoped for. In addition, as explained in the Introduction, the bibliography was also begun as a result of requests from numerous individuals and groups (geologists, hydrologists, cavers, etc.) for information on the caves, adits, tunnels, etc., of Afghanistan.

As a result of this demand for information, Lee Hadden, of the U.S. Geological Survey, transferred to the Army Corps of Engineers, where he undertook the development of a comprehensive bibliography of caves, tunnels, and other geological information in Afghanistan. As described in the abstract, this document combines selected citations from diverse sources that include cartographic, geological, and speleological materials, many of which were obtained from specialized library collections. The publications, reports, and maps in Arabic, English, French, German, Italian, Russian, and other languages were inventoried from several government and/or private libraries and geological information centers.

Citations were taken from sources openly published, which negated any need for military classification. It stands on its own. All URLs listed in the report (and there are many) were active as of November 2005. (Note the current web site date for this document is March 6, 2006, so it may have been updated some since its original publication.) As of the writing of this review, the web site for this bibliography was still available. However, should the site become inactive, this report will still be available from the National Speleological Society web site.

This is not light reading to settle in with before turning out the light at bedtime. As expected from a bibliography, it literally reads like the references section at the end of a journal article. However, it does contain a wealth of information and is detailed and carefully organized. Some color figures are published in the bibliography, and many URLs are listed in blue so they are readily visible even at a casual glance.

Because of the bibliographic nature of this document, it is difficult to recommend it to those with only a passing interest in Afghanistan. However, given the reasonable cost (a free download), large number of citations, quality, attention to detail, and the ongoing military operations in Afghanistan, it is worth checking out. Lee Hadden has produced a significant and important document that may be of considerable value to many individuals now and in the future. For these reasons, I recommend it to all interested individuals.

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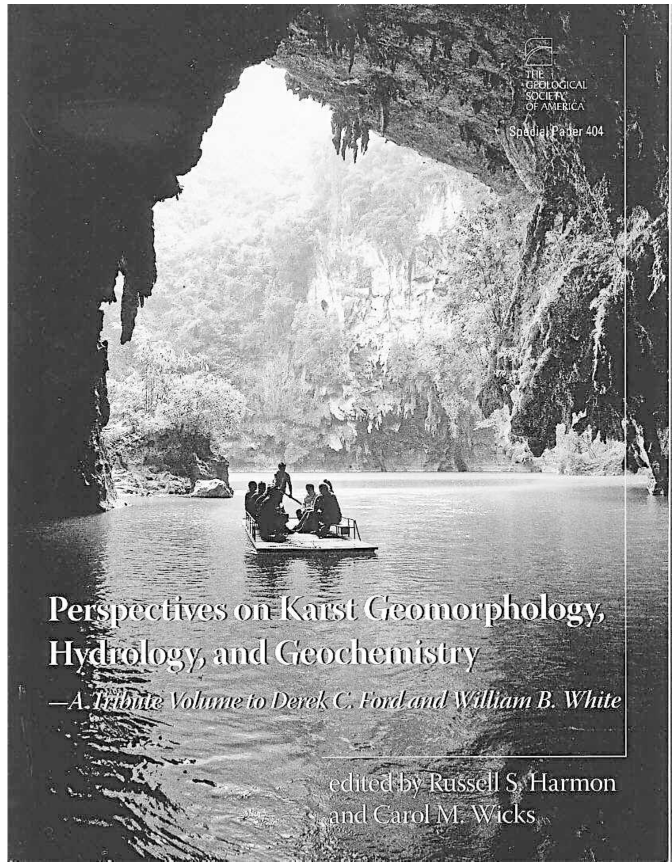

Perspectives on Karst Geomorphology, Hydrology, and Geochemistry—A tribute volume to Derek C. Ford and William B. White

Russell S. Harmon and Carol M. Wicks (eds.), 2006. Geological Society of America, Special Paper 404, 366 p. ISBN 978-0-8137-2404-1, softbound, 8.5 × 11 inches, $95 for nonmembers or $67 for members. Order online www.geosociety.org or from Geological Society of America, 3300 Penrose Place, P.O. Box 9140, Boulder CO 80301-9140.

This volume contains papers on a broad range of karst topics, many of them by professional colleagues and former students of Derek Ford and William White. Both Derek and Will have recently retired from highly successful teaching careers at McMaster University and Pennsylvania State University, respectively, and both continue to pursue active karst research. This book is a tribute to their careers and also to their joint receipt in 2004 of the Distinguished Career Award from the Quaternary Geology and Geomorphology Division of the Geological Society of America.

The book reflects the kinds of topics that Derek and Will championed, and which are now integral to karst research. The authors include a large proportion of North America's leading karst specialists, and a few from overseas. Typical for a commemorative book, many of the chapters are updates of previously published work, but they are expanded with new insight. To my knowledge, none are simple retreads of earlier papers.

The book's 28 chapters are divided almost equally into three sections: geomorphology, hydrology, and a loose category of geochemistry-mineralogy-biology. These are preceded by several tributes to Derek and Will. Two chapters are provided by the honorees themselves: Ford reviews North American contributions to karst geomorphology, caves and deposits, and White summarizes the past half century of karst hydrology.

The geomorphology chapters describe field sites around the globe. Topics include dating of karst events in the Cumberland Plateau of Tennessee; use of detailed structural mapping in West Virginia to determine early conduit development; and confined, bathyphreatic cave development in Missouri. Studies in other countries cover the origin of springs by rising volcanic sulfides in Tamaulipas, Mexico; the extensive karst drainage systems of the Yucatan Peninsula; caves in brecciated, non-bedded carbonates in Belize; the strange karst of the Nullarbor Plain in Australia; varied karst processes in young limestones of the Mariana Islands, and Kenyan caves dug by elephants to obtain salts from the volcanic host rock.

The hydrology chapters have a strong emphasis on the Florida karst. Of these, some deal with water supply, such as problems of groundwater overdraft in Florida; dewatering of aquifers by evaporation and enhanced drainage caused by excavations; and ground-water contamination in southern Indiana. Many chapters concern borehole investigations: comparison of head variations in monitoring wells to those in nearby cave passages to determine the hydraulic properties of an aquifer; geochemical tracing of ground water; estimating porosity from stratigraphy, borehole imagery, geophysics, and GIS-based spatial analysis. Other topics include sediment variation during storms to interpret the pattern of subsurface conduits; the persistent view of non-karst hydrologists that karst aquifers behave like porous media; and problems and promises of digital modeling of karst aquifers.

Geochemical-mineralogical topics include the storage of contaminants in cave sediments; changes in CO_2 level vs. saturation index in a karst aquifer; speleothem types and growth rates vs. water chemistry; geochemical clues to calcitization of aragonite speleothems; and speleothem luminescence and its value for interpreting past environmental changes. Finally, two biological topics are considered: a comparison of microbially-driven sulfur systems on Earth with potentially similar ones on Mars; and biological influence on speleothem growth, especially around cave entrances.

This may seem like an eclectic group of topics, but they all provide valuable information about recent advances and field techniques. In the future, this book will provide a clear snapshot of the state of karst research at the beginning of the 21st century.

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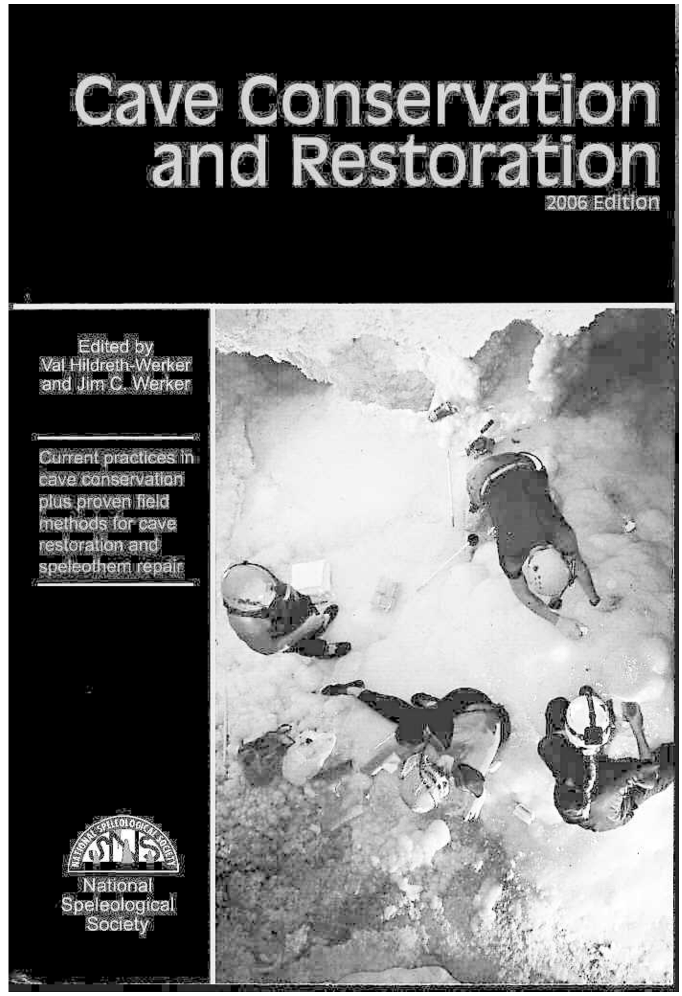

Cave Conservation and Restoration

Val Hildreth-Werker and Jim C. Werker, 2006. Huntsville, Ala., National Speleological Society, Inc., 600 p. ISBN 1-879961-15-6, softbound, 7.0 × 10.25 inches, $37 for NSS Members; $39 regular retail price. Order on-line at www.NSSBookstore.org.

This book was edited by the co-chairs of the NSS Conservation Committee, who also happen to be the co-editors for the annual Conservation issue of the NSS News, which is published in March of every year. In fact, the March 2007 issue of the NSS News includes a brief introduction to the book with a series of quotes from the Foreword of the book written by Ronal C. Kerbo (Werker and Hildreth-Werker, 2007).

The emphasis of this book is primarily on cave restoration and repair, but also includes discussions on conservation. It is recognized that any form of intrusion by man has an impact on a cave. In this instance, intrusion is not limited to physical entry, but may also include releases of waste streams and other similar types of impacts.

To be as broad as possible in coverage, this book utilized the expertise of 46 scientists, karst conservations, cave restorationists, and speleothem-repair experts. The intent of this book is for use as a field manual emphasizing best management practices in cave conservation and management. Information is presented in easy-to-find sections that are cross-referenced and indexed.

Most figures and photos appear as black-and-white, but a selected set of photos are shown in full color in the center of the book and are also cross-referenced. Units of measure are written in both metric and English throughout, but because construction materials sold in the United States are measured in English units, construction materials necessarily deviate from the metric/English format.

As with any undertaking of this magnitude, it is likely that some individuals will find some omissions, although I seriously doubt that very many will be noted. I did detect some typographical errors and some formatting discrepancies, but none of any real consequences.

Cave Conservation and Restoration consists of four parts, each of which is broken down into sections that are further subdivided into papers detailing a particular conservation or restoration issue related to caves; 84 separate papers in all, plus eight Appendices and Biographical Notes! Many of the papers are no more than a few pages long, which makes for quick reading in some instances. More complicated protection or restoration issues necessarily required longer papers.

Part One includes the Introduction which is broken down into a Foreword and Preface, both of which are well-worth reading. This part really explains how the book came about and its importance.

Part Two emphasizes Cave Conservation, Management, and Ethics. It is further divided into sections that include several papers each. The sections are: Section A Identifying and Protecting Cave Resources; Section B Developing Cave Management Programs; and Section C Improving Caver Ethics. Although perhaps less exciting than the physical restoration and/or repair of caves and cave features, it remains a vital aspect of cave protection and deserves the prominent position near the beginning of the book

Part Three focuses on Cave Restoration, which might be more exciting to some individuals. It includes the following sections: Section A Introducing Cave Restoration; Section B Organizing Cave Projects; Section C Restoring Cave Passages; and Section D Restoring Speleothems. Reading this section will likely get many cavers thinking about their impact on caves and possible plans for restoration. This section probably should be read over prior to undertaking even a minor cave restoration project (if there is such a thing as minor).

Part Four moves on to actual Speleothem Repair with the following sections: Section A Introducing Speleothem Repair; Section B Repairing Speleothems; Section C Specialized Mechanical Assists; and Section D Success Stories and Blunders. Referring back to the Foreword by Ronal Kerbo, one finds a disturbing discussion of a vandal's attempt to steal the Candle Table ("a beautiful stalagmite with rimstone encircling its top") from a cave high in the Guadalupe Mountains of southeastern New Mexico (Kerbo, 2006, pp. 3–5). It was later repaired by Ron Kerbo, Joe Spencer, and Jerry Trout (who is currently the National Cave Coordinator for the USDA Forest Service). Techniques developed over many years of experience by numerous individuals involved with such vandalism as the destruction of Candle Table went into the writing of Part Four, even though the number of authors for this part are limited to just a few.

Given the very reasonable price for this book and its importance to all cave and karst enthusiasts, I strongly recommend its purchase. From exploring to actual physical restoration or repair, it doesn't matter because of the nature of the information contained therein. Scientists planning on conducting studies in caves that might adversely impact the cave of interest should consider reviewing relevant sections of this book prior to initiating the study.

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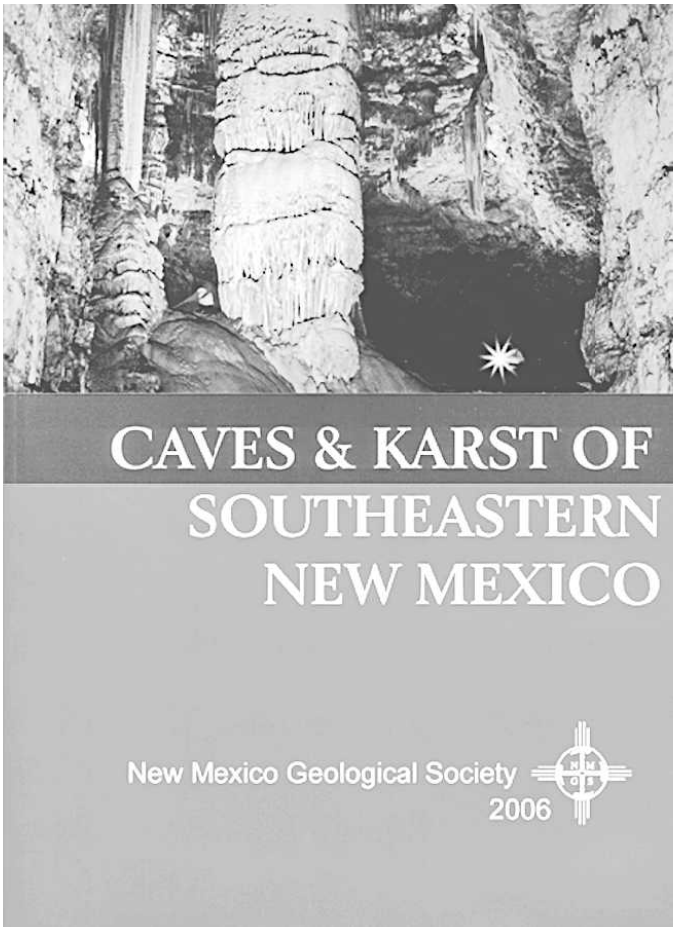
Reviewed by Malcolm S. Field, National Center for Environmental Assessment (8623D), Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC 20460 (field.malcolm@epa.gov).



Caves and Karst of Southeastern New Mexico

Lewis Land, Virgil W. Lueth, William Raatz, Penny Boston, and David L. Love (eds.), 2006. Socorro, NM, New Mexico Geological Society, 2006, 344 p. ISBN 1-58546-092-3, softbound, 8.5 × 11 inches, $50.

This is the guidebook for New Mexico Geological Society's 57th annual field conference, held in September, 2006, at Washington Ranch, near Carlsbad. The first 109 pages are heavily annotated road logs for geology field trips. Then 16 color plates are followed by 22 technical papers. While the road logs and their discussions necessarily cover mostly surface features, one of the articles is a detailed geologic guide to the self-guided tour of Carlsbad Cavern. Another article discusses Fort Stanton Cave, and in particular, the recently discovered Snowy River Passage, with an emphasis on the paleohydrology of the cave. A number of articles discuss sulfuric-acid speleogenesis in the area or compare it to examples elsewhere. Victor Polyak et al. give a longer exposition of the $^{40}Ar/^{39}Ar$ dating of Guadalupe Mountains caves first published in *Science* in 1998. Several articles discuss evaporite karst at the (radioactive) Waste Isolation Pilot Plant east of Carlsbad. A few of the articles are not really on topic, but I found one of them, about the history of geologic investigations in the area through 1928 and the long controversy about the date of the rocks there, particularly interesting.

The book is generally well produced, although some illustrations are reduced too much and the binding-edge margins are way too narrow. *Caves and Karst of Southeastern New Mexico*, which is dedicated to Carol Hill, gives a more readable, if less comprehensive, overview of the cave geology in the area than Hill's 1987 monograph.

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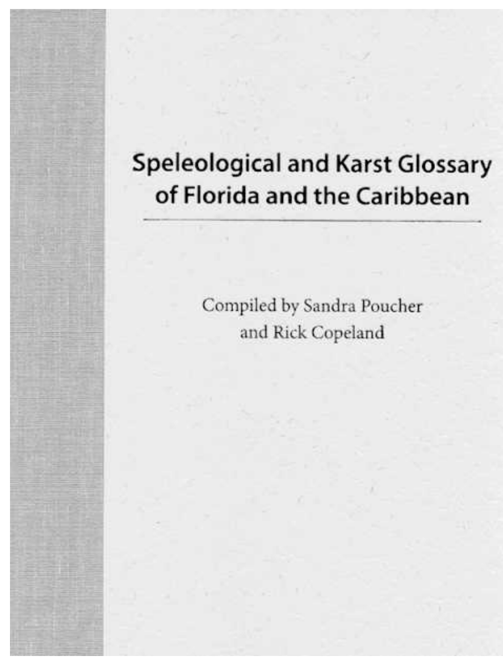


Speleological and Karst Glossary of Florida and the Caribbean

Sandra Poucher and Rick Copeland (eds.), 2006. Gainesville, Florida, University Press of Florida, 196 p. ISBN 0-8130-3006-4, hardcover, 6 ¼" × 9 ¼ inches, $34.95.

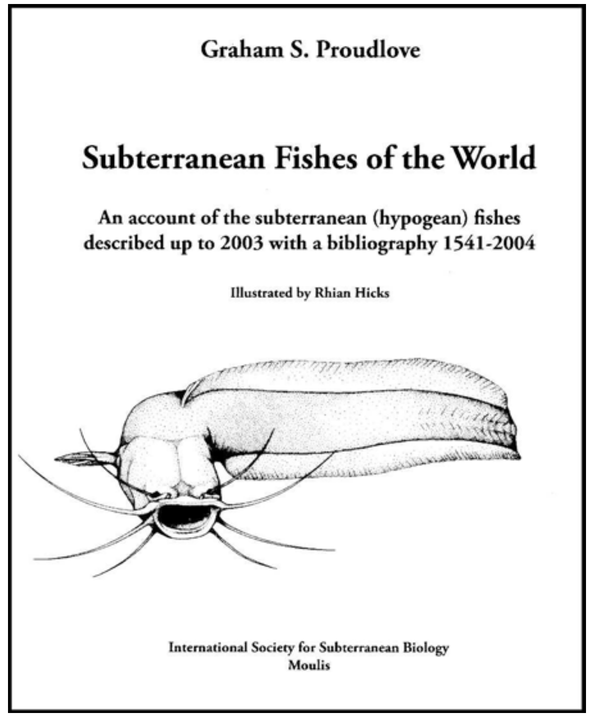
This volume brings together representative terminology from several distinct fields of study, notably caving and cave diving, speleology, geology, biology, hydrology, legislative and regulatory matters, toxicology and environmental monitoring, surveying, and resource management—

as well as various miscellaneous subjects that do not conveniently fit any category. At first glance, these may seem to be very disparate disciplines; however, they share a common ground in that they all relate to the scientific study, conservation, and long-term management of caves and underground water resources. Wise stewardship of these valuable and irreplaceable resources requires the coordinated efforts of a variety of professionals who must have at least a general knowledge of the roles played by each other. This glossary should serve as a useful reference for those who need definitions of terms that may only be tangentially related to their own particular fields, but are still allied to the general topic of karst hydrogeology.

Definitions in the book have been taken from a variety of sources—some more authoritative than others. References are included after each entry. When a term is commonly used in more than one context, multiple definitions are provided. Another useful feature is that frequent reference is made to other entries that may be synonyms, antonyms, or otherwise closely related to a particular term. Because of the technical nature of many entries, some definitions rely on the use of yet other technical terms, many of which are themselves defined elsewhere in the text. However, some definitions are based on specialized terms that remain undefined anywhere in the text. This can make it rather difficult to tease out the meaning of some words.

All definitions are terse and to the point. Coverage is not encyclopedic, and no significant attempts seem to have been made to clarify—or to simplify in lay terms—difficult concepts for the reader who is not already well informed about the field. Thus, the ease of fully understanding many of the technical definitions will vary with one's familiarity with the subject, or one's motivation to delve into other resources. This is not necessarily a shortcoming. The book is, after all, meant to be a glossary and not a comprehensive encyclopedia of terms. This compilation will serve admirably as a springboard to direct one's attention to certain topics that can be pursued in more depth elsewhere. In gathering together in one place such a diverse set of terms, this work represents a long-overdue first step in breaking down interdisciplinary barriers caused by specialized jargon and scientific terminology—definitions of which sometimes require considerable legwork to track down.

Reviewed by Danny A. Brass, 70 Livingston St., Apt. 3K, New Haven, CT 06511-2467 (brassda@yahoo.com).



Subterranean Fishes of the World: An account of the subterranean (hypogean) fishes described up to 2003 with a bibliography 1541-2004

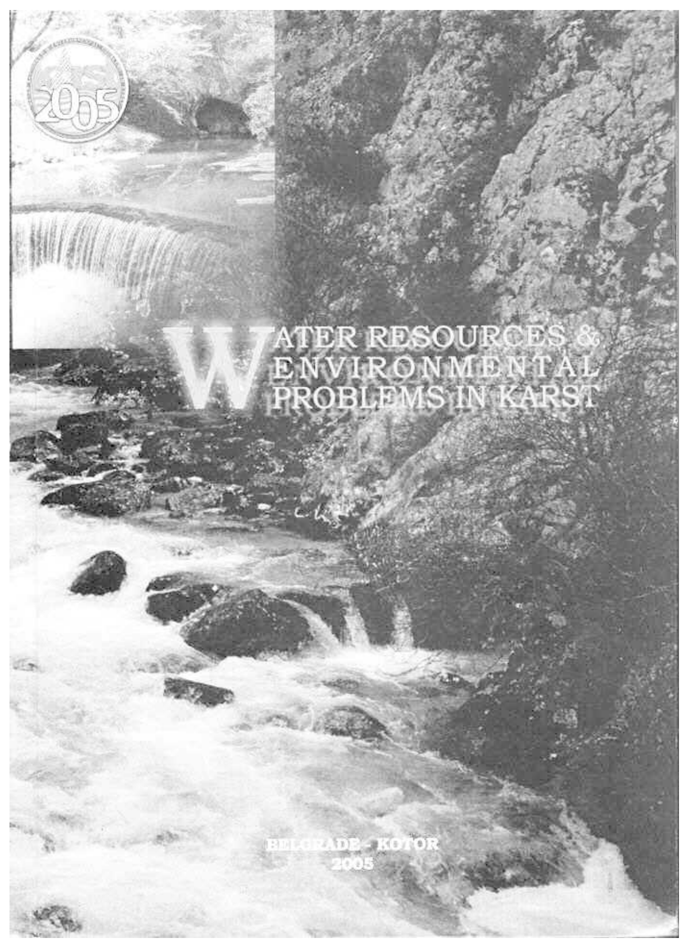
Graham S. Proudlove, July, 2006. International Society for Subterranean Biology, Format: 304 pages, 87 black and white figures, 20 colour plates. Illustrations by Rhian Hicks. ISBN 10 2-9527084-0-1. ISBN 13 978-2-9527084-0-1, 8.25 × 11.5 inches, $65, 50 €. Distributors: www.speleobooks.com (USA), www.caves.org (USA), www.nhbs.co.uk (UK), www.stevensimpsonbooks.com (UK) and www.speleoprojects.com (Switzerland).

There are almost 30,000 described species of fish. In comparison, the diversity of hypogean species—with somewhat more than 100 species—may seem limited, but these fish have proven to be of extraordinary interest in biological research. Hypogean fishes serve as model systems in various disciplines such as developmental biology, ethology, ecology, and evolution. The underground provides unique habitats in which fishes from various phylogenetic lineages have evolved. These products of evolutionary change are some of the most bizarre and fascinating creatures. The specialized morphology of cave fishes, with their reduced eyes and pigmentation, is but one consequence of life in darkness. Owing to the scarcity of energy, for example, many cave fishes have a reduced metabolic rate, which allows some species, like the northern cavefish *Amblyopsis spelaea*, to survive up to two years without food.

The interest in hypogean fishes is reflected in the vast number of publications currently available. One of the Proudlove's major objectives is to provide a complete overview of the published literature on this subject, and the bibliography is the key element of the book. With meticulous effort over more than 20 years, he has collected roughly 1600 references on the subject. He considered not only scientific journals but also "gray literature," which is often difficult to find. *Subterranean Fishes of the World* is certainly the most concise account of hypogean fishes to date.

The book is divided into the following sections: (1) A short introduction on the biology of hypogean fishes is provided, which highlights their geographic and systematic distribution. This section also includes an overview of non-stygobitic fishes in caves and a history of cave-fish investigations from 1842 through 2003. (2) A section dedicated to species described up to 2003, as well as some known but undescribed forms, with taxonomic and systematic information (Family, Types, Systematics, Museum holdings). A figure illustrating most of the species gives the reader an excellent impression of the morphological diversity of cave fishes. Some species are also shown in color photos at the end of the book. Information on distribution and habitats complete the individual accounts. Finally, a list of references (or key references for species that have been more extensively investigated) links the species accounts to the comprehensive bibliography. In places, Proudlove goes beyond reciting published literature and provides his own inferences and conclusions. For example, he suggests that various cave forms that are currently considered nonspecific with related surface forms (e.g. *Poecilia mexicana* or *Garra barreimiae*) should be treated as distinct taxa based on the phylogenetic species concept. Proudlove noncludes that the valid name for the Mexican cave tetras is not *Astyanax mexicanus* but *A. jordani*. This notion will certainly be debated in the scientific community and warrants more research. (3) Six appendices include explanations of abbreviations, institutions, and specific terms, as well as lists of blind and depigmented fishes from non-subterranean habitats, species that once were considered to be subterranean but are not known to be so, and non-troglobitic fish reported from caves worldwide (a contribution by Bill Poly). A compilation of relevant addresses leads readers to further sources.

While reading the accounts of individual species, one notices an enormous skew in the amount of research that has been conducted on the different species. For example, some species have only one reference (usually the first description), whereas others may have dozens. A drawback of the book is the lack of detailed data on the ecology of certain species. However, Proudlove cannot be blamed, because this information is only available for very few species. For the most part, we currently have no idea of how these fish behave, what they eat, or how they reproduce. Basic knowledge about the ecology and population biology of cave fishes would be important in developing efficient management and conservation plans. Many species of hypogean fishes, as Proudlove points out,



Water Resources and Environmental Problems in Karst

Zoran Stevanović and Petar Milanović, 2005. Institute of Hydrogeology, Faculty of Mining and Geology, University of Belgrade, Djušina 7, Serbia & Montenegro, 903 p. ISBN 86-7352-144-0, hardbound, 7.25 × 9.625 inches, 45 €. Order via e-mail from Zoran Stevanović (zstev@eunet.yu).

This book is a special publication of the Institute of Hydrogeology of the University of Begrade and is the Proceedings of the International Conference and Field Seminars organized by the National Committee of the International Association of Hydrogeologists (IAH) of Serbia and Montenegro held in Belgrade and Kotor in September 2005. It is dedicated to the famous Serbian karst scientist, Jovan Cvijić, to mark the 110th anniversary of his publication, "Karst" (see review of the book, "Cvijić and Karst," in this issue).

The five main topic areas, all environmentally focused, were emphasized at this conference. They are listed as:

1. Vulnerability of karst environments and ecological problems,
2. Management and sustainable use of karstic water resources,
3. Hydrogeology and multidisciplinary research of karst,
4. Impact of man-made structures on karst ecosystems, and
5. Vulnerability of geo- and bio-diversities in karst and their protection, legal aspects and environmental education.

A total of 132 papers by 304 authors representing 32 countries from six continents are roughly equally distributed among the five main topic areas.

The first topic area covers various vulnerabilities of karst environments, with papers raging from vulnerability mapping (e.g., EPIK, PI methods) and pollution assessment (e.g., DNAPL remediation), with an emphasis on ground-water protection, to more obscure topics such as seismic impact of explosive blasts in quarries on spring discharges. None of the papers really address ecological problems to any significant degree, which I found disappointing. Mostly, the papers address ground-water contamination problems that naturally affect the biota. In the future, I would like to see more detailed ecological papers, which is sorely in need of more comprehensive studies.

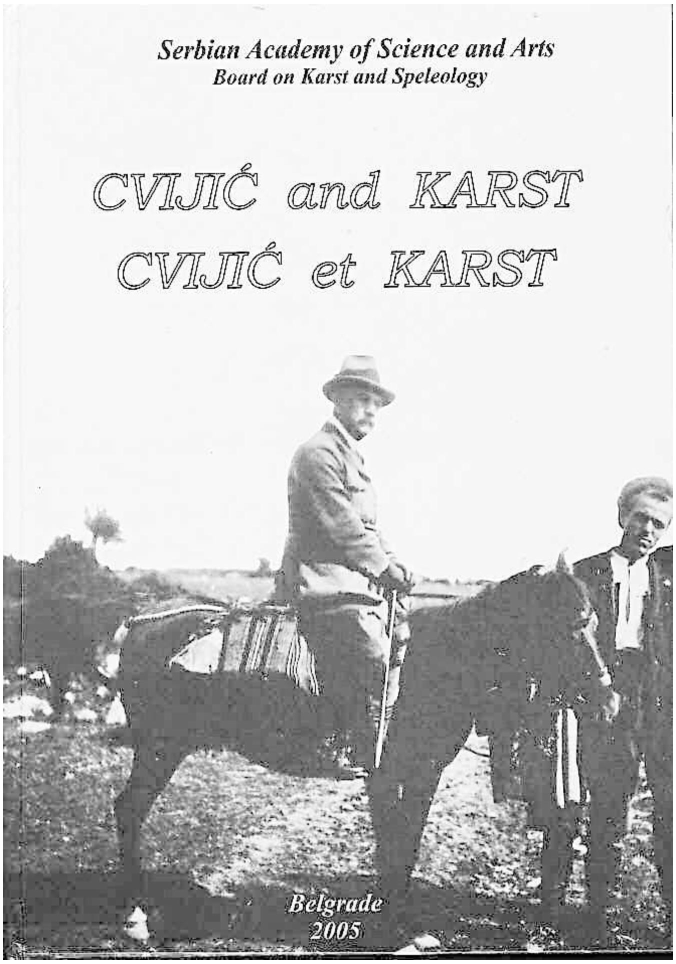
The second topic area on management of karstic aquifers will be very interesting to those individuals involved in the exploitation of water resources. Groundwater supply from karstic aquifers is often a difficult undertaking and this section covers many important aspects, from aquifer descriptions, to issues associated with coastal zone aquifers, to physical exploitation and regulation. Of particular significance to me was Richard Parizek's paper on enhanced management of karstic aquifers, which is practical and relevant to problems in many areas in the U.S.

The third topic area, hydrogeology, covers many aspects of common investigative techniques for groundwater flow and transport in karstic terrains. These techniques range from ground-water tracing and spring flow hydrograph analysis, to methods for addressing submarine springs. This is the largest section in the book with many very interesting papers that mostly address advances in the common techniques used for years.

The last two topic areas, impacts of man-made structures and vulnerability of geo- and bio-diversities, address more engineering and legal aspects, respectively. Impacts of man-made structures is the shortest section, but still significant. Most of the impacts papers cover the problems associated with tunnels and grout curtains. The vulnerabilities section is longer and mostly focuses on various aspects of protecting and managing karst aquifer systems. This section by far covers more ecological-based papers with its focus on biodiversity than any of the other topic areas. However, its inclusion of geodiversity adds to its value because the unique ecology of karstic systems is dependent on the geology, so one cannot be emphasized without the other.

The amount of information contained in this book makes it well worth the relatively modest price of 45 € ($61.21 at the time of this writing). It represents an up-to-date listing of some of the more pressing karst environmental problems and possible solutions we currently face.

Reviewed by Malcolm S. Field, National Center for Environmental Assessment (8623D), Office of Research and Development, U.S. Environmental Protection Agency, Washington, DC 20460 (field.malcolm@epa.gov).



Cvijić and Karst
Cvijić et Karst

Zoran Stevanović and Borivoje Mijatović, 2005. ZUHRA Belgrade, Serbian Academy of Science and Art (SASA) and its Board on Karst Speleology, 405 p. ISBN 86-7025-381-X, hardbound, 7.25 × 9.50 inches, 25 €. Order via e-mail from Zoran Stevanović (zstev@eunet.yu).

This book represents a special commemorative edition published by the Serbian Academy of Arts and Sciences to mark the 110th anniversary of publishing of the monograph *Karst* by Jovan Cvijić. It contains extracts of two of Cvijić's most important studies (one in English and the other in French), as well as articles written by well-known international scientists about Cvijić's work, life, and evaluations of his contribution to hydrogeology, geomorphology, tectonics and human sciences.

This book was arranged to (1) present a short biography of Cvijić's life, (2) translate and present Cvijić's essential theories and conclusions from his seminal works, and (3) present the opinions of some present day karst experts in geology and hydrogeology. Biographies developed by P. Vujevic in 1957 and more recently by M. Vasovic in 1997, along with a diary written by Cvijić's wife, form the first part of this book.

Part 2 of this book consists of selected extracts of Cvijić's famous monograph, *Karst, A Geographic Monograph* (published by the Royal Publishing House Belgrade in 1895), that were translated into English and published in this book. This monograph is essentially a translation of Cvijić's doctoral thesis *Das Karstphänomen, Versuch einer morphologischen Monographie*. The excerpts chosen for translation focus mostly on the influence of water, the genesis of karstic features, and the karstification process, with a particular emphasis on the formation of dolines (sinkholes). In terms of the formation of dolines, Cvijić's discussion in the monograph, with supporting examples based on practical experience, made the case for erosive processes working on fissure networks at the karst surface. His arguments were so persuasive as to render the theory of cave roof collapse almost an afterthought. This monograph also addresses karren, karstic rivers, sinking streams, karst springs, waterfall genesis, and various karst valleys (blind, semi-closed, and dry). In particular, his chapter on poljes is significant in that he provided a definition, classification and explanation of hydrologic functions, and geological structures and genesis of poljes as the largest karst-landscape feature.

Selected extracts from Cvijić's monograph *La Geographic Des Terrains Calcaires* (published in French) were also included in this book, but without translation into English. It is a compilation of Cvijić's work begun just before he died. The most important chapter, Factors in Karstification, emphasizes "karst underground hydrography" was based on two earlier articles, *Circulation des eaux et erosion karstique* and *Hydrographie souterraines et evolution morphologique du karst*. This was the one disappointing aspect of the book to me because I don't read French and would have liked an English translation.

Finally, the opinions, evaluations, and statements of some renowned karst experts round-out this book. Introductory essays by D. Ford and H. Zojer initiate this part. It is followed by extracts of previously published articles by J. Zötl, P. Lamoreaux, M. Bleahu (in French), and J. Nicod (in French) on the history of hydrogeology and karstology. This is followed by articles emphasizing Cvijić's role in hydrogeology, summaries of Cvijić's contributions to the state of modern karst science, analyses of Cvijić's contributions to geology and tectonics, and an assessment of Cvijić's effort at anthropogeography. Unfortunately, many of these reviews appear in French.

Although much of this book was published in French, it is well worth the price of 25 € ($33.86 at the time of this writing). It contains a wealth of historical karst information, as well as being very interesting to read regarding the development of modern karst studies.

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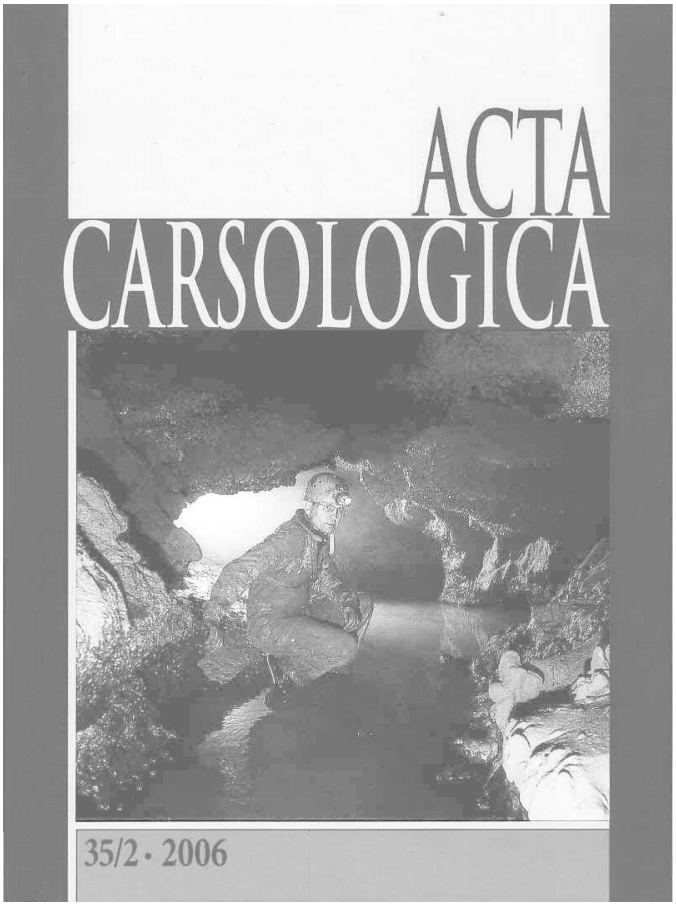

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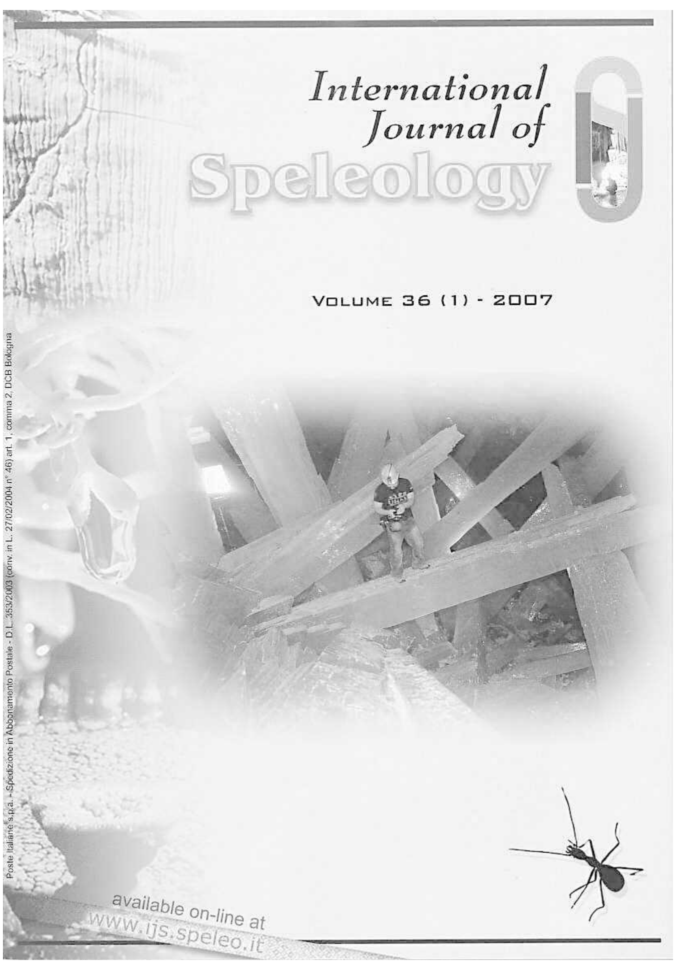

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Book Reviews

GUIDE TO AUTHORS

The *Journal of Cave and Karst Studies* is a multidisciplinary journal devoted to cave and karst research. The *Journal* is seeking original, unpublished manuscripts concerning the scientific study of caves or other karst features. Authors do not need to be members of the National Speleological Society, but preference is given to manuscripts of importance to North American speleology.

LANGUAGES: The *Journal of Cave and Karst Studies* uses American-style English as its standard language and spelling style, with the exception of allowing a second abstract in another language when room allows. In the case of proper names, the *Journal* tries to accommodate other spellings and punctuation styles. In cases where the Editor-in-Chief finds it appropriate to use non-English words outside of proper names (generally where no equivalent English word exists), the *Journal* italicizes them. However, the common abbreviations i.e., e.g., et al., and etc. should appear in roman text. Authors are encouraged to write for our combined professional and amateur readerships.

CONTENT: Each paper will contain a title with the authors' names and addresses, an abstract, and the text of the paper, including a summary or conclusions section. Acknowledgments and references follow the text.

ABSTRACTS: An abstract stating the essential points and results must accompany all articles. An abstract is a summary, not a promise of what topics are covered in the paper.

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